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Engineering geological and geotechnical appraisal of Northern Mekelle town, Tigray, Northern Ethiopia

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Abstract

As population number grows, the demand of constructing buildings for residential, commercial, industrial, and other purposes also increases. Mekelle town is presently rapidly and geometrically expanding towards all directions, and several civil engineering structures such as single to multi-storey buildings, roads, bridges, etc. are under construction. The main research aim is to characterize the engineering geological and geotechnical properties of soils and rocks, and develop detailed multi-purpose engineering geological map at a detail scale. Engineering geological and geotechnical characterization of soils and rocks are based on their index and engineering properties, and their classification is according to the standard proposed by Unified Soil Classification System (USCS) and International association of Engineering Geologists (IAEG (1981). According to USCS; soils are classified into: fat clay type; inorganic silt, elastic silt and (silty of clayey fine sand with slight plasticity) of silt soil types; lean sandy clay, inorganic silts, elastic sandy silt of sandy clay/ silt type; and clayey/ silty sand soil types. According to IAEG (1981); soils are classified into: clay of intermediate and high plasticity; silt of intermediate, high and very high plasticity; SAND clayey of intermediate plasticity, SAND silt of high plasticity; and CLAYEY sand of intermediate, high plasticity and SILT sand of intermediate plasticity). Classification of rock masses is based on their strength, degree of weathering and joint characteristics; classified into three major engineering geological subunits: rocks with low mass strength, rocks with medium mass strength and rocks with high mass strength.

Keywords: Classification; Geotechnical, Map; Mekelle town; Rock mass; Soil; Strength

1. Introduction

Mekelle is the capital city of Tigray National Regional State located in Northern Ethiopia. Its approximate geographic location is 39^o 28' Eastern Longitude and 13^o 32' Northern latitude. It has an average altitude of 2000 meters above mean sea level.

The city is growing into different directions and has to adjust its planning strategies to accomplish the demands of an abruptly growing population. The spatial effects of the surrounding mountain ridges and enclosing landforms have special importance for reservation of specific areas and facilitate development of the city.

At present, significant concentration of engineering structures mainly multi-story buildings, roads, bridges are under construction, especially they are concentrated in the north, northwest, and west directions of the city. There is a need for systematic work of detailed engineering geological and geotechnical mapping for Mekelle town and surrounding area.

Engineering geological mapping, plays a vital tool in most current civil engineering and mining works, has not been given the attention it deserves in most countries lying within the tropics [1]. According to [1], the reasons for this might be partially found in the unavailability of personnel and facilities in these countries and lack of awareness of decision makers and planners. A major reason, however, is the absence of methods specifically designed to cope with the special problems of the tropical regions.

Densely populated urban centers are often founded on steep slopes, or on poor soil conditions, and even in some cases with high seismicity areas. Knowledge of the geological and geotechnical conditions of an urban area is necessary to provide basic information of the ground condition to the local authorities, engineers and contractors. This necessary information also constitutes the basic concept for the evaluation of both the geological hazards, which are encountered in the area in question, and the dynamic response of the construction in the case of seismic activity.

The current research work was conducted by considering the present expansion of the town towards the northern and north western parts, the results of the research provides detailed engineering geological information that help for planning, design and maintenance of engineering structures on these areas.

2. Objectives

The general objectives are to determine the nature and type of soils and rocks and their engineering properties. To produce detail engineering geological map of the northern part of the Mekelle town at a detail scale.

Specifically rocks and soils of the area are characterised and classified according to the standard classification schemes and provide adequate engineering geological and geotechnical information for different construction industry in the area regarding the foundation and subsurface condition.

3. Description of the study area

3.1. Location

Mekelle town is the capital city and commercial center of the Tigray National Regional State, located about 783km north of Addis Ababa, capital city of Ethiopia. Geographically the town is located at 39^0 28' East longitude and 13^0 32' North latitudes, situated in the extension of the central highlands of Ethiopia. The study area is the northern part of Mekelle town. The altitude of northern Mekelle town is between 1940m and 2220m above sea level. The area is enclosed within the limit of 1492000-1500000 North and 546000-556000 East and covers about 50 km^2.

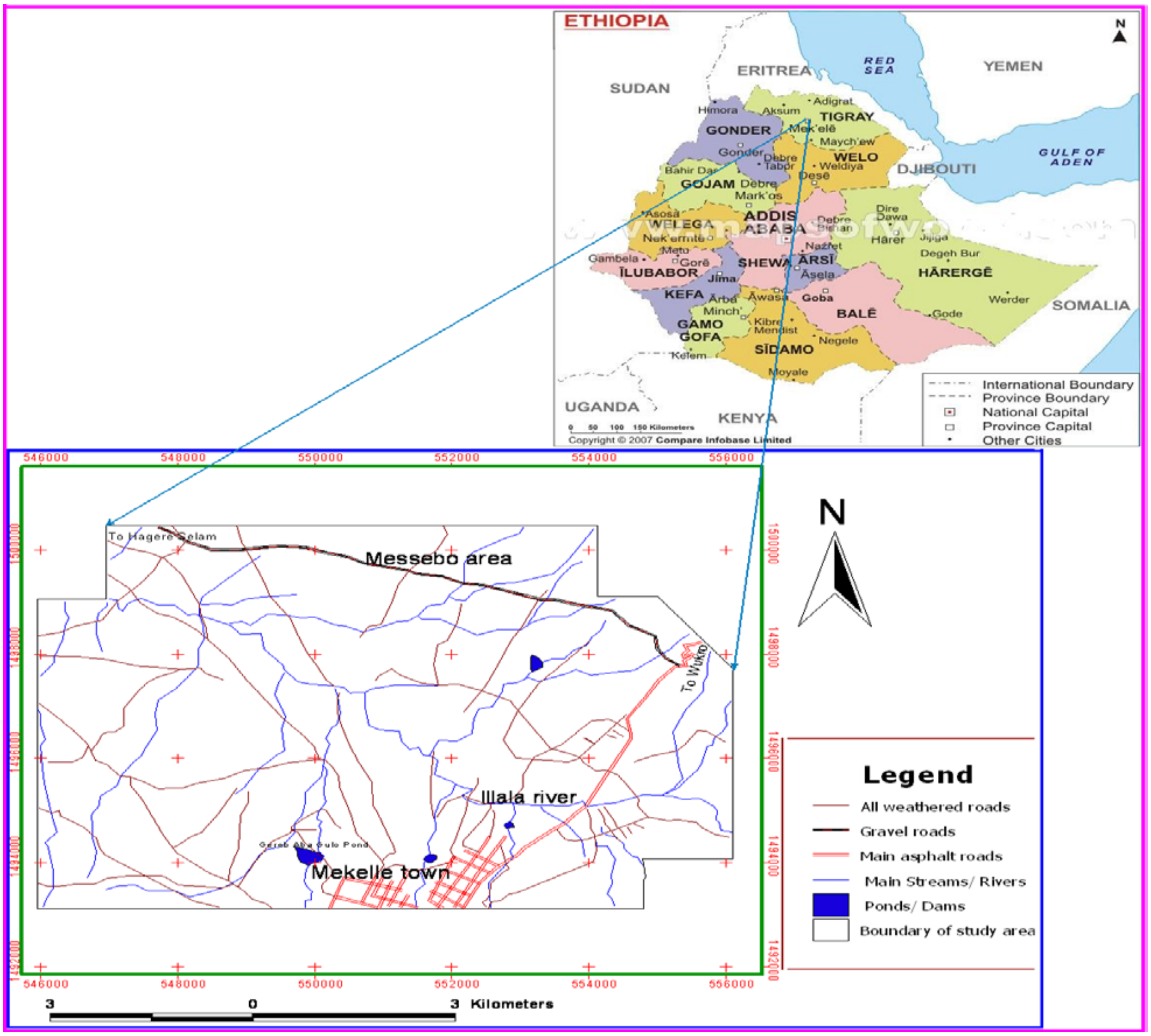

Figure 1: Location map of the study area.

3.2. Topography and drainage

The northern part of Mekelle is situated at the foot of a steep cliff of the Endayesus escarpment on the east side and steep bedded limestone cliff on the northern and northeastern side. The major part of the study area is gentle to flat lying land. The altitude varies from 2220m at eastern to 1940m in the northwestern part of the study area (lower reach of Illala river). Topographically, the northern part of Mekelle town has an overall tilt towards west and northwest direction. As the city is within the Tekeze river basin, the Illala River flows from East to West, in which many tributaries feed the river with substantial amount of water during rainy season. The stream is seasonal where the peak discharge is attained during summer and is a tributary to river Giba. Giba river is not far from the study area (about 3-4km far from the northwestern part of study area). Giba is also a relatively big river that flows to the major river Tekeze.

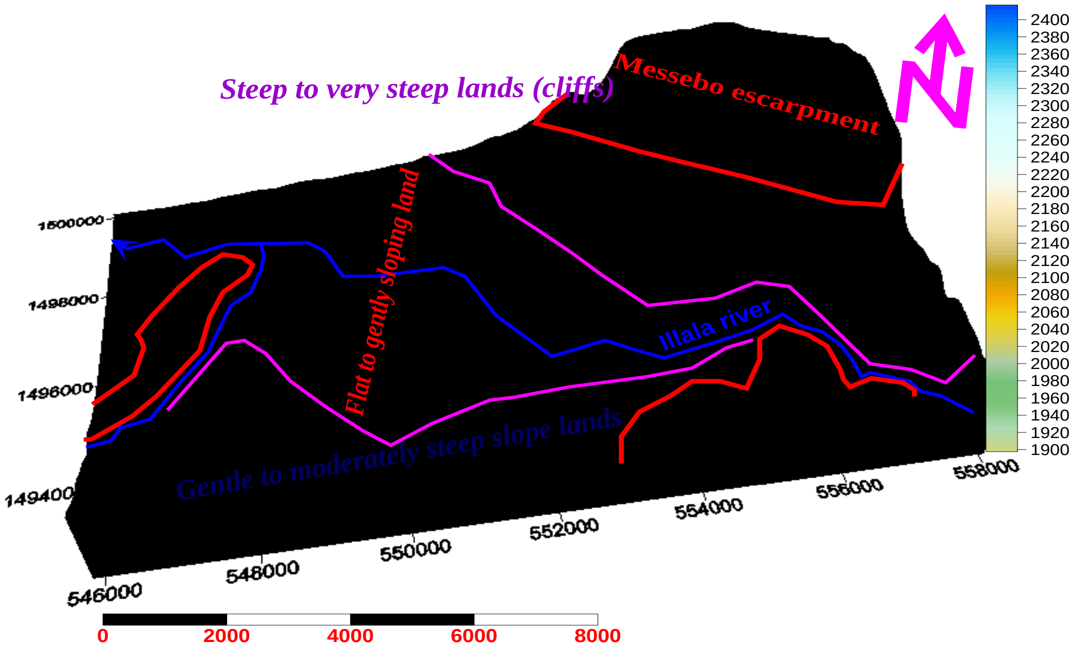

Figure 2: 3D-simulation of the topography, drainage, relief and landforms map of the study area from DEM (30m resolutions). Scale bars: in meters for both horizontal and vertical bars.

1.3. Climate

The Ethiopian Mapping Agency (1981) [2] differentiated five traditional climatic zones in the National Atlas of Ethiopia. According to this classification the study area is within “Weina Dega” or subtropical climatic zone with altitude 1500-2300 m and mean annual temperature and evapotranspiration of 15-20^{0}C and 1100-1250 mm respectively. The climate of Mekelle varies mainly according to elevation.

1.3.1. Temperature

Temperature determines the suitability of a site for settlement and development of various infrastructures. The temperature records (Annex A) were analyzed to determine the average maximum and minimum temperature of the area. According to this analysis, the area has an annual average maximum temperature of 27.35^{0}C and annual average minimum temperature of 11.52^{0}C. There is monthly variation in temperature. May and June are the hottest months with a monthly mean maximum temperature of 30.2^{0}C and 29.8^{0}C respectively, and monthly mean minimum temperature of 14.2^{0}C and 13.5^{0}C. December and January are the coldest months with a mean monthly maximum temperature of 25.4^{0}C and 26.6^{0}C and monthly mean minimum temperature of 8.6^{0}C and 8.3^{0}C respectively.

