# Engineering-geological properties of carbonates and shale: their implications for dam construction in Mekelle, Northern Ethiopia

**Asmelash Abay[1*] and Claudia Meisina[2]**
[1]Department of Earth Sciences, College of Natural and Computational Sciences, Mekelle University, P.O. Box 231, Mekelle, Ethiopia (*asmelashby@yahoo.com).
[2]Department of Earth and Environmental Science, University of Pavia, Italy.

## ABSTRACT

Growing water demand poses severe problems to the population in the Mekelle Outlier, Northern Ethiopia. Hence, storing of rain water for water supply becomes one of the top agenda in the area. Several earth-fill dams are constructed for irrigation and drinking water supply purposes over the last 15-20 years. However, as collected data indicated more than 60% of these earth-fill dams have excessive leakage due to the problematic engineering geological nature of the carbonates and shale rocks of the study area. Giba dam is one of the currently proposed largest dams to alleviate the water supply problem of the Mekelle city. In the current study, engineering-geological mapping, core drilling, geophysical surveys and laboratory works have been conducted for the dam project to evaluate the engineering-geological nature of rocks of the area. Qualitative and quantitative rock masses properties such as permeability, strength and deformation are analyzed using Packer test, Rock Quality Designation (RQD), and Rock Mass Rating (RMR) systems. Analyzed results displayed that: (i) the RQD values are highly variable for all the rock masses. For example, 60% of limestone (Lst), 50% marly limestone (MLst) and 72% shale (Sh) are categorized as poor /very poor RQD values. RMR values also imply that Lst, MLst and gypsum are classified class-III while Sh is classified in class-IV (ii) considering the rock mass shear strength parameters (C, $\phi$), the Lst, MLst, and gypsum have a moderate strength while Sh as low strength. More than 92% the Lst and 84% of the MLst falls in the 5-50 and >50 Lugeon Value classes. Thus, area covered by both the Lst and MLst needs treatment (e.g. grouting). Similarly, 50% and 20% of the packer test values of shale falls in the <1 and 1-5 Lugeon value classes respectively. The studied rock properties implies that the limestone layer is not suitable for the construction of the earth-fill dams in terms of water tightness while that of the calcareous shale and/or mud rock is good site for reservoir area as it is water tight.

**Keywords**: Carbonate rocks, Shale, Rock mass, Packer test, Giba dam, Mekelle, Ethiopia.

## 1. INTRODUCTION

Growing water demand poses severe problems to the population in the Mekelle Outlier and its surroundings, Northern Ethiopia. Hence, storing rainwater for both irrigation and domestic supply has become one of the top agenda in the area. To alleviate this problem, the Federal Government of Ethiopia and the National Regional state of Tigray have been trying to construct earth-fill dams at the area of interest. However, such water-resource development projects in the study area have a number of constraints in their planning and execution owing to the engineering geological problems posed by the various foundation rocks. For example, collected preliminary inventory data and their analysis showed that more than 70 earth-fill dams were constructed in all parts of the Tigray regional state (Northern Ethiopia) in the last 20 years (mostly between 1994 -2002) for irrigation purposes. Out of these more than 64% (>45 earth-fill dams) are located within the carbonate and shale rocks of Mekelle Outlier, which is more drought prone area of the Tigray region. Most of these earth-fill dams could not attain their planned objectives due to several combinations of technical and operational problems (Abdulkadir, 2009; Haregeweyn et al., 2005, 2006). More than 60% of the failure of earth-fill dams is related to excessive leakage (Haregeweyn, 2006; Abdulkadir, 2009) via the reservoir bottom and/or via the dam foundation. Generally, dam failure increases as head or reservoir capacity increases even with same geology. For instance according to ICOLD (1987), a dam is said to be large if it has a dam height of greater than 15m. Accordingly, 40% of the earth-fill dams constructed in the Outlier fall in the large category while 60% are in the small dams. Excessive leakage is more pronounced in the large dams (>72%) than the small dams (56.5%) in the study area. Nevertheless, CoSARET categorized all of these earth-fill dams in the Tigray region as mircodams considering their low risks and negligible threat to the safety of the local community (Abdulkadir, 2009). Hence the term micro dam and earth-fill dam are synonymously adopted in this paper. Measured leakage quantity estimated by Commission for Sustainable Agricultural and Environmental Rehabilitation of Tigray (CoSAERT) shows significant variability among reservoirs with the lowest being around $1m^3$/hr and the highest $292m^3$/hr. This excessive leakage may cause a threat to the safety of the dam leading to structural failure (Abdulkadir, 2009). The major lithologies responsible for such reservoir water loss are the fractured limestone and shale units that contain thin beds of limestone or else those affected by the dolerite intrusion. Some authors (e.g. Berhane et al., 2013) stated that the hydraulic conductivity of the alternating sequences of the limestone–shale–marl intercalation unit ranges from $10^{-4}$ to $10^{2}$cm/s and was found to be responsible for the excessive leakage of the Hashenge and Arato microdams in the Mekelle Outlier.

World wide experience also showed that several dams and reservoirs constructed on carbonate rocks (limestone, dolomite, marble) and anhydrites have suffered of excessive water loss in association of the various karstification and discontinuities natures of these soluble rocks (e.g.

Aziz, 1999; Ghobadi et al., 2005; Mohammedi and Raeis, 2007; Kamal, 2007; Mohammad, 2012; Morteza, 2012).

Recently other larger dams, like the Giba dam, are under investigation in the Mekelle basin to alleviate the water supply problem of Mekelle city. This paper discusses the engineering geological properties of the carbonate and shale rocks of the Mekelle Outlier with a view to the proposed Giba dam project (Fig 1). This proposed dam will have a crest length and maximum height of 1000m and 80m respectively while its reservoir capacity is estimated to be about 350MCM.

