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Research Final Report

Integrated Geological, Engineering Geological and Geophysical Investigation of Adama and Its Surrounding Areas: Implication to Engineering Practice

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ABSTRACT

Adama was founded hundred years ago and is one of the major and densely populated towns in Ethiopia. It is located 100 km south–east of Addis Ababa and at the heart of both Ethiopia and the National Regional State of Oromiya as well. It is the hub of a vast region of immense economic potentials accessible by means of rail ways and expressways. Due to the mentioned reasons, the urbanization is rapid. However as in many towns of Ethiopia, very little is known about the soil and rock engineering properties and subsurface condition of the town. The physical and mechanical properties of earth materials have major influences on the success, economy, and safety of engineering structures. Moreover, the town is located in the southern extreme of the active volcano-tectonic segment of the northern Main Ethiopian Rift (MER). The present research work is, therefore, aimed at assessing and evaluating the geological, engineering geological and subsurface condition of the town.Detailed field investigation, in-situ geotechnical test and laboratory analysis were carried out to studygeological, engineering geological and geotechnical condition of the rocks and soils.During current research work, 30 soil samples were taken from 16 test pits, which were dug manually to 3 m depth.In addition, geophysical technique involving Vertical Electrical Sounding (VES) was also implemented and the data were processed, inverted and interpreted. The natural moisture content of the soil of the study area ranges from 6.34 - 25.2%, liquid limit 26.06 - 54%, plastic limit 7.5 - 40.83%, plasticity index 2.22 - 26.83%, free swell 0 - 40%, specific gravity 2.12 - 2.67, and pH 4.48 - 6.7.Low to medium plastic silty sand and sand are the dominant soil type in the study area.The rocks of the study area were classified into Low Strength, Medium Strength and High Strength rock massbased on the strength (Unconfined Compressive Strength) of intact rock and discontinuity characteristics. Using interpolation methods, spatial distribution maps of electrical resistivity were produced from which the overburden material distribution in the town is shown. The overburden thickness is relatively thin and very thick on horest and graben, respectively and the thickness increases to wards south and south western part of the town. Gully erosion, ground fissure, seismic activity and flooding are the main geo-hazard that need attention.

Keywords: *Adama, geological, engineering geological, geophysical, engineering practice*

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1. INTRODUCTION

1.1. Research Background and Justification

As the economy and population number of a country grows, the demand of constructing buildings for residential, commercial, industrial, and other purposes, road networks, etc. also increases. Ethiopia is one of the developing countries in Africa and currently different projects like, Industry Park, wind farm, railways which connect the country with neighboring countries are under construction. For such engineering structures, site investigation is a prerequisite for the successful and economic design (Bell, 2007) and also necessary to obtain sufficient information for feasibility and economic studies (Bowles, 1996). Insufficient ground exploration may lead to inappropriate design and failure of structures. Therefore, to obtain information on the type, characteristics and distribution of rocks and soils and geodynamic conditions, engineering geological and geotechnical investigation should be done on the rocks and soils underlying any construction sites.

Like other civil engineering structures, engineering geological investigation is very important for the big towns. In other word, deep knowledge of the geomorphological, geological and geotechnical condition of an urban area is necessary to provide basic information of the ground condition to local authorities, engineers and contractors (Bowles 1996).Engineering geological research and mapping is directed towards understanding/determining the interrelationship between geological environment and the engineering situation, nature and relationships of the individual geological components and active geodynamic processes likely to result from the changes being made as result of construction (UNESCO, 1976). However, most of the towns of Ethiopia have founded without the basic understanding of the geological environment, engineering geological and geotechnical consideration. Investigations were done in few regional towns of the country like Addis Ababa, Mekelle, Bahir Dar, etc.

Adama was founded hundred years ago and is one of the major and densely populated towns in the region and in Ethiopia as well. It is located about 100 km south–east of Addis Ababa and at the heart of both Ethiopia and the National Regional State of Oromia as well. The town is the hub of a vast region of immense economic potentials accessible by means of railway and expressway. Due to these facts, the urbanization is rapid to the different directions of the town and investors are attracted to construct in the town and the nearby areas. Currently, many civil engineering structures such as roads, bridges, Industry Park and multistory buildings including international hotels and commercial centers are under construction in the town. In spite of these, the town has been vulnerable to geological hazards like erosion and associated landslides, ground fissure and flooding during rainy season. These hazards cause damage of dwelling houses, roads, bridges, farm land and other infrastructures like power and communication lines due to unplanned expansion of the town. In addition, the town is situated in a seismically active area, Main Ethiopian Rift (MER), where there is active internal tectonic movement as evidenced by recent ground crack in the southern part of the town.