Figure 3: Mean monthly average Maximum and Minimum temperature of study area

1.3.2. Rainfall

In view of the fact that Mekelle is found to the North of the Equator, its summer (rainy season) occurs by the months of June, July and August. This rainy season is characterized to be erratic, unreliable and unevenly distributed throughout the year. The variation of rainfall throughout the year, and from year to year, is very important to schedule appropriate construction period for any engineering project.

From the analysis of metrological data records the area, it has an annual average rainfall of 530.375 mm/year. Out of this, months of July and August in combination comprise the major share i.e. 386.4 mm (72.85%). The amount of rainfall varies from year to year and within months of the year in the study area. This rainy season has less significant effects up on engineering structures, due to their small amount and intensity of the rain.

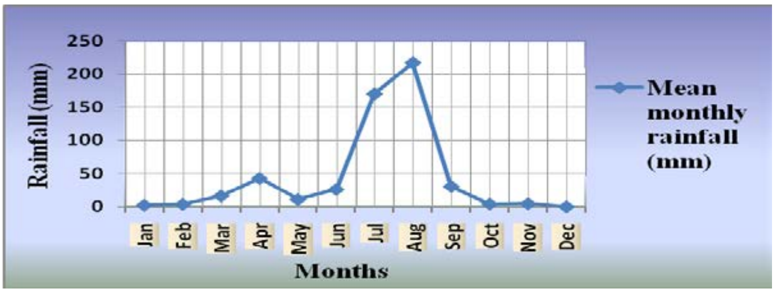

Figure 4: Mean monthly rainfall variations of study area

4. Methodology

The following approaches were used:

- Compilation of previous information concerning the climatic, geomorphologic, hydrologic, and geological and soil characteristics of the study area, these data were collected from various sources which include: geological maps, topographic maps, geotechnical and engineering geological maps, soils survey reports and maps.
- Review of similar studies and cases in different parts of the world and in Ethiopia. Particularly, emphasis was given to previous works done in the Mekelle area.

- Aerial photo interpretation of the study area at 1:50,000 scales (obtained from Tigray water resources, mines and energy bureau) and 1:20,000 scale soft copy of aerial photo were (obtained from Mekelle city master plan preparation office). From these aerial photos, tracing of major structures and zoning of similar litho units were done, that helped to prepare base map for the study area. The aerial photographs used were black and white, panchromatic, vertical stereo pairs.
- Interpretation of satellite images of Mekelle area (i.e. 30-m resolutions) in order to obtain data on slope conditions and structures of the study area.
- Base map preparation for study area. The topographic map of Mekelle area was used and enlarged to the required scale and plotting the information obtained from Aerial photos and satellite images on it. The base map of the study area were prepared and followed by field mapping of the area.
- Field work, geological mapping of the study area were carried out that provide detailed information on lithology and their characteristics. The filed investigation was carried out according to the IAEG Commission on Engineering Geological Mapping [3] [4] methods of description of rocks and soils. Soil parameters were described according to the American Society for Testing Materials [5], which describes a "Standard Recommended Practice Description of Soils (Visual-Manual Procedure)." This standard was supplemented by the IAEG standard description of soils [4] and the methods described by the Geological Society Engineering Group Working Party [6].
- Description and inspection of exposures along road cuts, local quarry sites, river/stream channels, foundation works, slope cuts and pits; measuring and recording the discontinuity characteristics; and collected previously available laboratory results that used considerably to determine the lithological, physical or engineering geological characteristics of the soils and rocks of study area.
- Assessment of geomorphological and landform condition, geodynamic phenomena and hydrogeological conditions, measurement and recording of the structural settings were performed during field work activity.
- Rock strength tests were carried out by using a Geological hammer; i.e. simple methods of rock strength determination. This method has been extensively tested and compared to existing laboratory unconfined compressive strength and point load strength test results. The assessment in the field by ’simple means’ is obviously partly subjective. However, the strengths determined by ’simple means’ by about 50 different people showed that the results of the ’simple means’ field tests are at least comparable to the quality of results obtained by the laboratory tests [7]. These data were correlated with lab results of strength measurement.
- Data processing and interpretation was made with the help of different professional computer software. Some of the software were; Microsoft office tools for preparation, synthesis and analysis of data, Adobe Photoshop (CS3), stereo net projection, Arc view 3.2, Global mapper 7, surfer 8, Corel Draw Graphics suite 12, AutoCAD version 2007, for preparation and manipulation of different maps.
- Finally, preparation of the overall manuscript.

5. Theoretical Concepts

Engineering geology has been an important scientific sub-discipline for as long as people have sought to build and construct their living environment. If nothing else, people soon learnt where buildings could be built safely and where poor foundation conditions or the presence of geohazards meant that unacceptable risks were present.

However, engineering geology came to greater prominence with the flowering of geology as a major science in the early 19th century, a time which saw the founding of the Geological Society of London, in 1807 [8].

Engineering geological studies for the preparation of maps and plans have been carried out since the early years of the 20th century, mainly in Europe. The purpose of these maps was to provide information about characteristics of the natural environment for planning land use and engineering structures of all kinds. Rapid urbanization due to population growth in developing countries requires infrastructure and housing development over large areas. Problems resulting from unfavorable engineering geological conditions have confirmed that engineering geological mapping is a fundamental prerequisite for planning [9]. Various authors have developed concepts about engineering geological maps or mapping. According to [8], an engineering geological map is the best way to depict the natural environment for engineering purposes. The purpose of engineering geological maps is to show the distribution of specific geological phenomena and characteristics of rocks and soils affecting engineering use of different terrains.

In Ethiopia, the preparation of engineering geological maps is not well known; perhaps the country demand and requirement of the map for the development of engineering structures and planning purpose in the near future became critical. From the report of [10], even the Geological mapping of the country is not fully addressed. Consequently, in many towns of Ethiopia, very little is known about the soil and rock conditions or engineering geology of the towns.

The boundaries of rock and soil units shown on engineering geological maps of various scales should delimit rock and soil units, which are characterized by a certain degree of homogeneity in basic engineering geological properties [11]. The term soil in the engineering geological sense, comprises all materials found in the surface layer of the earth crust that are loose enough to be moved by spade, shovel or can be excavated without the use of explosives or equipment for loosening [12]. The main problem in engineering geological mapping is the selection of geological features of rocks and soils which are closely related to physical properties, such as strength, deformability, durability and permeability, which are important in engineering geology. This is because, at present, we lack regional data on the variability of engineering properties of rocks and soils. Neither have suitable methods and techniques been developed for determining them in sufficient quantity, over large areas, quantitatively, quickly and cheaply [11].

Many engineering activities, foundations for buildings, roads, bridges, etc., are in most cases limited within the top few meters of the surface of the earth. Therefore, surficial material deposits are of prime importance in most engineering geological and geotechnical investigations. A soil layer in an area is considered as a unit if its thickness exceeds one meter [11]. If the soil thickness is less than one meter, the area is mapped as the underlying bedrock. Accordingly, the thickness of one meter is chosen, because of surface morphology of the underlying bedrock is usually recognizable if the overlying soil is less than one meter thick and not recognizable when the soil thickness exceeds one meter; and the engineering geological importance of a soil cover if less than one meter is limited. In this regards, the presentation of lithological and engineering geological units on geological and engineering geological maps respectively are done based on the above principle of mapping of soils and/ or underlying bedrocks.

A complete engineering geological rock mass description contains details of the rock material and the natural discontinuities. Adequate descriptors, a uniform format, and standard terminology must be used for all engineering geologic investigations to properly describe rock foundation condition. So, engineering geological rock descriptions should include generalized lithologic and physical characteristics using qualitative and quantitative descriptors. In this work the descriptive scheme proposed by [13] is adopted to systematically characterize the rock material and rock mass properties. These involve: a) determination of the fundamental rock name (lithological rock name), b) description of the properties of the rock material (color, texture, state of weathering and strength) and c) description of additional properties necessary to describe the features of the rock mass (structure, discontinuities and weathering profile). This method provides a descriptive rock name from which engineering properties may readily be inferred than from a lithological rock name. Units should be differentiated by their engineering properties and not necessarily by formal stratigraphic properties where differences are significant. So far engineering geological studies, each particular stratigraphic unit may require further subdivisions to identify engineering parameters.

A standard method is used for identifying and classifying soils into categories or groups that have distinct engineering characteristics. This enables a common understanding of soil behavior just by knowing the classification. Classification is usually the very first and most important step of activities to rock classification in to certain system for rock engineering purposes. Rocks may be classified by origin or genesis, geological/ lithological classification, engineering classification of intact rocks on the basis of rock strength and/ or a combination of these [14].

6. General geology of Mekelle area

Regional geological mapping of parts of northern Ethiopia by [16] are standard references for the geology of the region. Northern Ethiopia is characterized by highly diversified and laterally extensive coverage of sedimentary rocks of varying genesis. The Mesozoic sedimentary succession, unconformably overlying the Precambrian basement, forms a nearly circular 8,000 km^2 area around Mekelle [17] [18]. Detail mapping of Northern Ethiopian provinces (Central and Western Tigray) was done by [15]. According to this work the history of the sedimentary basin in Tigray (Mekelle Outlier) began in either the Ordovician or Carboniferous and probably ended in lower Cretaceous before the eruption of the Trap Volcanics.

The general stratigraphies of the Mekelle outlier were summarized from bottom to top by [17], the stratigraphies are mainly Paleozoic-Mesozoic (in age) sedimentary terrain of northern Ethiopia, these are Edaga-Arbi glacial and Enticho sandstone, Adigrat sandstone, Antalo limestone, Agula shale, Amba Aradam formation, Mekelle dolerite and flood basalts of Tertiary age.

7. Geological structures and Tectonics

Reference [16] investigated the structure and tectonics of the Mekelle area (central part of sheet ND37-11) and he pointed out that faulting and tectonic movements control the structure of the area. Three main fault systems exist in the area; two of them are limited to the Ethiopian plateau and one to the rifts of the Danakil depression.

The fault systems of the plateau are normal. The longest of these faults in the area is the Mekelle fault which passes about 9 kilometers northeast 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 Mekelle, which means a throw of about 400 meters [16].

Faults and lineaments are Late Cretaceous and early Tertiary structures developed in the area particularly in the sedimentary succession of the Mekelle Outlier. These are pre-rift structures aligned obliquely to the NNW-SSE directed marginal faults of the rift. At present the area is dissected by three sub-parallel faults forming four major blocks. The Amba-Aradam block is the most southern block, bounded by the Fulcea fault from the south and the Chelekot fault from the north. Next are the Mekelle, the Agulae-Wukro, and the Negash blocks bounded by the Chelekot-Mekelle, Mekelle-Wukro, and Wukro-Senkata faults, respectively (Fig. 5).

The structure and Tectonics of the sedimentary rocks of Mekelle outlier and those found in the escarpment are also studied by [15]. He identified two main fault systems by considering the third fault systems of [16] as a lineament. The two fault system were the Mekelle outlier fault system that are concentrated along En-echelon WNW running fault belts comprises of Wukro, Mekelle, Chelekwot and Fuicea-Mariam fault belts and the rift valley fault system that comprises of the rift valley escarpment and the Danakil depression.