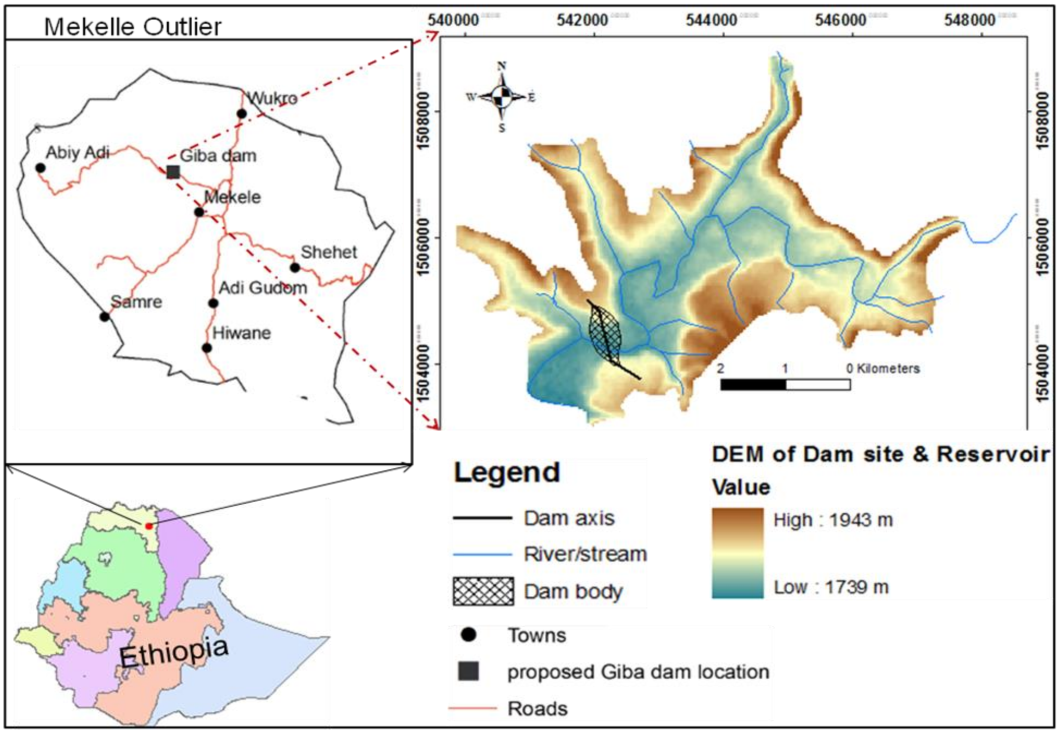

Figure 1. Location of the Giba dam foundation and reservoir.

## 2. Geological setting of the Mekelle Outlier

Mekelle Outlier is near circular with an area of 8,000km$^2$ comprising Mesozoic sedimentary successions and younger intrusive (Beyth, 1972). The general regional stratigraphic sequence of the Mekelle area (from top to bottom) including the dam projects consists of recent sediments (Qh), Mekelle dolerite (Tlm), minor remnants of basalts (P2a) and Ambaradom sandstones (Ka), Agulae shale (Jag), Antalo limestone formation with Oxfordian-Kimmeridgian age, and the

Adigrat and lower sand stone (Triassic-Middle Jurassic) in age (Bosellini et al., 1997). Out of the total coverage of the Outlier, about 75% is covered by the calcareous and shale rocks (Antalo limestone and Agula shale) intercalated with some anhydrites. The rest part is covered by the Sandstones (Adigrat and Ambaradom) and the intruding Mekelle dolerite (Cenozoic in age) acting as sill and/or dykes. The Adigrat sandstone exposure is found at the peripheries of the outlier and along the banks of major tributaries of Giba River and/or fault planes. According to Beyth (1971), four major sub parallel normal fault systems exist in the Mekelle Outlier regionally which are normal faults with steeply dipping fault plane and probably active after deposition of Agula shale and before Amba Aradom Formation. This sub-parallel type fault belts cross the Mekelle Outlier and are designated from north to south as Wukro (F1), Mekelle (F2), Chelekwot (F3) and Mai-Nebri (F4) fault belts. The Mekelle fault passes near the proposed Giba dam site (Fig 2). Most micro dams and the newly proposed Giba dam are located on (a) the Antalo limestone and calcareous shale (b) at the down thrown blocks of the fault belts, mainly at Mekelle and Chelekot fault belts (Fig 2).

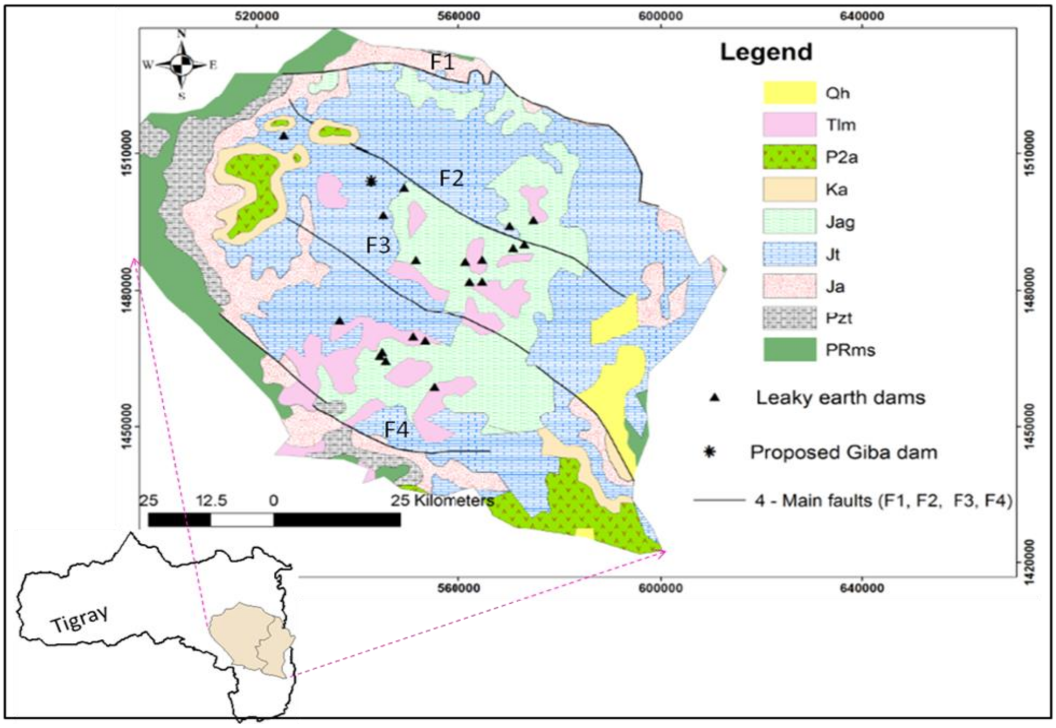

Figure 2. Geological map of Mekelle outlier (modified from Tefera, et al., 1996) and location of leaky microdams. (PRms = basement complex; Pzt = paeozoic classic sediments; Qh = recent sediments; Tlm = Mekelle dolorite; P2a = basalt ; Ambaradom sandstone = ka; Agulae shale = Jag; Antalo limestone = Jt; Adigrat sandstone = Ja.

## 3. METHODOLOGY

The site investigation programs include geological field surveys, geophysical exploration (seismic refraction, 2D imaging and Vertical electrical sounding), core drilling, packer tests, test pits and laboratory works. The engineering geological mapping of the dam site and reservoir area is carried out along a systematically arranged North-South and East-West parallel traverse lines to intersect various lithologies. Discontinuity characteristics such as orientation, spacing, persistence, roughness, aperture and filling are measured and described from the surface exposures and core logs following ISRM (1981) recommendations. Moreover all the geophysical and drilling works are also performed along the systematically arranged traverse lines. A total of 21 boreholes having total length of 1283m, were drilled on the dam foundation, reservoir and spill way. Out of these, nine boreholes are located along the proposed dam axis while the remaining boreholes are drilled in the reservoir area. The depth of these boreholes varies from 30m to 120m. To determine the permeability of rock masses of the foundation, a total of 75 packer tests were performed in 18-boreholes using a pneumatic type, Nitrogen gas inflatable double packer system. A 1.5-5m test section interval is adopted based on the nature of the geology. Sequences of pressure level mostly used in bars were 1-2-3-2-1, 2-3-5-3-2 and 2-4-6-4-2 the higher sequence being used as depth increases. Multiple pressure tests are applied in three approximately equal steps. Each pressure is maintained for 15 minutes, and water take readings are made at 5minute intervals. The pressure is then raised to the next step. After the highest step, the process is reversed and the pressure maintained for 5 minutes at the same middle and low pressures. The Lugeon values were then computed and flow types were determined for each of the test sections. Moreover, the computed Lugeon values at the various test sections of the boreholes along the foundation are correlated and classified into intervals based on Fell et al. (2005), and permeability zone is prepared (Fig 9) to see their vertical and lateral variations. A total number of eighty three soil and twenty six rock samples were collected from bore holes, test pits and from surface outcrop of construction material sources for various laboratory analyses. Laboratory tests on rocks include petrographic analysis, unit weight, uniaxial compressive strength, water absorption ratio, Los Angeles abrasion, soundness, and porosity. Qualitative and quantitative assessment of the rock masses of Giba dam has been evaluated using the rock mass classification systems such as RQD (Deere et al., 1967) and RMR (Bieniaswki, 1989).