Despite the rapid urbanization and construction activity in Adama town, no work was done in engineering-geology aspects.Regional geology of the area, the Rift in general, is covered at a very small scale (Wolde Gabriel et al., 1990; Morton et al., 1979, etc.)which provide limited information for engineering applications. Asfaw Erbelo and Hassen Shube (2019) mapped the faults around Adama and assessed their activity and potential to trigger earthquake. Dejene Tesema et al. (2017) investigated the flood hazard risk in Adama twony using Analytical Hierarchical Process (AHP)and multicriteria approach. According to their finding, 10.4% of total area of the town, which composed of different urban land uses, lies within high flood hazard zone.The only research to be mentioned in geotechnical aspect is the work of Dagnachew (2011), in which he has studied some of the engineering properties of soils of the town. However, the work missed some important details viz. geomorphological, structural, geo-hazard and geological information. More importantly, the engineering properties of rocks is not investigated and the engineering geological map of the townhas not produced as well. An engineering geological map is the best way to depict the natural environment for engineering purpose (IAEG, 1981; Bell, 1983). Medium to large scale geological and engineering geological maps and data are widely used for urban land use planning, engineering site selection and other related works. The present work is therefore intended to fill these gaps by integrating geological, geotechnical and geophysical techniques.

1.2. Objectives

1.2.1. General objective

The main objective of the research was to characterize engineering geological and geotechnical properties of rocks and soils of the town, subsurface conditions and provide important engineering geological data that may help land use planning of the town

1.2.2. Specific objectives

The specific objectives of the present research were:

- To map the lithological and geological structures of the study area at large scale
- To characterize engineering properties of soils and rocks prominent in the town
- To conduct engineering geological classification of soil and rocksaccording to the standard classification systems
- To produce large scale multipurpose engineering geological map of the town
- To determine the spatial variation of subsurface lithology and depth to bed rock

1.3. Significance of the Research

Unplanned expansion of towns can exposed people and economic assets to the risk of natural disaster. This study significantly contributes to the understanding of the engineering behavior of soils and rocks and geodynamic condition in the town of Adama. The data, particularly the engineering geological map of the town, would guide the urban/ town planners and designers for properland use planning of the town and designing of structures. Public building officials can consider the data prior to issuing a building permit (i.e. the type of foundation and building need to be constructed), particularly if there is a chance that the project will endanger the public safety andthe area is vulnerable to natural hazards.

2. DESCRIPTION OF THE STUDY AREA

2.1. Location

The study area, Adama town, is located in the Main Ethiopian Rift, East Showa Zone of Oromia National Regional State (Figure 1). Geographically, the town is located between 52500 to 534000mE Longitude and 937000 to 950000mN Latitude. The town is 100 kilometers far from Addis Ababa along the road that connects Addis Ababa with eastern towns of the country and Djibouti port. It is established one hundred years ago and one of the biggest and most populated town in the region.

2.2. Climate

Climate is a weather condition of a given area which characterized by a long term period. It affects both the distribution of temperature and rainfall and is triggering factor which facilitates chemical and physical weathering of rocks.According to the climatic zones of Ethiopia,the study area with an altitude ranging from 1500-2000 meters above mean sea level is classified as Weina-dega or sub-tropical climate.