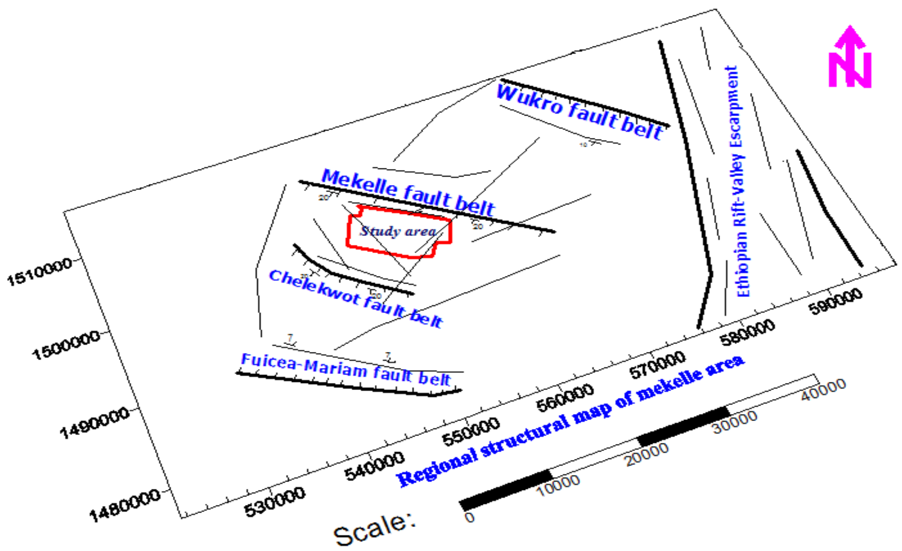

Figure 5: Regional Structural sketch of the Mekelle Area. Modified from [15] and [18], Scale bar is in meter

8. Lithologic Units

The study area is found in the center of Mekelle Outlier composed of a thick sedimentary sequence and intrusive dykes and sills. The main lithologic units in the northern part of Mekelle town according to their age are bedded limestone, limestone-marl-shale intercalations, dolerite and unconsolidated sediments. Description of each lithologic unit is briefly presented below.

8.1. Bedded Limestone

This rock unit is found dominantly in the northern and southwestern part of the study area. Particularly in the Messebo area, it forms a prominent cliff. The upper most part is yellowish to gray in color, with minor fossils, fractured, and intercalated with variegated, calcareous shale and marl. Towards the foot of the cliff dark, dark-brownish, massive with thin beds of fossiliferous and oolitic limestone, black shale and mudstone is observed. At the central part of the study area north of Illala river the karastified limestone is observed, where, solution voids and with some stalactite-stalagmite features. Previous exploration of boreholes drilled in the Messebo area shows that a sulphide (pyrite) mineralization and stylolitic features, solution voids and karst features.

Generally, it is well bedded, black and yellowish in color, crystalline and slightly weathered. Traces of fossils and shell fragments are observed in some hand specimens. Bed thickness is variable (50cm to more than 2m). Thin layers of shale-mudstone and marl are found in this unit, i.e. alternating limestone and thin beds of shale and marl.

Figure 6: Characteristics of bedded Limestone units: (A) crystalline bedded limestone, (B) travertine features formed due to dissolution effects

8.2. Limestone-Marl-Shale intercalations

This intercalation unit covers large part of the study area. It shows cyclic nature of the interbeds and commonly observed along gentle slopes, and it is less resistance to weathering as compared to the cliff forming bedded limestone. It is stratified, fine grained, and variegated in color, and friable up on weathering. The limestone layer is finely crystalline, black and in places light yellow in color containing some fossils (e.g. gastropods and brachiopods), in places the massive and friable mudstone is also observed in this intercalation unit. It is stronger than marl and shale layers; the bed thickness varies from 0.3 to 2m. The marl is mostly yellowish with few beds of brown-yellow to black coquina and sandy limestone. The marl bed thickness varies from 1.5cm to 2m. Shale layer in the unit is thinly bedded or laminated. It is variegated, light yellowish, greenish gray, dark in color, friable, moderately to highly weathered. The thickness of this bed varies from 0.2 to 2m. In places swarms of dolerite dykes and sills are observed. Weathering is more intensive in shale beds than limestone beds.

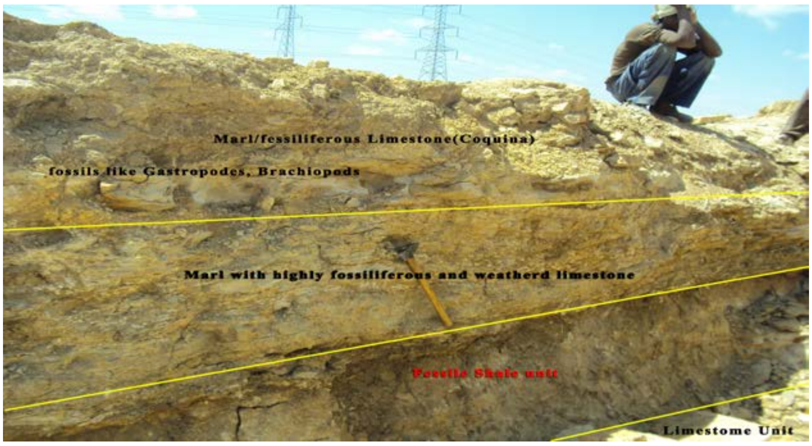

Figure 7: Limestone-Marl-shale intercalation

8.3. Dolerite

This Lithologic unit is mainly exposed at the southeastern part of the northern Mekelle town. It forms steep cliff, in the northwestern and western part of the study area. The dolerites in these areas are exposed as aligned intruded small stocks following the main fault lines and southern part of Illala River, near the center of the town. It is dark green to light gray in color, fine to coarse grained, crystalline, formed as sills, dykes and small stokes, intruded throughout the sedimentary sequence. The unit shows weathering surface of rounded or exfoliation. In some places, sub-rounded fragments are observed with elongated feldspar minerals and fine secondary inclusions. This rock unit is jointed vertically and horizontally. Swarms of dolerite are observed here and there aligned mainly along faults forming dykes and in places forming sills parallel to the bedding plane of the sedimentary sequences. It shows differential weathering surface from place to place that affects the quality of the rock mass and in many localities remnant corestones are common especially in foundation excavations.

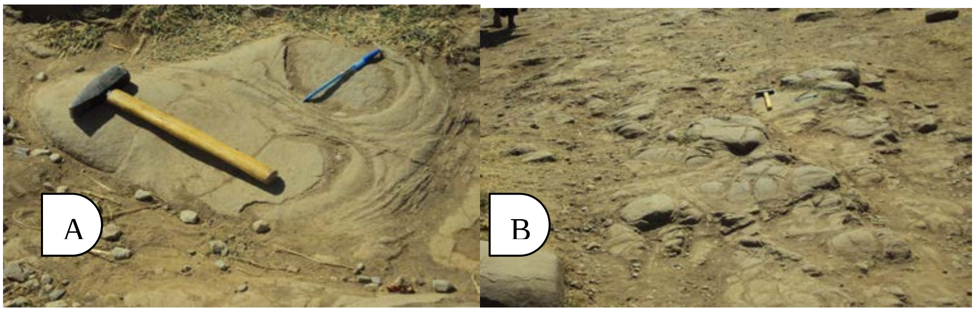

Figure 8: Dolerite rock units and its typical characteristics: (A&B) spheriodal weathering

8.4. Unconsolidated sediments

These sediments consist of alluvial deposits, residual soils and occasionally colluvial deposits. The alluvial deposits range in grain-size from clay to sand with very minor boulders and have been transported to its present location by water. It is widely observed along flatlands, streams and northern and northwest of the area, in particular along Illala river. It is dark to gray in color, loose to stiff and in places stratified. The residual or elluvial soils are formed in places and ranging in grain-size from clay to sand with some inclusions of angular boulders, mainly yellowish in color. They are found in areas of gentle slopes to moderately steep slopes along southeastern part of study area. They are the results of weathering from the bedrocks of shale's / limestone's and dolerites. Colluvial deposits are slow to instantaneously moved soils and/or transported by gravity, common along foot of steep slopes, east of the center of the town. They are dominantly contains of angular boulders and cobbles. The cobbles and boulders are mainly shale, limestone and dolerite fragments.

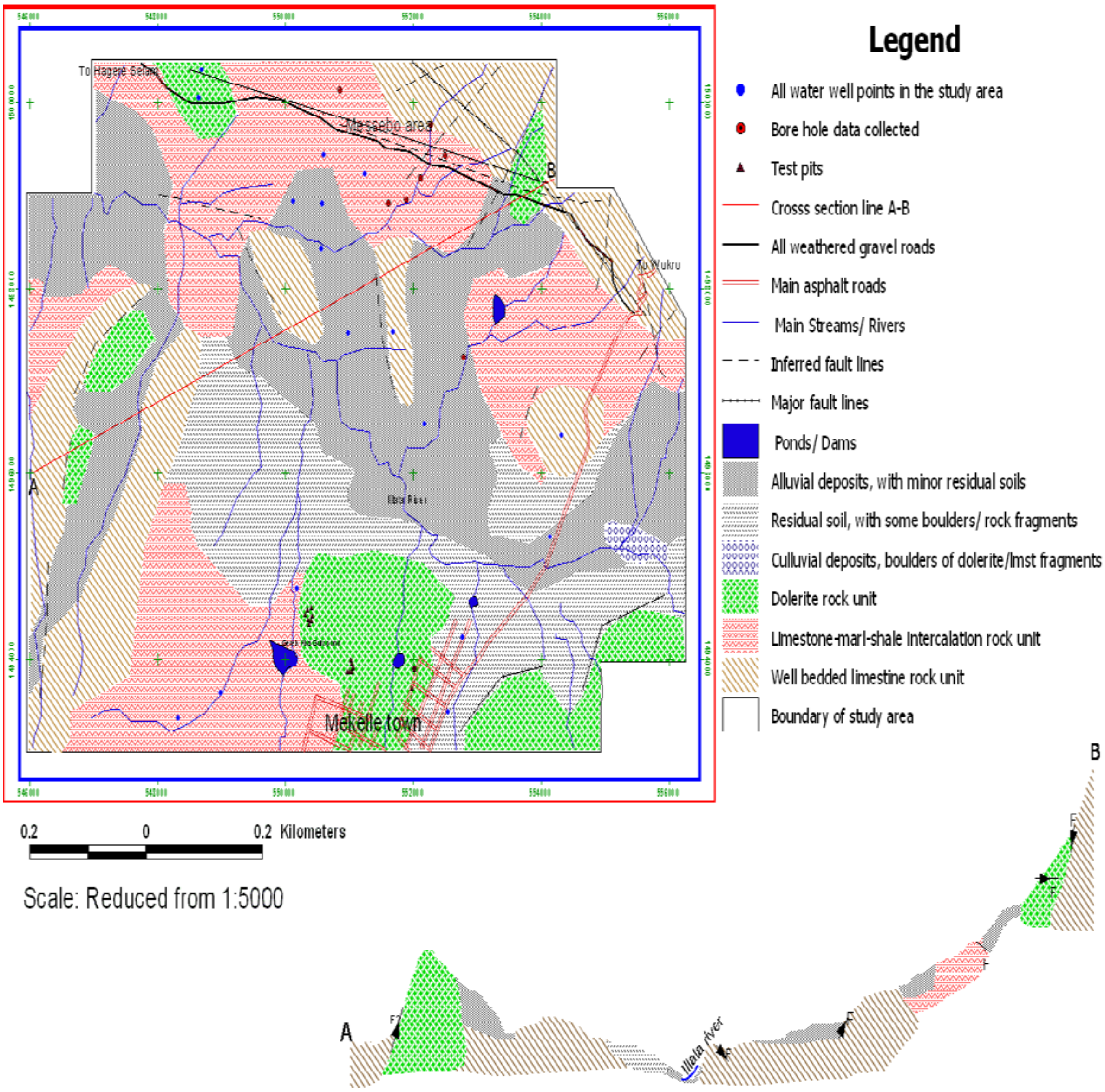

Figure 9: Geological map of the Northern Mekelle town and cross-section from A-B

9. Geological structures of the study area

The study area is highly affected by major and minor faults and joints. Sedimentary structures are also present. Two fault systems of WNW-ESE and NNE-SSW are dominant in the area. The WNW striking faults are more dominant. The largest Mekelle normal fault is within this system, which is running several kilometers along its strike with considerable vertical displacement and dips 80^0 to SWS, forming about 250m high cliff in the Messebo area. minor folds observed in the study area might be formed by the up doming effect of the dolerite or syn-depositional folding

The second fault system in the study area is the NNE-SSW and NE-SW striking faults. The vertical displacement of these fault system is not prominent and difficult to measure due to absence of marker beds. Faults of insignificant displacement and length are also common that might be initiated during the dolerite intrusion and the alignment of the dolerite intruded small stocks indicate that, the presence of fault line. Sedimentary structures of solution voids, karst features, horizontal and inclined bedding planes in the sedimentary rock units are very common.