The RQD values obtained from the boreholes drilled in the study area have been calculated and evaluated using equation 1:1 as developed by Deer et al. (1967). During calculation of RQD values, length measurements of core pieces have been done along the centerline based on the ISRM (1981). Moreover, core breaks caused by drilling process are tried to be fitted and considered as one piece.

$$RQD = \frac{\sum Length\ of\ sound\ core\ \geq\ 10cm}{Total\ core\ run\ length} \qquad 1{:}1$$

$$GSI = RMR_{89} - 5\ (for\ RMR > 23) \qquad 1{:}2$$

The geo-mechanical properties of the carbonate and shale rock masses (cohesion, friction angle, compressive strength, and deformation modulus) at the dam foundation are estimated using the RockLab software (Hoek et al., 2002) developed in Rock Science Inc. Canada, which takes input data such as the Geological Strength Index (GSI), Uniaxial Compressive Strength of intact rocks (UCSi), material constant of intact rock (mi) and disturbance factor (D). The disturbance factor value of 0 was used in the RocLab Software assuming no excavation works exist on the natural ground condition. The GSI of the study area is also estimated from the RMR89 using equation 1:2 (Table 4) as it is important parameter in the calculation of the engineering properties of rock masses.

For comparison purposes, modulus of deformation (equation 1:3) and shear parameter of the rock masses (equation1:4) are also estimated using the RMR (Bieniawski, 1989), GSI values (Hoeck et al., 1995; Hoeck et al., 2002). Accordingly, the shear parameters of the rock masses are presented in table 4.

$$Em = \sqrt{UCSi/_{100}} * 10^{\frac{GSI-10}{40}}, \quad UCSi < 100 \qquad 1{:}3$$

$$\phi = 0.5RMR + 5\ and\ C = 0.05RMR \qquad 1{:}4$$

Where, UCSi = unconfined compressive strength of intact rock; Em = elastic deformation, GSI = geological strength index; ϕ = angle of internal friction; C = Cohesion

## 4. RESULTS AND DISCUSSION

### 4.1. Dam site and Reservoir Geology

The central part of the dam foundation and the reservoir area are composed of the alluvial soils of active river deposit (Ard) and calcium cemented Old river deposit (Ord) (Fig 3a). Their thickness varies from 7 to 12m except in one borehole drilled upstream of the dam axis reaches 20m. While the sloping part of the foundation and reservoir rims consist of talus deposit (Tal) of average thickness 5m. The coarser (GP, SP) soils are dominating over the finer (ML, CL, CH) soils. Thus, positive cut of trench must be attained at the foundation to avoid excessive leakage. However, the excavated soils can be used in the construction of the dam body. Hence, their physical and geotechnical properties are studied in this context.

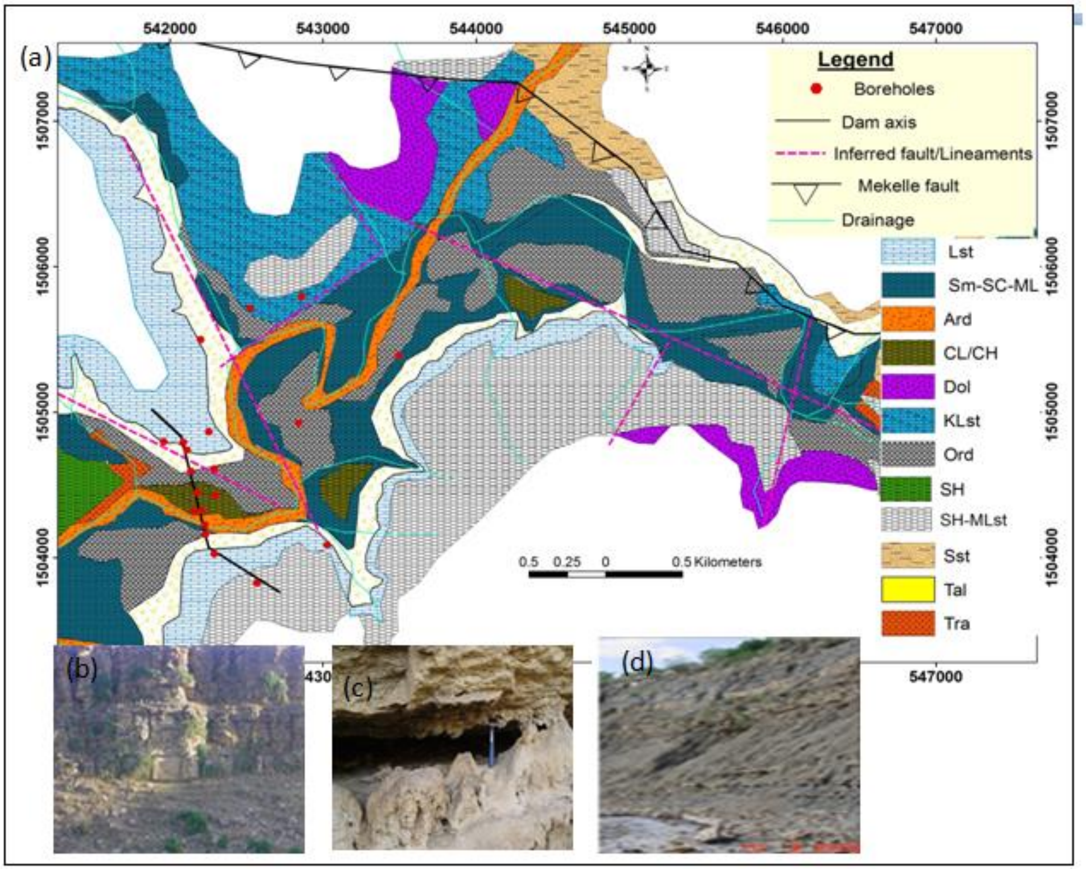

Figure 3. (a) Geological map of Giba dam foundation and reservoir area (b) Fractured Lst with solution voids at the dam foundation (c). Klst with solution cavity at the tail of the reservoir (d) Sh at downstream of dam axis [Lst = limestone; SM-SC-ML = Silty and-clayey-sand-silt soil; Ard = active river deposit; CL/CH = leanclay/fatclay; Dol = dolerite; KLst = karstified limestone; Ord = old-river-deposit; Sh = Calcareous shale; Sh-Lst = Shale-limestone-intercalated; Sst = sandstone; Tal = talus; Tra = Travertine].