The third major structure which affects the strength or quality of rock mass is joint. Joints of various orientations have been measured (Annex-E). The strikes of the joints are generally parallel to the faults in the area and seldom perpendicular. Most of the joints are vertical and some are horizontal, parallel to bedding planes in sedimentary rocks. Four major joint sets are observed. The NNE-SSW, NE-SW, NW-SE and WNW-ESE striking joint sets are the dominant once. In the limestone, shale and marl beds, horizontal and vertical joints are very common, while in the dolerite only vertical or columnar joints were dominantly observed.

The other geologic structure is bedding plane, which is considered as discontinuity in engineering geological investigations and could facilitate landslide or slope instability. In large part of the town beds are horizontal, but inclined beds are also observed resulted from dolerite intrusion and faulting.

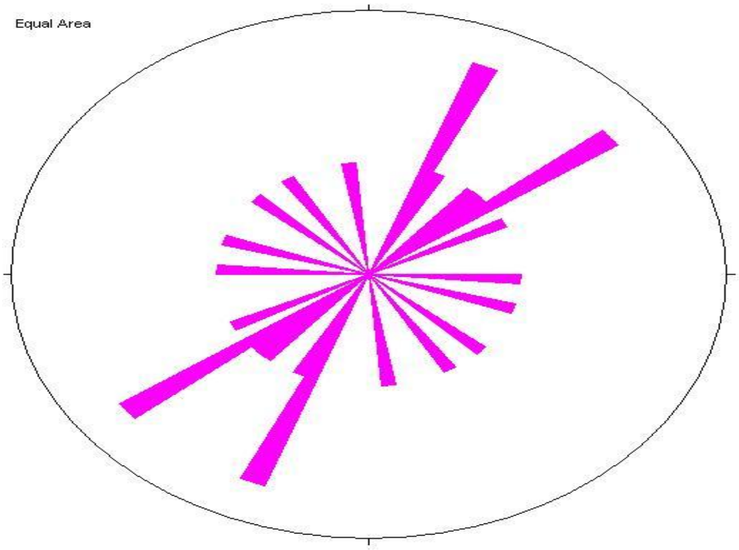

Figure 10: Rose diagram of joints

10. Result and discussion

Geotechnical and Engineering Geological Characteristic and Classification of soils and rocks

10.1. General

The characteristics of soils and rocks of the study area were classified based on their related engineering properties, and according to the standard classification systems of soils and rocks. As a result, multi-purpose geotechnical and engineering geological map was prepared.

10.2. Geotechnical and engineering geological characterization of soils and rocks

Engineering soils, of various genetic types, for example alluvial, residual soils formed by the weathering of rocks, occupy an important position in the sedimentary group. Among these types, the alluvial soils and residual soils and very small area coverage of colluvial deposits are found in the study area.

Characterizing the geotechnical and engineering geological properties of soils were started by describing the main lithological and/ or textural descriptions and discussion of geotechnical laboratory results of the study area.

10.2.1. Results and discussion of soils of the study area

I. Natural Moisture content (NMC)

Natural moisture content (NMC) of soils was determined. According to results (Table 1), the moisture content of the soils of the study area shows that the clay soils have moisture content of 16.5-28.5%, silt soils have 22.8-29.14%, sandy clay / silt have 11.42-20.53% and the clayey / silty sand soils have 13.5–14.9%. Accordingly**,** clay and silt dominating soils of the area shows high capacity to absorb water that can swell and shrink during varied climate conditions.

II. Grain-size Analysis

The results of grain size analyses of soil samples obtained were presented in Table 1. The range of the gravel, sand, silt, and clay fraction is very wide and reflects the wide range of composition, weathering, fracturing, and geologic history of the parent materials. From the result of the grain size analysis, soils of the study area were categorized in to four classes of soil sizes. Ranges of gravel size varies from 0-14%, sand size soils varies from 6-55%, silt size soils ranges from 28-85%, and clay sized soils varies from 8-57%. Generally, % of fines soils are dominant in the study area from the grain size analyzes obtained.

Table 1: Natural moisture content, grain size analysis, consistency limit, liquidity index and consistency index values of laboratory result analysis of the study area.

Test pit/ Borehole No	Depth (m)	NMC in (%)	Sieve analysis (%)				Consistency limit (%)			Liquidity index (LI)	Consistency index (CI)	Lithologic type
			Gravel	sand	silt	clay	LL	PL	PI			

SHBH2	1.9	16.5	0	20	36	44	59.3	28.6	30.7	-0.394	1.394	Clay soils
SHBH2	3.8	25.2	0	11	34	55	80.8	40.7	40.1	-0.386	1.386	
SHBH2	5.3	23.5	0	16	41	43	67.1	36.3	30.8	-0.415	1.415	
SHBH3	2.8	28.5	0	10	33	57	71.6	32.3	39.3	-0.096	1.096	
SHBH3	5.6	28.4	0	12	36	52	70.7	36.2	34.5	-0.226	1.226	
WCHP1	0.6-1.5	24.76	0	26	43	31	50	16	34	0.2576	0.7424	
WCHP2	1.5-2.0	23.03	0	36	55	09	51	17	34	0.1774	0.8226	
MPBH214	1.5	25.5	0	7	85	8	61	26.6	34.4	-0.032	1.032	Silt soils
MPBH215	1.5	26.5	0	6	85	9	64.7	22.7	42	0.0905	0.9095	
SHBH1	2.2	25.5	0	13	47	40	61.2	33.3	27.9	-0.279	1.279	
SHBH1	2.8	22.8	0	10	52	38	61.8	31.4	30.4	-0.283	1.283	
WCHP4	1.0-2.3	27.89	0	34	57	09	44	19	25	0.3556	0.6444	
WCHP5	1.5-2.4	29.14	0	28	56	16	71	40	31	-0.3503	1.3503	
MPBH206	12	Nd	0	44	36	20	48	24.6	23.4	Nd	Nd	Sandy clay/silt soils
MPBH216	12.2	Nd	0	55	28	17	45.5	24.2	21.3	Nd	Nd	
MPBH216	17	Nd	0	30	46	24	50	27.2	22.8	Nd	Nd	
MCHP1	1.1-2.0	11.42	0	23	49	28	48	24	24	-0.5242	1.5242	
WCHP7	1.9	20.53	0	19	63	18	70	34	36	-0.3742	1.3742	
MPBH213	5.8	14.9	14	19	29	38	40.6	24.3	16.3	-0.5766	1.5766	Clayey /silty

MPBH213	7.4	13.5	1	12	47	30	37	24.1	12.9	-0.8217	1.8217	sand soils
MPBH218	13.8	Nd	0	15	45	40	52.6	33	19.6	Nd	Nd	

NMC= Natural moisture content; LL= liquid limit; PL= plastic limit; PI= plastic index=LL-PL: Test pit/ borehole Naming such as SHBH= sport hall bore hole; WCHP= near water bureau (03 Kebele) condominium house test pits; MPBH= Messebo cement plant bore hole, and MCHP= near Mesfin industry (05 Kebele) condominium house test pits, Nd- Not determined

III. Atterberg (consistency) Limits and Plasticity Index

Table 1 also presents the consistency limit values of soils of the area, the clay soils have liquid limit value of 50-80.8%, silt soils 44-71%, sandy clay / silt soils 45.5-70% and fine fraction of clayey/ silty sand soils non-plastic to 52.6%. Their plastic limit of these soils ranges 16-40.7%, 19-40%, 24-34% and non- plastic to 33% respectively. According to the description of plasticity based on range of liquid limits proposed by [13], (Annex-E), most of the soils of the study area fall in intermediate to high plasticity type, except some of the clayey / silty sand soils which fall in soils of low plasticity type.

The plasticity index of clay soils ranges 30.7 to 40.1 % which is highly plastic to extremely plastic range; silt soils 25 to 42% (highly plastic range); sandy clay / silt soils 21.3 to 36% (highly plastic to extremely plastic range) and clayey/silty sand soils non-plastic to 19.6%, based on the range of plasticity index proposed by [13]. In general, most of the plasticity values of the soils of northern Mekelle town fall in the highly plastic range (17-35%).

IV. Liquidity Index (LI) and Consistency Index (CI)

The characterization of such index properties like Liquidity index (LI) of the soils (the nearness of its water content to its LL) and consistency index (CI) (firmness of a soil), were also determined from results of LL, PL and NMC (Table 1).

From the analysis of results of liquidity index (LI) and consistency index (CI) values, majority of the results indicate that negative value of liquidity index that implies those soils that have smaller water content than their plastic limits, and consistency index of greater than one indicate that most of the soils of the study area are relatively stronger in their semi-solid state.

V. Activity of soils

Table 2 presents the activity values of soils of the study area. From the analysis of the data, clay soils varies from 0.663-3.777 from these values, the activity of soils found in the southeastern part of study area are below 0.75 which is inactive soils. Whereas the activities of silt soils of the study area ranges from 0.697-4.666, these values indicate that most of the soils found in the central and north central (Messebo) part of the area are active soils that have high water holding capacity and expansive nature. Sandy clay/ silt soils varies from 0.857-2.0, their activity values fall in the range from normal to active soils and found mostly southern side of Messebo area and near south eastern part of the study area. Clayey/ silty sand soils vary from 0.428-0.49, which indicates the values of activity of soils are below 0.75 i.e. inactive soils. Results of the activity of soils of study area are plotted on the activity chart.

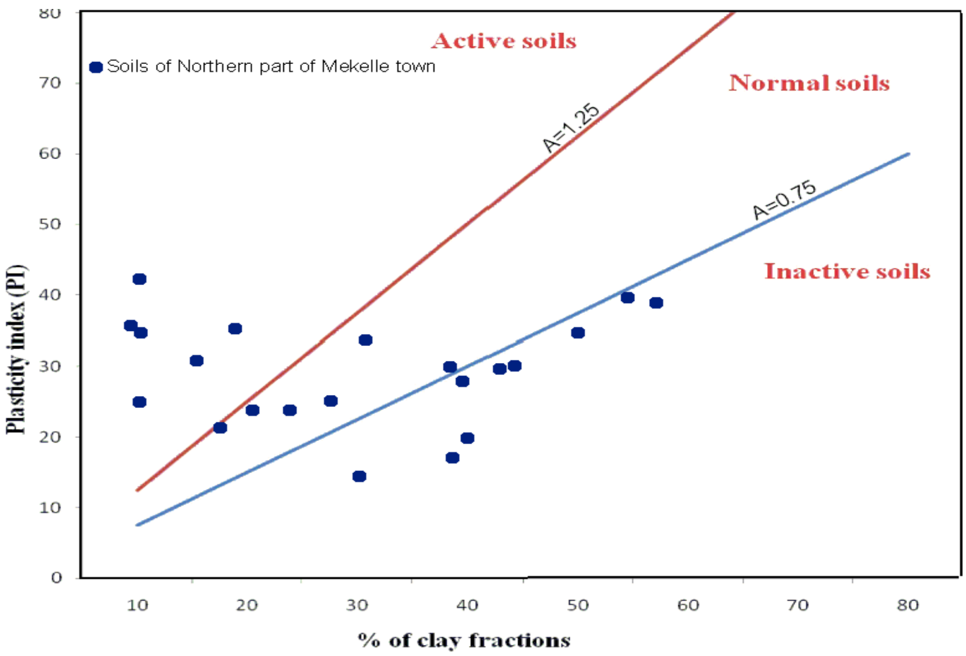

Figure 11: plot of activities of soils of the study area on the activity chart.

VI. Free Swell

The free swell values of the soils of the study area are presented in table 2. From these results soils found in Messebo area have 100% free swell value which is highly expansive soils and serious consideration should be given to these area during construction of engineering structures, it can bring considerable damage to lightly loaded structures basically depending up on the clay mineralogy and soil thickness. Generally the free swell values of soils of the study area vary from 0 to 100%. Some of the soils in the study area were not determined their free swell values.

Currently identification and classification of expansive soils are either on direct measurement of free swell value or on correlation of simpler test results with swell potential measurements. Reference [19] classified clays according to their activity values; this method is used to correlate the activity of soils of the study area with their potential expansiveness. Predictions of swelling potential of soils of the study area were made roughly from the analysis of the activities of the soils. Terms used to determine the potential expansiveness of soils of the study area are Low for soils having activity value of less than 0.75, Medium for soils having activity value between 0.75 to 1.25 and High for soils having an activity value of greater than 1.25.

Table 5.2: Activity and Free swell potential of soils of the study area.

Test pit/ Borehole No	Depth (m)	NMC in (%)	Plasticity Index (PI)	(%) of clay fractions	Activity of soils	Free Swell (%)	Potential expansiveness of soils	Lithologic type
SHBH2	1.9	16.5	30.7	44	0.697	Nd	Low	Clay soils
SHBH2	3.8	25.2	40.1	55	0.729	Nd	Low	
SHBH2	5.3	23.5	30.8	43	0.716	Nd	Low	
SHBH3	2.8	28.5	39.3	57	0.689	Nd	Low	
SHBH3	5.6	28.4	34.5	52	0.663	Nd	Low	
WCHP1	0.6-1.5	24.76	34	31	1.096	Nd	Medium	
WCHP2	1.5-2.0	23.03	34	09	3.777	Nd	High	
MPBH214	1.5	25.5	34.4	8	4.300	100	High	Silt soils
MPBH215	1.5	26.5	42	9	4.666	100	High	
SHBH1	2.2	25.5	27.9	40	0.697	Nd	Low	
SHBH1	2.8	22.8	30.4	38	0.800	Nd	Medium	
WCHP4	1.0-2.3	27.89	25	09	2.777	Nd	High	
WCHP5	1.5-2.4	29.14	31	16	1.937	Nd	High	
MPBH206	12	Nd	23.4	20	1.170	50	Medium	Sandy clay/silt soils
MPBH216	12.2	Nd	21.3	17	1.253	50	High	
MPBH216	17	Nd	22.8	24	0.950	30	Medium	
MCHP1	1.1-2.0	11.42	24	28	0.857	Nd	Medium	
WCHP7	1.9	20.53	36	18	2.000	Nd	High	
MPBH213	5.8	14.9	16.3	38	0.428	Nd	Low	Clayey /silty sand soils
MPBH213	7.4	13.5	12.9	30	0.430	Nd	Low	
MPBH218	13.8	Nd	19.6	40	0.490	60	Low	

Nd: Not determined

VII. Chemical tests of soils

In the study area, the chemical tests of soils were determined from the laboratory results obtained from the above mentioned sources. According to the results presented in Table 3, soil of the study area have pH value of greater than 7 which is alkaline in composition and their value reaches maximum of pH 7.8, which indicates most minerals of the soils are stable, whereas the concentration of chloride ranges from 0.0053-0.212 and sulfate ranges from 0.032-0.2. However, alkali-silica reactions, external sulphate and chloride attack is often manifested, by expansion or cracking of concretes, loss of cohesion and strength. Attention should be given for engineering structures to be built in the area and proper soil chemical tests and hydrochemical analysis should be done for further understanding of their effects to the foundation materials. And if their presence is proved special cement need to be incorporated into a concrete mix to prevent their attacks.

Table 3: Chemical test result of soils of the study area

Item no	Borehole No	Depth (m)	PH-value	Chloride (%)	Sulfate (%)
1	MPBH206	12	7.2	0.0142	0.064
2	MPBH213	1.5	7.6	0.0212	0.216
3	MPBH213	5.8	7.6	0.0142	0.032
4	MPBH213	7.4	7.4	0.0142	0.064
5	MPBH214	3.6	7.3	0.0053	0.080
6	MPBH214	9.0	7.4	0.0140	0.040
7	MPBH215	5.8	7.8	0.0106	0.330
8	MPBH216	3	7.3	0.0212	0.240
9	MPBH216	4.1	7.1	0.0106	0.312
10	MPBH216	11.3	7.5	0.0071	0.344
11	MPBH216	17	7.1	0.0106	0.048
12	MPBH217	5.4	7.8	0.0120	0.200

VIII. Shear Strength of Soils

The shear strength test values of soils of the study area were obtained from the laboratory results of the above mentioned sources. Table 4, presents the shear strength parameters of soils of the study area. From the result of the analysis, the shear strength parameters such as the normal stress values, shear stress values, cohesion and internal friction angles of soils were determined. In addition, the unconfined compressive strength of these soils was determined. The maximum applied normal stress values ranges from 1.5-3.0 kg/cm^2 and their corresponding shear stress varies from 1.39-2.62 kg/cm^2. The plotted points of shear stress (τ) versus normal stress (σ_n) establish a straight line (Mohr envelop), the value of shear stress at zero normal stress are the cohesion of soils varies from 0-0.86 kg/cm^2 for clay soils, 0.4-0.61 kg/cm^2 for silt soils, 0.32-0.98 kg/cm^2 for sandy clay/ silt soils and 0.2-0.21 kg/cm^2 for clayey/ silty sand soils. The value of shear resistance is obtained from the angle between the normal stress and Mohr envelop, the internal friction angle of soils indicate that clay soils vary from 23.22-30^0, silt soils 14-21.5^0, sandy clay/ silt soils vary from 13-27.18^0 and clayey/ silty soils of the study area varies from 22.9-24.24^0.

The unconfined compressive strength is, under practical conditions, twice the cohesion (shear strength) of a clay soil. The unconfined compression strength of soils of the study area were indicated in Table 4, according to the UCS results of the soils, the clay soils ranges from 2.97 up to 4.5 kg/cm^2, silt soil ranges 1.95-3.5 kg/cm^2, sandy clay/ silt soils ranges 0.88-45 kg/cm^2 and clayey/ silty sand soils have 4.5 kg/cm^2 and above.

Parameters of shear strengths: σ-normal stress value to shear plane, τ-shear strength values, c-cohesion value and Φ (degree)-angle of internal friction values of soils. SHBH-Sport Hall Bore Holes, MPBH-Messebo cement Plant Bore Hole, WCHP-near Water bureau Condominium House test Pits, ACHP-Ayder Condominium House test Pits, and MCHP-near Mesfin industry Condominium House test Pits. Nd- Not determined.

Table 4: Shear strength parameter value of soils of the study area

Pit No	Depth in (m)	Material strength (kg/cm^2)				UCS in Kg/cm^2	Lithologic type
		σ	τ	c	Φ(degree)		
SHBH1	2.8	3.0	2.1	0.6	27	3.61	Clay soils
WCHP2	2.0	1.5	1.77	0.52	23.22	3.5	
SHBH3	5.6	3.0	2.62	0.86	30.0	2.97	
ACHP5	1.4	1.5	1.39	0	27.8	>4.5	
MPBH214	1.5	3.0	1.40	0.43	18	2.91	Silt soils
MPBH215	1.5	3.0	1.20	0.45	14	1.97	
WCHP4	2.3	1.5	1.66	0.61	19.37	3.5	
WCHP5	2.4	1.5	1.54	0.40	21.50	3.0	
MCHP1	2.0	1.5	2.04	0.45	27.18	Nd	Sandy clay/ silt soils
SHBH2	3.8	3.0	1.48	0.80	13.0	0.88	
ACHP2	1.2	1.5	1.3	0.32	18.6	>4.5	
MCHP3	1.4	1.5	1.39	0.39	18.66	Nd	
MCHP4	1.0	1.5	2.11	0.98	20.43	Nd	
ACHP7	1.4	1.5	1.34	0.38	17.6	>4.5	
MCHP2	1.4	1.5	1.58	0.20	24.24	>4.5	Clayey/ silty sand soils
ACHP4	1.4	1.5	1.5	0.21	22.9	>4.5	

10.2.2. Geotechnical and Engineering geological characterization of rocks

Description is the initial step in an engineering geological investigation of rock masses. The description should also be uniform and consistent for easy understanding and to gain acceptance. In view of this, to characterize the engineering properties of rocks of the study area, detail field description and determination of engineering properties of rocks was conducted, the descriptions of rocks of the northern Mekelle town was carried out according to the descriptive schemes proposed by [13]. Some engineering property determination tests were conducted at the field. The simple means of determination of strength of rocks were done according to the scheme proposed by working party report of Geological society of London, 1977 based on the modified scheme of [20] cited in [21]. According to this method about 22 tests are done using geological hammer in the field and more than 40 site investigation boreholes (Annex-G) obtained from previous works and were used to determine the engineering properties of the rock masses of the study area. The engineering geological characteristics of rocks of the study area were described basically according to the lithological units and characterizing with their similar engineering geological subunits of the rocks. The engineering geological descriptions of the rocks of the study area are discussed below.

10.2.2.1. Dolerite

In the study area, these rocks are widely exposed along the escarpments sides and some rocks are exposed due to the structural setting and river/stream cuts and excavations for quarry sites, road and foundation work. These exposures help to describe the rock mass characteristics. From engineering geological point of view, this rock unit has variable properties such as fresh to slightly weathered strong dolerite having high mass strength, moderately weathered moderately strong to strong dolerite having Medium mass strength and highly weathered weak to moderately strong dolerite having Low mass strength.

I. Fresh to slightly weathered, strong dolerite (Rock with high mass strength): this engineering geological subunit is found in the southeastern side of the study area forming a steep cliff. Due to the high strength, slight effect of weathering and narrow to widely spaced joints are observed, the simple geological hammer strength estimate value of this unit indicate that strong rock and unconfined compressive strength of 50-100MPa, which is strong to very strong. Two sets of joints are dominant. WNW and NNE, in places columnar joints are observed. The joint wall or surface is planar and smooth and have strong wall strength. The aperture of the joints varies from tight to narrow.

II. Moderately weathered, moderately strong to strong dolerite (Rocks with medium mass strength): these subunits are found in the southern, western and northwestern part of the study area and the rock unit has mass strength ranges from medium to strong. It is moderately weathered medium to coarse grained rock mass, where the strength determination from the estimation range of geological hammer test value indicates that from 13 to 45MPa that is moderately strong material. Two sets and random joints are dominant which are vertical and medium to widely spaced. The joint surface for the systematic once, is planar and rough, and weak to moderately strong wall strength .the separation or aperture is variable and ranges from very narrow to moderately narrow, Clay and calcite are the common infill materials in some of joints, occasionally silica veins are observed

III. Highly weathered, weak to moderately strong dolerite (Rock with low mass strength): this rock is mainly found at the south central part, southeastern (foot of Endayesus ridge), western and northwestern part of the study area. It is moderately to highly weathered dark greenish, fine to coarse grained dolerite rock unit. The material strength estimated in the field indicates varies from 2 to 20MPa (weak rocks). Joints of WNW strike are common. In places NNE strike joints are observed. The joints are in general vertical and the spacing varies from 4 to 20cm (very closely to closely spaced). Joint surfaces are planar and rough, low wall strength and very narrow and moderately narrow aperture. Clay, calcite and silica are common infill materials in some joints.

5.2.2.2. Limestone-Marl-Shale intercalation

This rock mass unit covers large part in the study area. From engineering geological point of view, this rock mass is characterized by moderately to highly weathered, weak to moderately strong to strong Limestone-Marl-Shale intercalation rock mass (Rock with low mass strength).