The two abutments and the reservoir rims comprise of the black micritic limestone (Lst) of 20-30m thickness. It is fractured, with stylolitic seams, some solution voids and karst features as confirmed from the cliff exposure and core samples. Petrographic analysis result displayed that it is composed of calcite (86%), plagioclase (7%), fossil (5 %) and opaque (2%). The NW part of the reservoir is constituted by karistified limestone (KLst) of thickness 15m. Petrographic analysis result showed that the KLst is composed of calcite (80%), fossil (10%), opaque (3%), and Porous (7%). Dolerite (dol), sandstone (Sst), travertine (Tra) exposures are found at the upper periphery of the reservoir following the Mekelle fault belt. Drill core data showed that the micritic limestone and the alluvial deposits are underlain by the marly limestone-shale intercalation unit (Mlst) of 48-85m thickness. The third layer towards depth within this section is the shale/marl- anhydrite/ gypsum unit found at a depth of 56m at the central foundation and at depth of 105 to 109m under the two abutments. Similar petrographic tests carried out in the various intercalating units depicted that marly limestone contains calcite (50%), clay (20%) fossil (12%) opaque (10% and plagioclase (8%) while that of the shale part contains calcite (27%), clay (62%), fossil (5%), opaque (5%) and plagioclase (1%). The anhydrite unit also contains anhydrite (87%), gypsum (12%), calcite (1%) and opaque as trace.

Results of the geophysical survey (Fig 4II) also confirmed that the top fractured and weathered Lst at the two abutments and coarser sediments at the central foundation are dominantly characterized by very low compressional wave velocities (<1500m/sec). These are represented by the top deep blue color as shown in. The lower part of dry Lst which is fractured with minor solution cavities under the two abutments and the Mlst with significant shale (Sh) intercalation at the central foundation, are characterized by relatively higher p-wave velocities (1500-2500m/sec). The 3rd unit in the cross section consisting of moderately weathered and fractured Mlst intercalated by thin beds of shale at the abutments and by the moderately to slightly weathered shale and compact marly limestone in the central foundation has high p-wave velocity of 2500-3500m/sec. This layer is represented by the greenish to yellowish color in figure 4(II).

The bottom layer has very high p-wave velocities (3,000-4,500m/sec) at the abutment which reduces in the central part due to variations in moisture, lithology and degree of fracturing. This unit involves slightly massive gypsum anhydrite (WG)-shale intercalation unit. It also includes thin beds of marly limestone, dominant in the central foundation. As seen from the core logs, the gypsum unit is massive and with no evidence of solution cavities or opening. However, due to its solubility nature it could be a threat to dam project with severe problems involving potential leakage and ground collapse. Gypsum-dissolution rates may be particularly high in the vicinity of dams, due to the extremely high hydraulic gradients induced by impounded water in the reservoir (Dreybrodt et al., 2002). Hence further verification is necessary during foundation treatment.

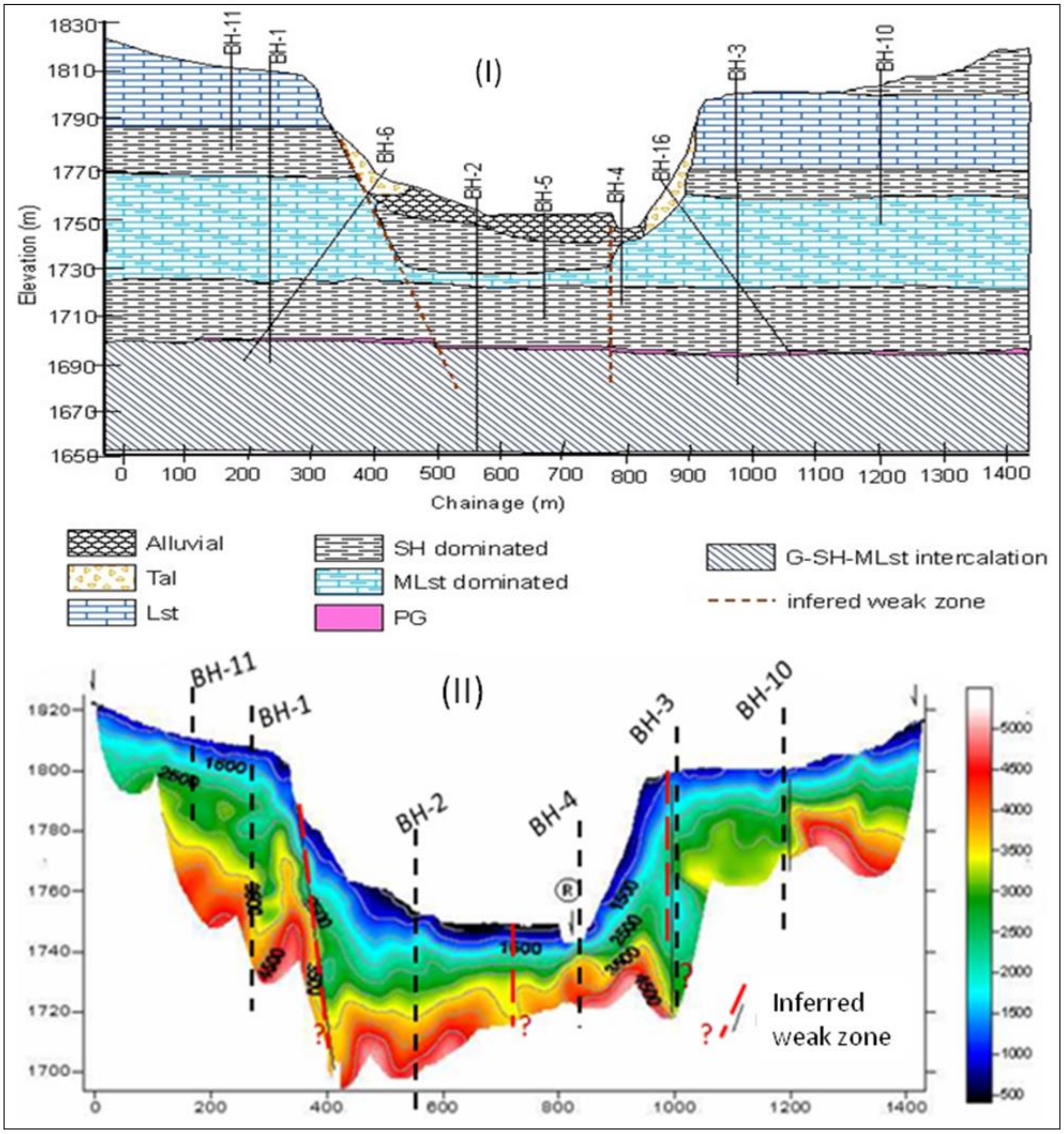

Figure 4. (I) Geological cross-section along dam-axis, (II) Seismic refraction (2D tomography, with some boreholes located at the dam axis (modified from Geomatrix, 2008). (PG = purple gypsum; WG = White gypsum intercalated with Sh and Mlst.

Structurally, the dam site is located at the down thrown side of the Mekelle fault belt that extends through the upper part of the dam, just about 2km northeast of the dam axis where the head of the water is very low (Fig 3a). Field observation and geophysical studies also indicated that lineaments and faults cross the reservoir and both abutments at various angles. These are potential threats of the dam stability and reservoir water tightness problems requiring high attention during foundation treatment.

The ground water nature is shallow, which is mainly related to the alluvial sediments of the reservoir as observed during core drilling. The relative water tightness nature of the shale dominated layer is witnessed by the dry bore hole (>300m depth) drilled at the central reservoir area for water supply purpose. However, some seepage is observed at the foot of reservoir rims and abutments just at the contact between fractured limestone and shale dominated unit.

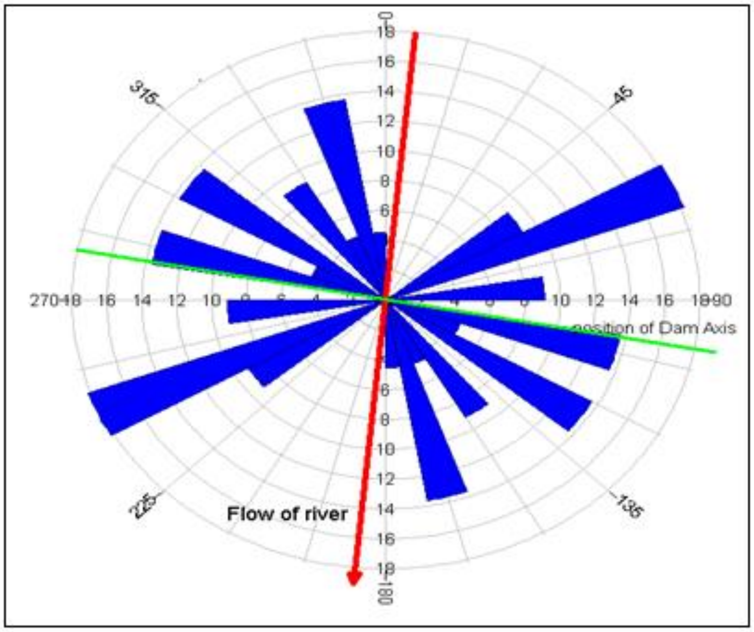

Figure 5. Rose diagram of Joint measurements (using strike class). Red line and green lines represent river flow and dam axis directions respectively.

## 4.2. Rock Mass Characterization

### *4.2.1. Discontinuity Data*

The mechanical properties of the rock mass are obviously influenced by the presence of discontinuities and their characteristics. Discontinuity data such as joint spacing, opening, orientation, condition (infill material, roughness) and number of joints were collected from the exposed rock face at the two abutments and borehole cores logs. The knowledge of join characteristics is important to study the rock slope stability, reservoir water loss and as an input for the calculation of rock mass rating values. Three major joint sets, namely J1 (with strike range: 285-315); J2 (with strike range: 40-80); and J3 (with strike range: 325-355), have been identified. It is common to see rocks falls of different size at the cliff forming limestone units of the Mekelle Outlier following the intersection of these joint sets. For example, the intersection J2 and J3 at the cliff forming black lime stone at the two abutments and reservoir rims causes wedge failure in the Giba dam project. While J3 are also favorable to leakage as it crossed the dam axis at nearly parallel direction to the flow path (Fig 5). The joint parameters measured for the black limestone found at the two abutments is given in table 1. Similarly, the characteristics of the major discontinuities (e.g. spacing, opening, joint condition) of the marly limestone, shale and gypsum/anhydrite are collected and analyzed from surface exposures and drilled boreholes and used in the RMR systems.

Table 1. Discontinuity data measured at the two abutments (15-20m cliff forming black limestone).

| **Joint set** | **Strike range (deg.)** | **Dip amount (deg.)** | **Ave. spacing (m)** | **Average opening (cm)** | **continuity (m)** | **infilling material** | **Remark** |
|---|---|---|---|---|---|---|---|
| J1 | 285-315 | Vertical/ Sub-vertical | 1-1.2 (av.=1.1) | 5-10 (av.=7) | 1-3 | Calcite | |
| J2 | 40-80 | Vertical/ Sub-vertical | 1.3-1.5 (av.1.4) | 1-50 (av. =1.3) | 2-3 | soil/open | Rough |
| J3 | 325-355 | Vertical/ Sub-vertical | | 3-50 (av. =15) | - | soil /open | Slightly rough |

### *4.2.2. Rock Quality Designation (RQD)*

RQD is a simple, inexpensive and reproducible way to qualitatively assess the rock quality of rock core (Deer et al., 1967). Then obtained RQD values of the various rock units are used to directly assess rock mass quality and also as parameter input of the RMR system.

Analysed results depicted (Table 2 and Fig 6) that 60% of the RQD of values of the Lst fall within the very poor/poor qualities while 27% and 13% are in the ranges of fair and good quality zone respectively. This shows that this unit is fractured, altered and with small solution cavities and is inter-bedded with thin-beds of shale. 50% of the RQD value of Mlst belongs to the very poor/poor quality while 16% and 34% are in the ranges of fair and good quality zone respectively. This unit in general has better quality than the Lst but still it is also fractured and altered in places. 72% of the Sh falls in the very poor to poor rock mass quality due to its weak lithological nature. The engineering quality of gypsum/anhydrite varies from fair to good. However, gypsum has a soluble nature and is potential threat of leakage, especially for the dams with higher hydraulic head.

Table 2. Average RQD values obtained from core drilling data of the Giba dam site.

| **Lithology/rock type** | **RQD at RA (BH-1&11)** | **RQD at CF (BH-2,4 &5)** | **RQD at LA (BH-3 &10)** | **Overall Average RQD** | **Remarks (as per BS 5930, 1981)** |
|---|---|---|---|---|---|
| Black micritic limestone | 47.7 | - | 42.5 | 45 | Falls in the poor range |
| Marly Limestone | 74.8 | 80.8 | 20 | 62 | Varies from very poor to good |
| Calcareous shale | 36 | 58 | 15.5 | 40 | Varies from very poor to fair |
| Gypsum/anhydrite | 91 | 66 | 88 | 82 | Varies from fair to good |

(***Note***: RA= Right abutment: CF= Central foundation: LA= Left abutment).