Moderately to highly weathered, weak to moderately strong Limestone-Marl-Shale intercalation rock mass (Rock with low mass strength): Even though the strength of each layer varies from weak (shale) to strong (limestone), it is considered as weak engineering geological unit or rock with low mass strength, because in most engineering designs it is the weak layer that governs the stability of the structures and design parameter of the weakest layer is considered. It is variegated (gray, yellowish, dark brown, etc.) crystalline and moderately to highly weathered, especially, the shale layer is highly weathered. The rock material strength is variable and difficult to estimate the whole rock mass, i.e. from very weak for shale (1.5-5MPa) to medium to strong for limestone. Generally three vertical joint sets and horizontal joint are observed in this intercalation unit. This Joint surfaces or wall is generally planar and rough, and have variable wall strength, weak to strong, and tight to moderately narrow aperture (0-3cm). The spacing of the systematic joint set is on average 0.5 to 1.5m. This intercalation unit is horizontally to sub-horizontally bedded with bed thickness of 0.2 to 1.5m. In place the beds are inclined in different direction due to the intrusion of dolerite.

5.2.2.3. Bedded Limestone

This rock unit is found mainly along the northern Messebo escarpment, forming a steep cliff, central and southwestern part of the study area. From engineering geological point of view, the rock mass is characterized by slightly weathered strong limestone (Rock with high mass strength) and moderately weathered moderately strong to strong limestone (Rock with medium mass strength). Their descriptions are as follows.

I. Slightly weathered, strong limestone (Rock with high mass strength): This subunit is mainly observed in the northeastern and southwestern part of the study area and forms a steep cliff. It is characterized by fresh to slightly weathered, crystalline, light yellowish to black in color. The exposures of this subunit are outcropped along the escarpment and streams. The rock material strength determined from geological hammer estimation varies from 50-100MPa at the foot of the escarpment and greater than 100MPa at the midway part of the escarpment. Three vertical joint set and horizontal joint parallel to bedding planes are the dominant once. The joint surface or wall is planar and rough to smooth, and shows strong wall strength and the aperture varies from tight (for horizontal joints) to 4cm (for vertical joints). The vertical joints are widely spaced (0.5 to 2.5m). This limestone unit is bedded in most places horizontal and bed thickness reaches up to 1.2m.

II. Moderately weathered, moderately strong to strong limestone (Rock with medium mass strength): This unit is mainly observed at Messebo area, western and southwestern part of the study area. It is characterized by light to brownish yellow, moderately weathered limestone. The material strength of the rock mass varies from 12.5 to 50MPa which is a moderate strength of material. Horizontal and two vertical set of joints, the horizontal joints are parallel to the bedding plane, shows that moderately strong to strong wall strength and the aperture varies from narrow to widely spaced joints.

10.3. Geotechnical and Engineering Geological classification of soils and rocks

The main aim of soil and rock classification is to arrange or divide the soils and rocks into limited number of groups such that the engineering materials in a particular group have similar behavior. A classification system is also meant to provide a common language for the exchange of information and experience about various types of soils and/or rocks. Soil and rock classification system leads the engineering geologist or geotechnical engineer to estimate their engineering properties from tables and charts for preliminary design and planning.

In view of the above principle the soils and rocks of the study area are classified according to their physical and engineering geological properties characterized. The classification system used for the soils and rocks of the northern Mekelle town is described as follows.

10.3.1. Classification of soils

In this work, to classify the soils of the study area, the Unified soil classification system and classification system proposed by [13] which is modified form of the unified soil classification (USC) and the British soil classification for engineering purposes (BSCS) are used. The unified soil classification system, originally proposed in united states, and most popular for use in all types of engineering problems involving soils, is based on both gain size and plasticity properties of the soil and is applicable to any use (Annex-F).

Soil is defined and allocated to an appropriate group on the basis of grading and plasticity after excluding boulders and cobbles (>300-mm and 300-75-mm respectively). Gravel particles are those passing a 75-mm (3-in) sieve but retained on a 4.75-mm (No. 4) sieve. Sand particles pass a 4.75-mm sieve and are retained on a 0.075-mm (No. 200) sieve. Fines are soil particles that pass a 0.075-mm (No. 200) sieve; they are further characterized as silt or clay, based on their plasticity. The soils are broadly classified into two categories, coarse-grained, if more than 50% of the soil is retained on the 0.075 mm (No.200) sieve, fine-grained, if more than 50% of the soil passes the 0.075mm (No. 200) sieve. The coarse-grained soils are further subdivided based on grain sizing, plasticity index and liquid limit. For fine grained soils exact type of the soils is determined by their behavior from plasticity or casagrande chart.

Once a soil is determined to be fine grained by the grain-size curve, its classification into one of the six groups is done by the results of Atterberg limits tests as plotted on the plasticity chart, with attention being given to the organic content. Inorganic fine-grained soils with PI greater than 7 and above the `A' line are CL or CH, depending on whether their liquid limits are below 50 percent or above 50 percent respectively. Similarly, inorganic fine-grained soils with PI less than 4 or below the `A' line are ML or MH, depending on whether their liquid limits are below or above 50 percent, respectively. Fine-grained soils which fall above the `A' line but which have a plasticity index between 4 and 7 are classified ML-CL. In view these, the soils of the study area are classified and plotted on the plasticity charts based on both USCS.

The classification system proposed by International association of Engineering Geologists commission on engineering geological mapping [13] is also based on grading and plasticity of soils. Grading and plasticity are divided into a number of clearly defined ranges. Each of which may be referred to by a descriptive name and letter (Table 6). The descriptive plasticity ranges used to classify the soils of the study area proposed by [13] is presented in Annex-F.

Table 5: Classification of soils of the study area based on Unified soil classification system

Test pit/ Borehole No	Depth (m)	Sieve analysis (%)				Consistency limit (%)		USCS		Lithologic type
		Gravel	sand	silt	clay	LL	PI	S**	Soil name	
SHBH2	1.9	0	20	36	44	59.3	30.7	CH	Fat clay	Clay soils
SHBH2	3.8	0	11	34	55	80.8	40.1	CH	Fat clay	
SHBH2	5.3	0	16	41	43	67.1	30.8	CH	Fat clay	
SHBH3	2.8	0	10	33	57	71.6	39.3	CH	Fat clay	
SHBH3	5.6	0	12	36	52	70.7	34.5	CH	Fat clay	
WCHP1	0.6-1.5	0	26	43	31	50	34	MH	Elastic silt	Silt soils
WCHP2	1.5-2.0	0	36	55	09	51	34	MH	Elastic silt	
MPBH214	1.5	0	7	85	8	61	34.4	MH	Elastic silt	
MPBH215	1.5	0	6	85	9	64.7	42	MH	Elastic silt	
SHBH1	2.2	0	13	47	40	61.2	27.9	MH	Elastic silt	
SHBH1	2.8	0	10	52	38	61.8	30.4	MH	Elastic silt	
WCHP4	1.0-2.3	0	34	57	09	44	25	ML	Silty of clayey fine sand with slight plasticity	
WCHP5	1.5-2.4	0	28	56	16	71	31	MH	Elastic silt	
MPBH206	12	0	44	36	20	48	23.4	CL	Lean sandy clay	Sandy clay/silt soils
MPBH216	12.2	0	55	28	17	45.5	21.3	CL	Lean sandy clay	
MPBH216	17	0	30	46	24	50	22.8	MH	Elastic sandy silt	
MCHP1	1.1-2.0	0	23	49	28	48	24	ML	Sandy Silty, clayey with slight plasticity	
WCHP7	1.9	0	19	63	18	70	36	MH	Elastic sandy silt	
MPBH213	5.8	14	19	29	38	40.6	16.3	SC	Clayey sand	Clayey /silty sand soils
MPBH213	7.4	1	12	47	30	37	12.9	SC-SM	Clayey, silty sand	
MPBH218	13.8	0	15	45	40	52.6	19.6	SC-SM	Clayey, silty sand	

S**= Symbol, LL= liquid limit; PI= plastic index: Test pit/ borehole Naming such as SHBH= sport hall bore hole; WCHP= near water bureau (03 Kebele) condominium house test pits; MPBH= Messebo cement plant bore hole, and MCHP= near mesfin industry (05 Kebele) condominium house test pits.

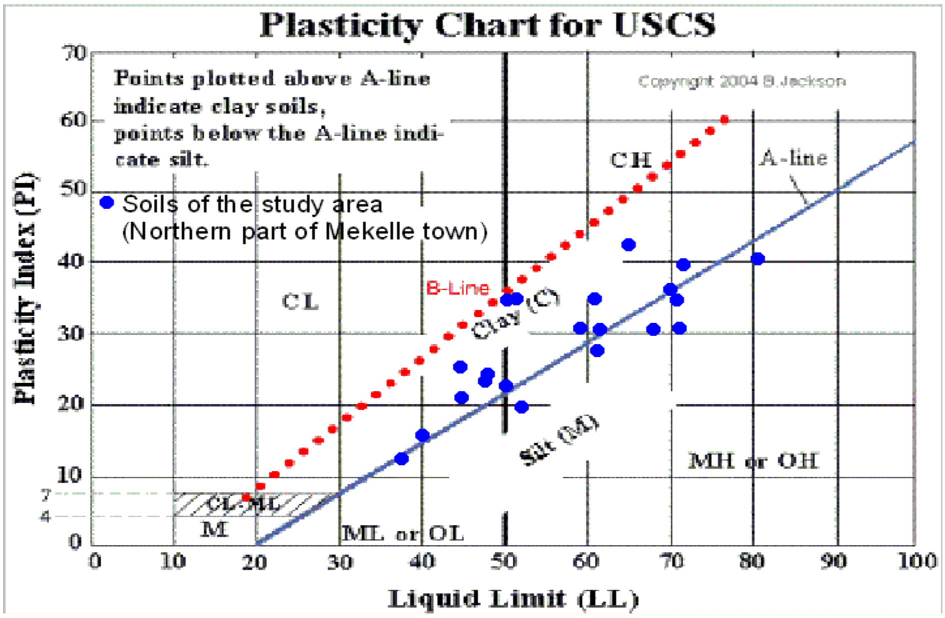

Figure 12: Plots of soils of the study area on casagrande plasticity chart based on USCS

Table 6: Classification of soils of the study area based on International Association of Engineering Geologists commission on engineering geological mapping (IAEG (1981))

Test pit/ Borehole No	Depth (m)	Sieve analysis (%)				Consistency limit (%)		IAEG (1981)		Lithologic type
		Gravel	sand	silt	clay	LL	PI	S**	Soil name	
SHBH2	1.9	0	20	36	44	59.3	30.7	CH	CLAY of high plasticity	Clay soils
SHBH2	3.8	0	11	34	55	80.8	40.1	CV	CLAY of very high plasticity	
SHBH2	5.3	0	16	41	43	67.1	30.8	CH	CLAY of high plasticity	
SHBH3	2.8	0	10	33	57	71.6	39.3	CV	CLAY of very high plasticity	
SHBH3	5.6	0	12	36	52	70.7	34.5	CV	CLAY of very high plasticity	
WCHP1	0.6-1.5	0	26	43	31	50	34	MI	SILT of high plasticity	Silt soils
WCHP2	1.5-2.0	0	36	55	09	51	34	MH	SILT of high plasticity	
MPBH214	1.5	0	7	85	8	61	34.4	MH	SILT of high plasticity	

MPBH215	1.5	0	6	85	9	64.7	42	MH	SILT of high plasticity	
SHBH1	2.2	0	13	47	40	61.2	27.9	MH	SILT of high plasticity	
SHBH1	2.8	0	10	52	38	61.8	30.4	MH	SILT of high plasticity	
WCHP4	1.0-2.3	0	34	57	09	44	25	MI	SILT of intermediate plasticity	
WCHP5	1.5-2.4	0	28	56	16	71	31	MV	SILT of very high plasticity	
MPBH206	12	0	44	36	20	48	23.4	SC (SCI)	SAND clayey of intermediate plasticity	Sandy clay/silt soils
MPBH216	12.2	0	55	28	17	45.5	21.3	SC (SCI)	SAND clayey of intermediate plasticity	
MPBH216	17	0	30	46	24	50	22.8	SM (SMH)	SAND silty of high plasticity	
MCHP1	1.1-2.0	0	23	49	28	48	24	MI	SILT sand of intermediate plasticity	Clayey /silty sand soils
WCHP7	1.9	0	19	63	18	70	36	MV	SILT sand of very high plasticity	
MPBH213	5.8	14	19	29	38	40.6	16.3	CI	CLAYEY sand of intermediate plasticity	
MPBH213	7.4	1	12	47	30	37	12.9	MI	SILT sand of intermediate plasticity	
MPBH218	13.8	0	15	45	40	52.6	19.6	CH	CLAYEY sand of high plasticity	

S**= Symbol, LL= liquid limit; PI= plastic index: Test pit/ borehole Naming such as SHBH= sport hall bore hole; WCHP= near water bureau (03 Kebele) condominium house test pits; MPBH= Messebo cement plant bore hole, and MCHP= near mesfin industry (05 Kebele) condominium house test pits.