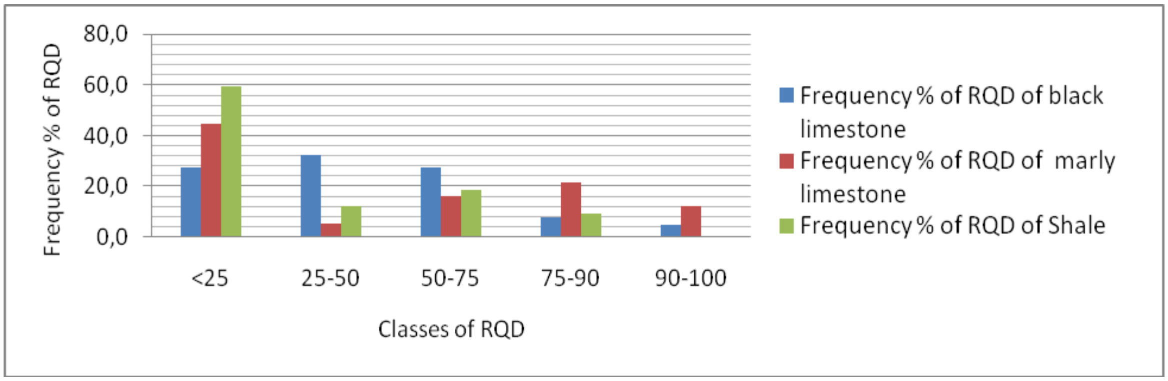

Figure 6. Percentage of RQD variation of study area in each RQD classes of Deer et al. (1967).

### ***4.2.3. Rock Mass Rating (RMR) System***

Rock mass classifications form the back bone of the empirical design approach and are widely employed in rock engineering (Singh et al., 1999). Among many of the geo-mechanical systems, Rock Mass Rating (RMR) system proposed by Bieniawski (1978, 1989) is commonly used to characterize the rock mass nature for engineering application. The RMR system considers six parameters namely unconfined compressive strength of intact rock (UCS), Rock Quality Designation (RQD), spacing of discontinuities, and condition of discontinuities, groundwater condition and orientation of discontinuities that are readily determined in the field as well as in the laboratory. Hence, in this work most of the mentioned input parameters of RMR were collected in the field using compass and meter tapes as well as from the core logs. Accordingly, the RMR value of black micritic limestone is calculated using the above mentioned six parameters (Table 3). Similarly the RMR values of the marly limestone, calcareous shale and gypsum/anhydrites are calculated and the results are presented in table 4.

Table 3. RMR calculation for black micritic limestone found at the dam foundation.

| **S/N** | **Parameter** | **Average Value** | **Rating** |
|---|---|---|---|
| R1 | USC of intact rock (MPa) | 25 | 4 |
| R2 | RQD value (%) | 46 | 8 |
| R3 | Spacing of joints | 1.4m | 15 |
| R4 | Orientation of joints | Most joints are steeply dipping | -2 |
| R5 | Condition of joints | Rough; opening (7mm), continuity (1-3m), slightly weathered, open | 20 |
| R6 | Ground water condition | Damp (slightly wet) | 10 |
| Total | RMR=R1+R2…+R6 | | 52 |
| Class | Description | | III/F |

(***Note***: III/F = Fair Rock Quality).

Table 4. Calculated rock mass parameters.

| Lithology | $UCS_i$ (Mpa) | $RMR_{89}$ | GSI | mi | **Based on** | | | | | | **Classification of rock mass by shear strength based on ϕ and C values** (Bieniawski, 1989; ISRM, 1981) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | **RMR** | **RockLab software** | | | | **GSI** | |
| | | | | | **ϕ ($0^0$)** | **$UCS_{rm}$ (Mpa)** | **ϕ ($0^0$)** | **C (Mpa)** | **$E_m$ (Gpa)** | **$E_m$ (Gpa)** | |
| Lst | 55 | 52 | 57 | 8 | 31 | 4.96 | 30.6 | 2.9 | 9.9 | 7.5 | Moderate |
| Mlst | 51 | 54 | 62 | 7 | 32 | 6.1 | 30.9 | 2.85 | 10.1 | 13 | Moderate |
| Sh | 13 | 40 | 48 | 6 | 25 | 0.696 | 25.7 | 0.54 | 0.7 | 3.2 | Low |
| WG | 28 | 57 | 65 | 13 | 34 | 3.97 | 37.2 | 1.9 | 6.2 | 12.5 | Moderate |

The calculated RMR values and corresponding geotechnical parameters imply that all limestone/marly limestone and the gypsum/anhydrite are classified in the range of fair quality (class III) while the calcareous shale (Sh) is classified in the range of poor rock quality (class IV) (Table 4).

### *4.2.4. Estimation of Strength and Deformation Parameters of the Rock Mass*

In the study, no field testing of rock mass is done. Thus, The geo-mechanical properties of the carbonate and shale rock masses (cohesion, friction angle, compressive strength, and deformation modulus) at the dam foundation were estimated using the RockLab software (Hoek et al., 2002) developed in Rock science Inc. Canada, which takes input data such as the GSI, UCSi of intact rock, material constant of intact rock (mi) and disturbance factor.

The calculated angle of internal friction ($\phi$) for all the rock masses is similar for both methods (Table 4). While the deformation modulus ($E_m$) value showed that some variations exist between the methods attributed to the input parameters of the calculation. The $\phi$ - of Lst varies from 30.6 (using RMR) to 31 (Rocklab method) and Cohesion (C) of 2.9 MPa while the $\phi$ and C of MLst varies from 31 to 32 and 2.85MPa respectively. Similarly, the Shale and Gypsum have $\phi$-value of 25 and $34\text{-}37^0$ as well as C-values of 0.54MPa and 1.9 MPa respectively.

Comparing the calculated shear parameters ($\phi$, C) of the rock masses of the study area with that of Bieniawski (1989), the black limestone (Lst), Marly limestone (Mslt), gypsum (WG) falls in the range of moderate strength while that of shale (Sh) is characterized by low rock mass strength (Table 4). This means that the rock masses found along the Giba dam foundation vary from low to moderate rock mass strength. The reason for the less strength nature of all the limestone types shows that they are fractured and weathered while the shale /mud rock is naturally weak besides to it is also weathered.

### *4.2.5. Rock Mass Permeability and Packer Test Analysis*

No permeability tests were performed in connection with the site investigation stage of the micro dams in the Mekelle Outlier and hence the permeability of the various lithologies was not determined. Nevertheless, post construction observation illustrates that excessive leakages are seen in many of the micro dams constructed on Antalo and Agula formations following the fractured limestone units and contact zones. Recently, permeability test is carried out in the proposed Giba dam to estimate the hydraulic conductivity of the rock masses exposed at its foundation and reservoir part using the pneumatic type double packer system. The permeability tests are based on measuring the amount of water taken by the ground under pressure during a given time.

A plot of water intake against pressure for the five steps has been then used to evaluate hydraulic conductivity and flow types based on the BS5930 (1981). The statistical distribution of all packer test results carried out in dam project, the vertical and the lateral variations along the dam foundations are provided in table 5 and figures 7 to 9.

Table 5. Statistical distribution of percentage of Lugeon values in different rock mass permeability classes for the rocks exposed at the Giba dam foundation and reservoir areas.

| **Permeability description (as per Fell et al., 2005)** | | | **% of distribution of Lugeon values in each lithologies** | | |
|---|---|---|---|---|---|
| Lugeon | Ranges | Condition | Lst | MLst | Sh |
| <1 | Low | Joints tight | 0 | 12 | 50 |
| 1-5 | Low-Moderate | Small joint openings | 7.7 | 4 | 20.8 |
| 5-50 | Moderate-High | Some open joints | 69.2 | 76 | 29.2 |
| > 50 | High | Many open joints | 23.1 | 8 | 0 |

(***Note***: Lst = Black limestone; MLst = marly limestone; Sh = shale).

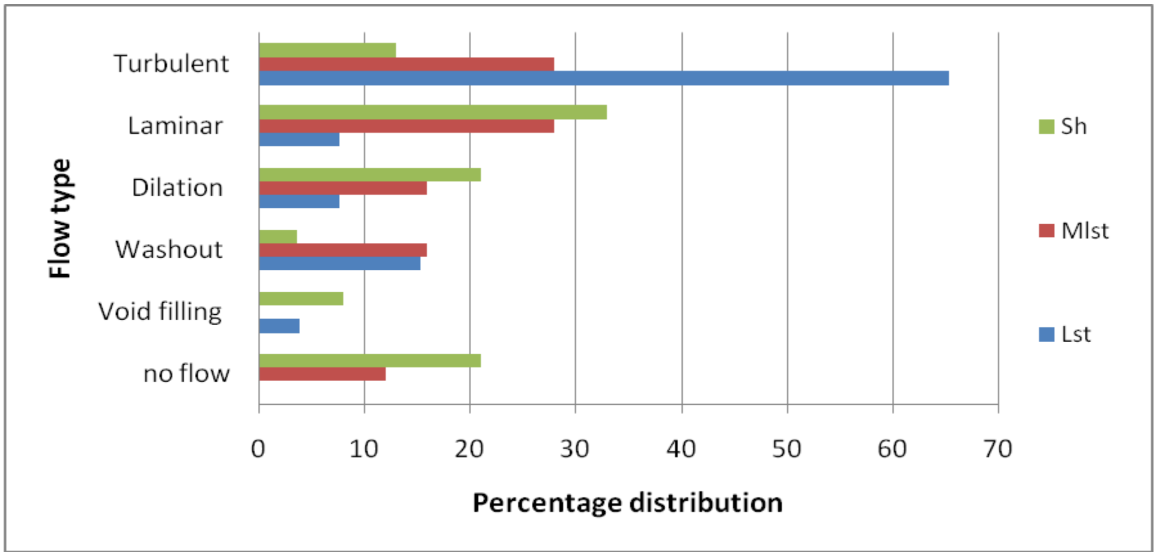

Figure 7. Statistical distribution (in %) of water flow types for various rock exposures of pressure tests conducted at Geba dam site and reservoir.

Out of the total packer tests conducted in Giba dam, 26 and 25 of them were performed in the black limestone and marly limestone respectively while 24 of them were in the shale dominated unit. The Lugeon value of black limestone varies from a minimum of 4 to a maximum of 94 averaging to 33 while that of marly limestone varies from 0 to 53 averaging to 22. Similarly the Shale has minimum, maximum and average values of 0, 12 and 2.3 respectively. As indicated in table 5, 92.3 % of the black limestone and 84% of marly limestone falls in the 5-50 and >50 Lugeon value classes. Similarly, 50% and 20% of the packer test values of shale falls in the <1 and 1-5 Lugeon value classes respectively.

The flow types are also determined from the packer tests. Accordingly the black limestone is dominated by turbulent flow (>65%) followed by washout flow type (15%) and less laminar flow (≤8%). This depicts that it is characterized by open fractures or some fractures are filled by washable soils and solution voids. While the marly limestone exhibits quasi-similar proportion of turbulent and laminar flow types (28%), washout and dilation flow (16% each) indicating it contains some open fractures and wide fractures, fine and tight joints filled by washable soils as well as some solution voids. Furthermore this unit is intercalated by significant beds of shale unit which increases in the number of laminar flow.

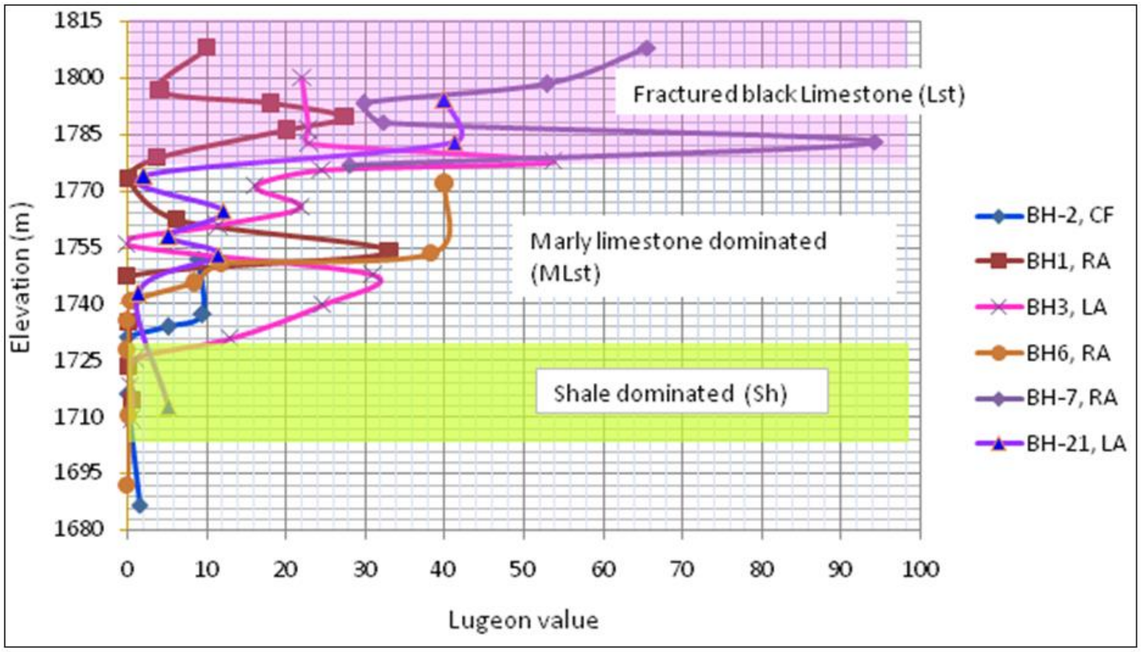

Figure 8. Lugeon value variation of lithologies with depth (CF = Central foundation, RA = right abutment; LA = left abutment).