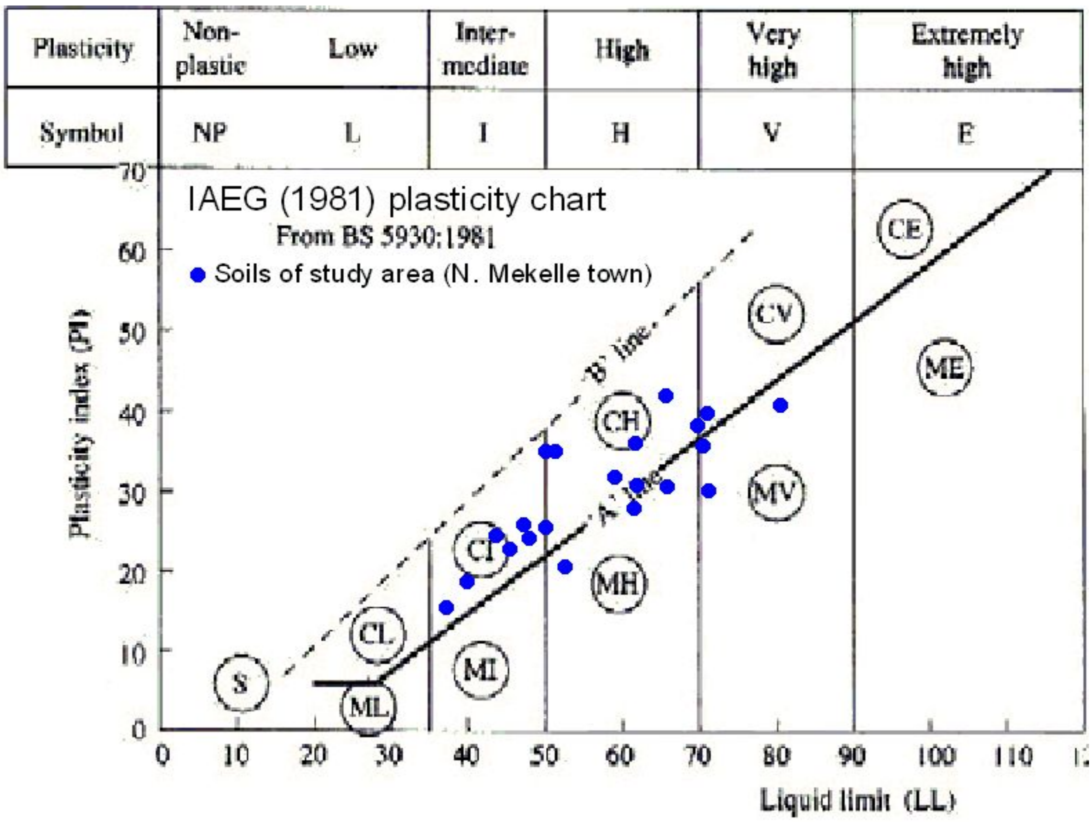

Figure 13: Classification of soils of the study area based on the IAEG (1981) on plasticity chart

10.3.2. Classification of rocks of the study area

Geotechnical classifications for intact rock and rock masses have been devised; many of the classifications have been designed for specific engineering applications such as tunneling, open-pit mining and foundations. Although some feel there is a need for an acceptable universal classification of rock for geotechnical purposes, the difficulty in arriving at such a classification indeed, even the feasibility of trying to do so. And it has been noted by several specialists in rock mechanics [22] [23] [24] [25] [26]. The presently available specialized classification provide for the unique requirements for which each was devised. The more universal the intended use of a classification, the greater the number of intact rock and rock mass properties that must be measured for the classification to meet the intended purposes.

In a classification system empirical relations between rock mass properties and the behavior of the rock mass in relation to a particular engineering application, are combined to give a method of designing engineering structures in or on a rock mass. Rock mass classification has been applied successfully for some years in tunneling and underground mining. Some rock mass classification systems [7] result in empirical strength criteria for a rock mass.

In view of the above mentioned principles, systematic ways of classifying the rock masses of the study area are reviewed. Simple approaches of classifying the rocks are the main options indeed. These are based on their intact rock strength values and joint characteristics and the weathering degree of rocks. During field works, the measurements of joint characteristics, in-situ strength determinations by simple means of intact rock strength estimation by using geological hammer and descriptions of engineering geological properties of rocks are carried out. Based on these data's the rocks of the area are classified and delineated in the multi-purpose engineering geological map.

10.3.2.1. Classification of rock mass based on strength values and joint characteristics

The rock mass classification of the study area is done based on the strength values determined from the simple geological hammer test results and the joint characteristics determined from field observations. According to this, the rock masses of the study area fall in to three major classes, such as rocks with low mass strength, rock with medium mass strength and rocks with high mass strengths. Distributions of these engineering geological units are represented in the multi-purpose engineering geological map prepared.

I. Rocks with low mass strength

This engineering geological unit is grouped for rocks that can be characterized by the intact rock strength value mostly less than 20MPa. The limestone-marl-shale intercalation and moderate to highly weathered dolerite rock units are found in this classification system. The low to moderately strong dolerite unit is mostly observed in the southern part of Illala River and foot of the eastern escarpment and the intercalation of limestone-marl-shale cover large part in the study area and mostly found in the northern, northeastern, western and southwestern part of the study area. The weathering activity in this unit is moderately to highly active, played vital role in reducing the strength of the rock mass unit. The characteristics of joint spacing is mainly ranges from 1-10cm, and these joint characteristics influenced the rock mass strength to reduce in addition to the lithological properties, and grouped the rocks under the low mass strength unit of rock masses of the engineering geological mapping.

II. Rock with medium mass strength

The rocks that can be classified to medium mass strength are characterized by the intact strength values ranging from 13-50MpPa, where some exaggerated intact strength value up to 100Mpa is estimated because of the some resistant boulders of the dolerite fragments and thick beds of the limestone in the rock masses. The main rock units grouped in this engineering geological unit is moderately weathered dolerite and limestone units where 50-60% of the rock mass is fabrics of the intact rocks (Annex-F). They are characterized by moderate weathering (spheroidal characteristics in dolerite) and closely to medium spaced joints ranging 1-20cm where in places the spacing ranges up to 0.5m. The distribution of these units is observed in the down side or foot of Messebo escarpment, northwestern, western and southern part of study area and represented on the multi-purpose engineering geological map of the area.

III. Rocks with high mass strength

In this unit, the thick well bedded limestone and fresh to slightly weathered dolerite rock units are the major engineering geological subunits, they are characterized by their intact rock strength of mostly 50-100Mpa and some sound rocks indicate their strength values are exceeding the 100Mpa and gives thin sound when blown by the geological hammer. More than 60-80% of the rock masses are fragments of the intact rocks. whereas the discontinuity characteristics in limestone rocks shows horizontally bedded and in the dolerite rocks stay as crystalline but showing discontinuities and exfoliations of weathering effects on the rock mass. The weathering activity in this unit is slight that has not yet brought reduction in the strength of the rock mass. Where typical spheroidal weathering is observed in the dolerite and along the bedding and joints of limestone rocks weathering activity is also observed. The joint characteristics are medium to widely spaced joints and spacing ranges from 10-60cm in the dolerite rock unit and tight to 50cm spacing is observed along the well bedded limestone unit. The distribution of this engineering geological unit is along the southeastern escarpment elevated side and at the Messebo escarpment cliff part of the study area and represented on the prepared multi-purpose engineering geological map of the northern Mekelle town.

10.3.2.2. Variations of Unconfined compressive strength with rock types

Moreover, the variation of unconfined compressive strength with main lithologic unit is portrayed in Figure 14 below. The measurement of the UCS values obtained from Messebo cement plant site investigation report and Gebremedhin Berhane (2002) (Annex-B) are used to evaluate the variation of engineering properties of the lithologic units found in the area. The rocks of the area shows ranges of strength from very strong (225MPa) obtained from bedded limestone unit to moderately strong (25MPa) of dolerite rock unit (Annex-F).

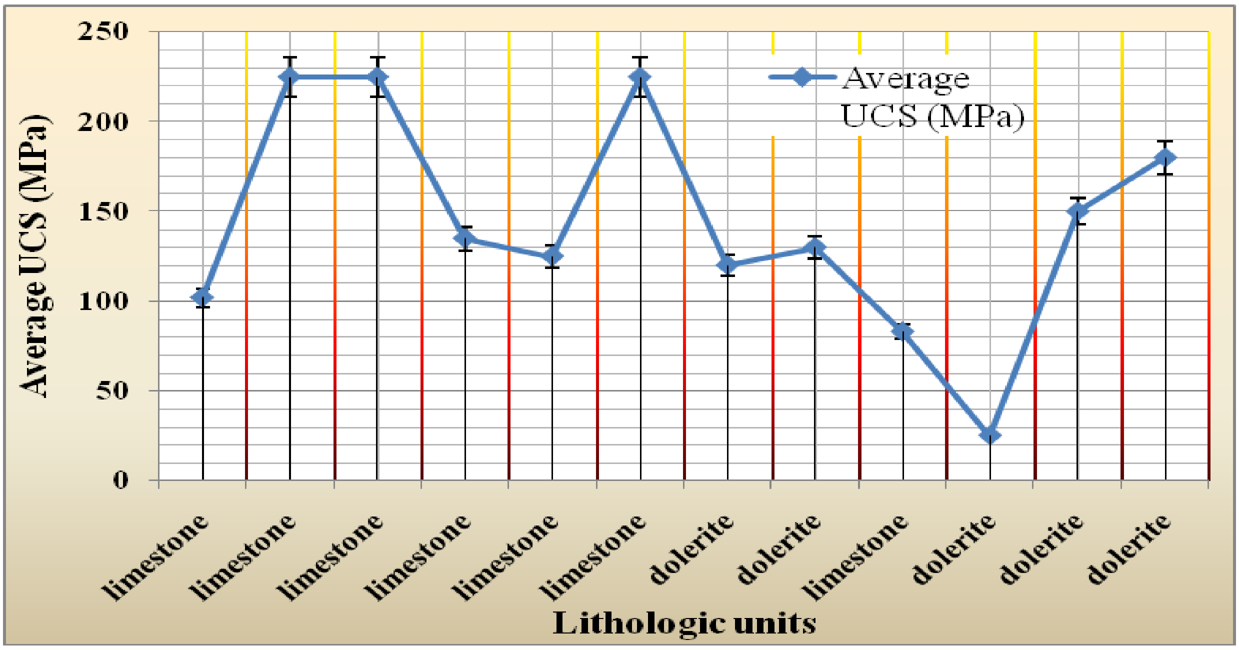

Figure 14: Variation of Unconfined Compressive Strength values with rock types of study area.

11. Preparation of Multi-purpose engineering geological map

Multi-purpose maps are produced to provide information on many aspects of engineering geology for a variety of planning and engineering purposes. Most of these maps are comprehensive in content, depicting all the principal components of the engineering geological environment, where on one map sheet areas classified as units based on the uniformity of their engineering geological conditions are shown. As a result, the preparation of multi-purpose engineering geological and geotechnical map of the northern part of Mekelle town is mainly based on the detail field work mapping and results of engineering geological and geotechnical field and laboratory tests. Basic components of the geological environment needed for the engineering geological mapping was well assessed and discussed, and presented in addition to the engineering geological subunits on the produced maps.