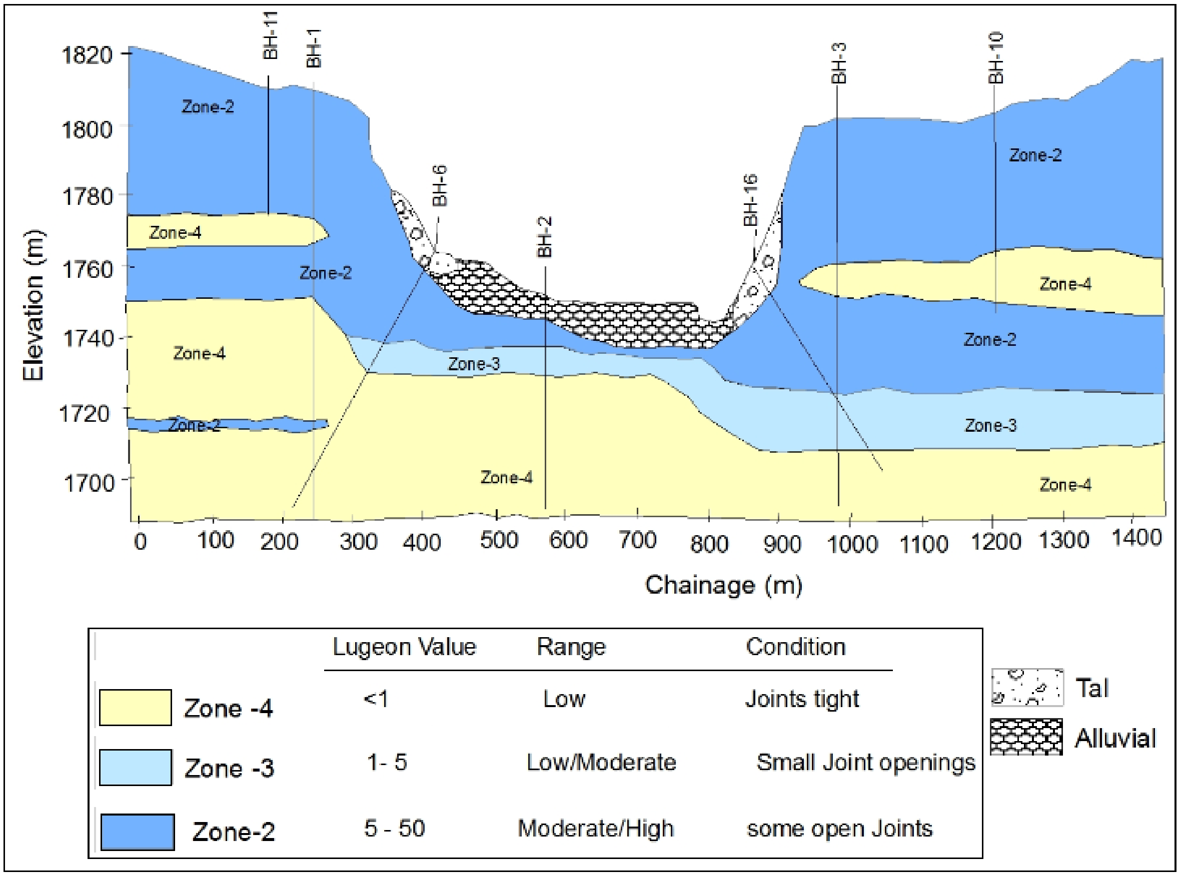

Figure 9. Permeability zoning of foundation materials based Lugeon values (Rock permeability and descriptive terms (after Fell et al., 2005).

On the other hand, the shale dominating unit exhibits more laminar (33%), no flow or no intake of water (21%), and less than 13% turbulent flow (Fig 7) illustrating that it characterized by tight discontinuities. Moreover washout flow types were significantly recorded (21%) in the shale unit displaying that the infilling materials could easily be washed out permanently when the test pressure is higher.

Laminar flow predominates where the intake is 1, 2 or 3 Lugeons and whereas turbulent is commonest type of flow when the intake is 4 or more Lugeons (Houlsby, 1976). In this study, the turbulent flow were dominantly observed in all the limestone units when the packer test result is greater than six while laminar flow was observed in the shale unit when the Lugeon value is less than nine.

The variation of Lugeon values with depth is analyzed and plotted as shown in figure 8. From this plot, the Lugeon values decrease to a value of <5uL from an elevation of 1,810 to 1,725m.

Furthermore, permeability zoning map indicating the vertical and lateral variation of the Lugeon values is prepared by correlating the values in each test sections of boreholes along the dam axis (Fig 9). The map depicts generally that the foundation is characterized by moderate to high Lugeon values (5-50uL) to depth of 65m, starting from the maximum dam level (1,810m) to a depth of 1,745m at the right abutment, and up to a depth of 85m (1,810 to 1,725m) at the left abutment. Both abutments and reservoir rims are composed of fractured black limestone underlain by the marly limestone up to the mentioned depths.

While the central foundation and reservoir is dominated by the relatively thin marly limestone (5-50uL) underlain by the shale –gypsum intercalating units (<5uL). This part of dam foundation is pervious up to a depth of 30m (1,750m to 1,720m) as can be referred in figures 8 and 9.

The shale- gypsum intercalating unit encountered at lower depth characterized by low Lugeon value (<1uL) and tight joints. However, gypsum are soluble rocks and hazardous with the expected hydraulic head of the impounded water. Hence, the foundation needs treatment and improvement to depths of 65m, 30m and 85m along the right, central and left parts of the foundation respectively. Grouting of foundations with permeability of 1 to 3 Lugeons is commonly unnecessary, this being the range of solely laminar flow (Houlsby, 1976). Accordingly, a treatment (e.g. grout curtain) with three rows of grouting holes has been suggested to the depths that are mentioned above along the chainage.

## 5. CONCLUSION

This study assessed with the engineering-geological properties of carbonates and shale of Outlier in relation to the data of the proposed Geba dam project. The carbonates and shales, which comprises of more than 75% of the Mekelle Outlier are problematic for dam construction, especially in terms of their water tightness aspect as evidenced by the failed micro dams. The carbonate (limestone, marl) and shale in the study area has cyclic nature with variable engineering behavior.

The black limestone is dominated by calcite (86%), and crystalline. It is also intensively fractured, karstified, with rating of poor to fair rock mass quality. It is generally fair in strength and high in deformation. Packer test results showed that more than 92% of the Lugeon values fall in medium to high permeability range and is capable of excessive leakage. The marly limestone (MLst) is mainly composed of 50% calcite and 20% clay and is hence affected by rare solution cavities. The MLst is characterized by moderately fractured and weathered, with rating of fair rock mass quality. More than 84% of its Lugeon value shows that it is also in the moderate to high permeability range. The calcareous shale (Sh) is highly weathered, poor rock, highly deformable, impermeable and unstable. Thus it is water tight but with low bearing capacity. The combination of the various rock mass properties in the cyclic nature of these rocks resulted in water tightness problems of the micro dams of the Mekelle Outlier in general. So, this implies that the proposed Giba dam may not be an exception from this problem as it is located in the same geological setting. For instance, the limestone exposure at both abutments of the Giba dam varies from wide to very wide (7-15cm average opening) indicating that it highly liable to excess leakage unless properly treated. Grouting is thus recommended to depths of 65m, 30 and 85m at the right, central and left abutment of the Giba dam foundation combined.

The other potential problem in the case of the proposed Giba dam is the presence of gypsum at depth. Although no evidence of solution cavities or opening is seen in the core logs in all the gypsum beds encountered beneath the dam foundation, its high soluble intact rock nature may result in the formation of caves and sinkholes with the expected hydraulic head of the impounded water of Giba dam. Thus, a due consideration is necessary during detail design to address the required remedial measure

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