The multi-purpose engineering geological map is produced based on the principle of similar physical and engineering geological properties of soils and rocks at their present state suggested by the international association of engineering geologists [13] commission on engineering geological mapping beside the description and classification schemes used. So, soils and rocks of the study area that have uniform physical and engineering geological properties and their spatial distributions are described and delineated on the multi-purpose engineering geological map. As a result, this map (Fig. 15) generally consists of the lithological and engineering geological sub units with accompanying geomorphological, geodynamic phenomena and hydrogeological conditions of the northern part of Mekelle town.

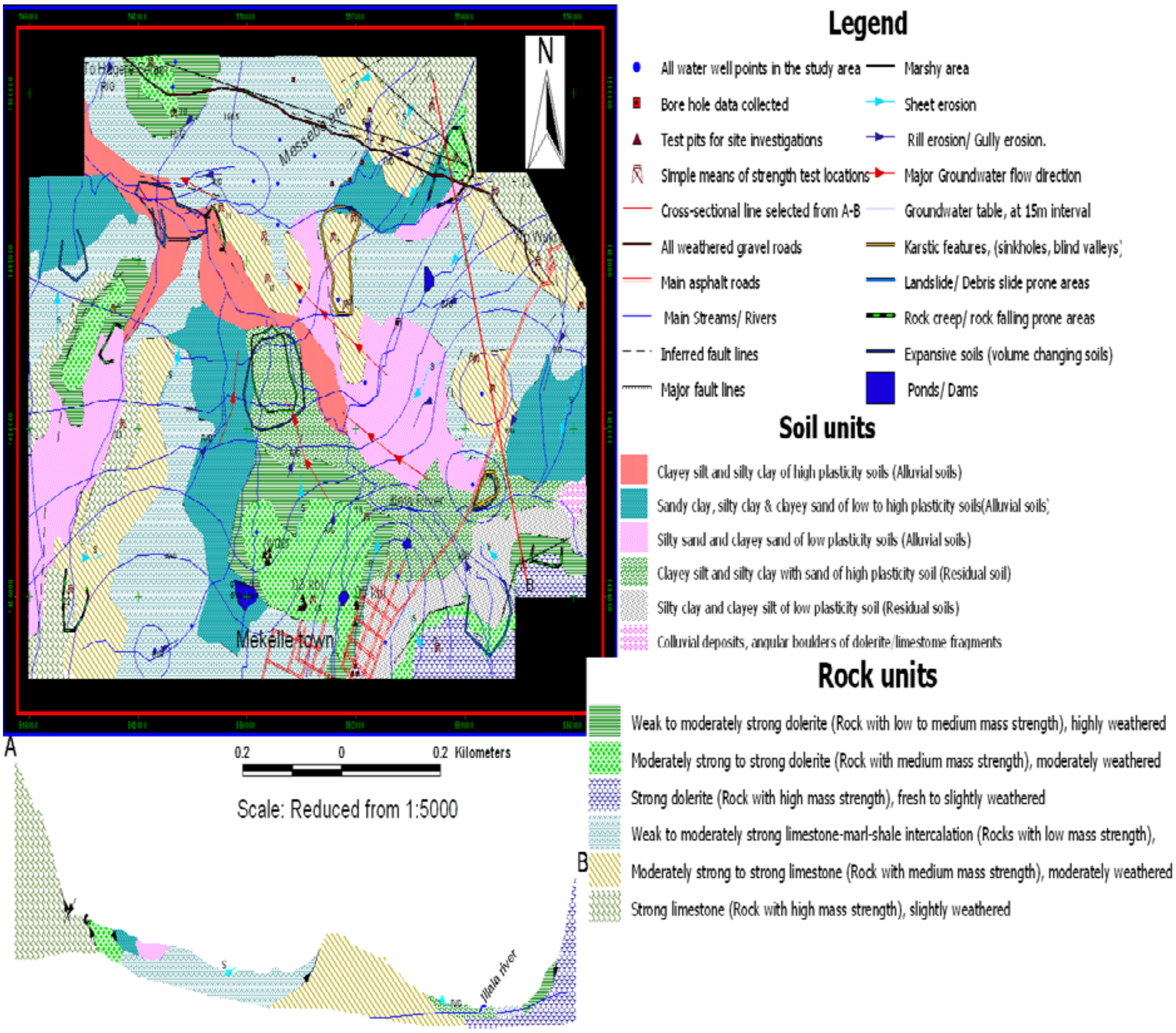

Figure 5.6: Multi-Purpose Engineering Geological Map and engineering geological cross section (A-B)

12. Conclusion and Recommendations

12.1. Conclusion

From this research work, the following points are concluded:

- In the study area, the dominant rock units are dolerite, limestone-marl-shale intercalation and bedded limestone, and the major soil units mapped are the alluvial, residual and colluvial soil deposits.
- Two fault systems (WNW and NNE striking) are dominant in the study area and inferred faults are trending in these two fault systems. The WNW-ESE trending faults are more dominant and the strike of the main Mekelle fault line is within this trend. The major joint sets of the study area have similar orientation with that of the two major fault systems, striking (NNE, NE, NW and WNW). Following the above dominant fault system, the NW and NNE striking joints are dominant.
- Assessment of the geomorphological condition of the study area revealed that four major landform units are common in the area: flat to gently sloping, gently sloping to rolling, sloping to moderately steep (hilly land), and steeply to very steeply sloping (escarpment) landforms.
- Four types of lithological soils (i.e. clay, silt, sandy clay/ silt and clayey/ silty sand) are identified in the study area. The evaluation of the laboratory result indicates that:

► Clay soils are characterized by a moisture content of 16.5-28.5%, liquid limit of 50-80.8%, plasticity index of 30.7 to 40.1 % (highly to extremely plastic), activity of 0.663 to 3.777 (inactive to active soils, i.e. low-high potential expansiveness of the soil) and UCS of 2.97-4.5 Kg/cm^2.

► Silt soils are characterized by a moisture content of 22.8-29.14%, liquid limit of 44-71%, plasticity index of 25 to 42% (highly to extremely plastic soils), activity of 0.4697-4.666 (inactive to active soils, i.e. low to high potential expansiveness) and UCS of 245-392 Kg/cm^2.

► Sandy clay/ silt soils are characterized by a moisture content of 11.42-20.53%, liquid limit of 45.5-70%, plasticity index of 21.3 to 36% (highly to extremely plastic), activity of 0.857 to 2.00 (normal to active soils, i.e. medium to high potential expansiveness) and UCS of 0.88-4.5 Kg/cm^2.

► Clayey/ silty sand soils are characterized by a moisture content of 13.5-14.9%, liquid limit of 37-52.6%, plasticity index of 12.9% to 19.6% (moderately to highly plastic), activity of 0.428 to 0.49 (inactive soils, i.e. low potential expansiveness) and UCS of 4.5 Kg/cm^2 and above.

► The soils, as determined from chemical tests, are alkaline (pH>7). Sulphate concentration is found to vary from 0.032% to 0.20%. Chloride concentration in these soils ranges from 0.0053% to 0.212%. These values of sulphate and chloride concentration can bring deterioration of concretes when in contact with such types of soils.

- Each lithological rock types are classified into their engineering geological subunits.

► The dolerite rock unit is subdivided into: (a) fresh to slightly weathered, strong rock mass (rock with high mass strength); with UCS value of 50-100MPa, (b) moderately weathered, moderately strong to strong rock mass (rock with medium strength); with UCS value of 13-50MPa, and (c) highly weathered, weak to moderately strong rock mass (rock with low mass strength); with UCS value of 2-20MPa.

- The limestone-marl-shale intercalation unit is characterized by moderately to highly weathered, weak to moderately strong rock mass (rock with low mass strength) and has UCS value of 1.5-5MPa.
- The bedded limestone unit is subdivided into: (a) slightly weathered strong rock mass (rock with high mass strength) with UCS value of 50-150MPa and moderately strong to strong rock mass (rock with medium mass strength) moderately weathered, that has UCS value of 13-50MPa.

- The classification systems used for the soils of the study area are based on the Unified Soil Classification System (USCS) and classification system proposed by [13].
  - According to the USCS: (a) the clay soils fall in CH (fat clays) type, (b) the silt soils fall in MH (inorganic silt, elastic silts) and ML (silty of clayey fine sand with slight plasticity), (c) sandy clay/ silt soils fall in CL (lean sandy clay), ML and MH (inorganic silts or fat clay with sand, lean sandy clay or very fine sands, elastic sandy silt or silty/ or clayey fine sand), and (d) the clayey/ silty sand soils fall in SC (clayey sand) and SC-SM (clayey sand or sandy clay mixtures, and silty, clayey sand soils) types.
  - According to IAEG (1981): (a) the clay soils fall in CV (clay of intermediate plasticity) and CH (clay of high plasticity soils), (b) the silt soils fall in MI, MH and MV (silt of intermediate, high and very high plasticity), (c) the sandy clay/silt soils fall in SC (SCI) (SAND clayey of intermediate plasticity) and SM (SMH) (SAND silt of high plasticity) and (d) the clayey/ silty sand soils fall in to CI, CH (CLAYEY sand of intermediate, high plasticity) and MI (SILT sand of intermediate plasticity).

- The rock masses of study area are classified based on the strength values and joint characteristics of the lithological rock units. According to this, the rock mass of the study area are classified into three major engineering geological subunits:
  - Rocks with low mass strength (rocks that has intact rock strength less than 20Mpa and joint spacing ranges from 1-10cm).
  - Rocks with medium mass strength (rocks that has intact strength value ranges from 13-50Mpa and joint spacing ranges from 1-20cm).
  - Rocks with high mass strength (rocks that has intact strength value ranges from 50-100Mpa and greater than 100Mpa and joint spacing ranges of 10-60cm).
- Multi-purpose engineering geological map of the northern part of Mekelle town is prepared and it provides information on the engineering geological and geotechnical characteristics of soils and rocks, geomorphological, geodynamical and hydrogeological conditions of the study area.

12.2. Recommendation

Based on the geotechnical and engineering geological investigation of the study area, the following recommendations are made.

- The engineering behaviors of soils and rocks of the study area are identified and presented on the engineering geological map of study area. Areas dominated by soils with swelling and shrinking behaviors require careful consideration during design and construction of engineering structures in these areas.
- In the north central part of study area karstic limestone features were identified, and collapse/ or subsidence could be the main problem to be encountered. During site investigation for an engineering structure,

the lateral and vertical extent of the features (voids) should be investigated by using indirect geophysical techniques and direct subsurface investigations methods such as trenches, drilling, etc.

- Attention should be given to the way of handling geotechnical and engineering geological laboratory results collected and recorded in the data base format. This can be implemented by an authorized concerned body that could set guidelines for soils and rocks laboratory analysis system and record all the results done so far in and around Mekelle area. This could help the country's efforts in geotechnical and engineering geological activities in a better way.
- In order to provide easy, adequate and well organized geological, geotechnical and engineering geological information of a particular site (for planners, engineers, designers and others that require it), it is recommended to prepare a database for the engineering geological map of the Mekelle town, where the database should demonstrate the attribute and spatial values of lithological, structural, geomorphological condition, geodynamic processes, hydrogeological conditions, geotechnical and engineering geological characteristics and classification of the soils and rocks of the Mekelle area.
- If there are quantitative geotechnical and engineering geological property descriptive records, there is the possibility to prepare the 3-Dimentional engineering geological map of the Mekelle town. It is recommended to undertake further research in order to prepare the 3-Dimentional engineering geological map of the town. This could further benefit subsurface investigations for engineering structures built in the Mekelle town. It can provide data on the lateral and vertical lithological, geotechnical and engineering geological information which could be used for the design and construction of large-scale engineering works.

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