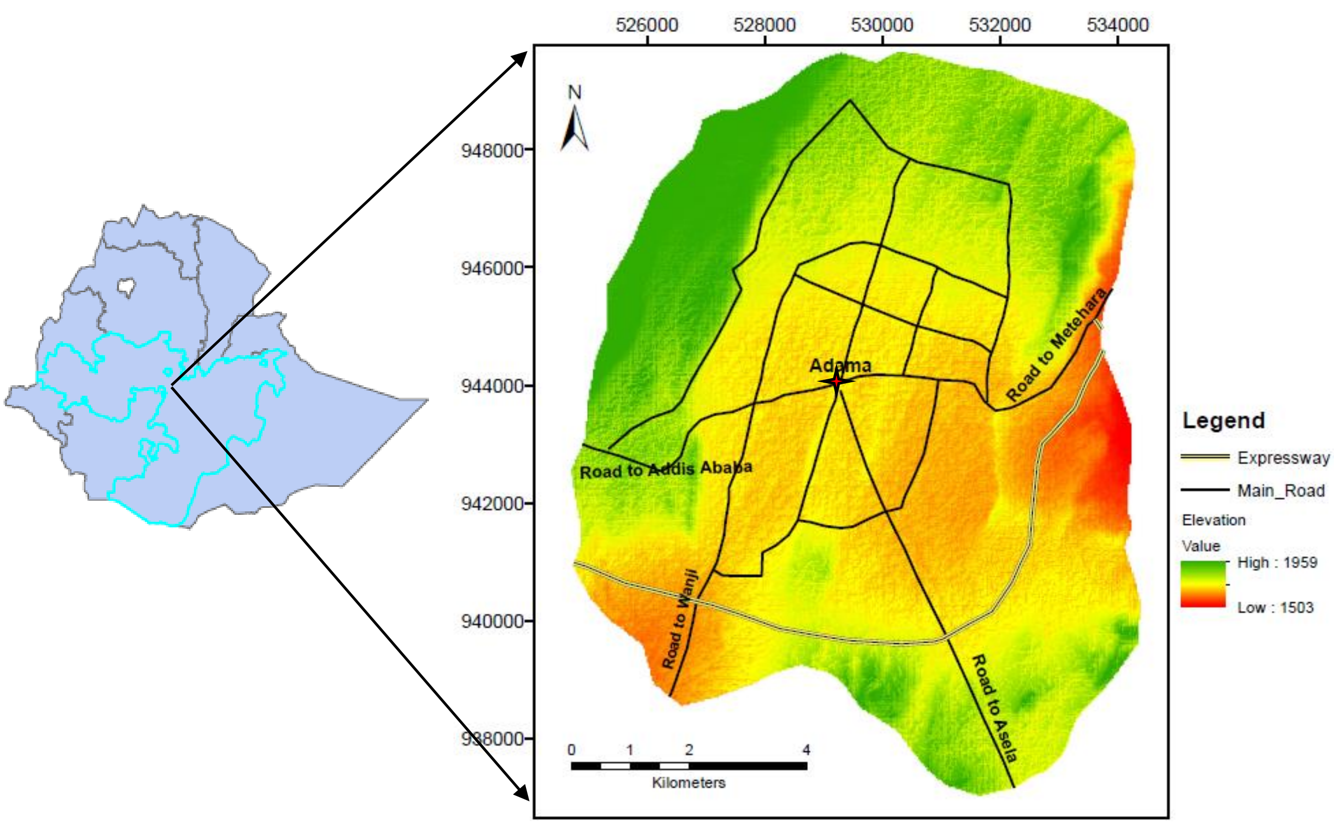

***Figure 1**: Location map of the study area*

2.2.1. Rain fall

The study area is located in the Main Ethiopian Rift that receives maximum rainfall during summer season (July and August). The area is characterized by high seasonal concentration of rainfall amounts. The analysis of long-term(i.e. 31 years) from 1984-2015 rainfall data obtained from National Meteorological Agency (NMA) of Ethiopia located at Adama branch indicates that the mean annual rainfall of the study area is about 885.7mm. Figure 2.2 below shows average monthly rainfall of the years from 1984-2015.

2.2.2. Temperature

The data from National Meteorological Agency of Adama branch indicates that the long-term (1984-2017) mean minimum monthly temperature is computed to be about 12°c, while the mean monthly maximum temperature is about 30°c. The warmest period in a year is from the months of March to June, while the lowest annual temperature occurs between the months of October and December (Figure 2.3).

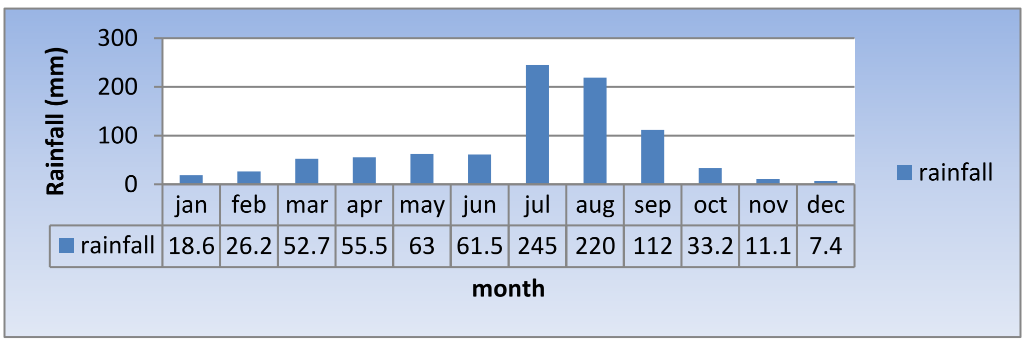

Figure 2: *Average monthly rain fall (1984-2017) ((Source: National Meteorological Agency of Ethiopia, Adama Branch office Directorate))*

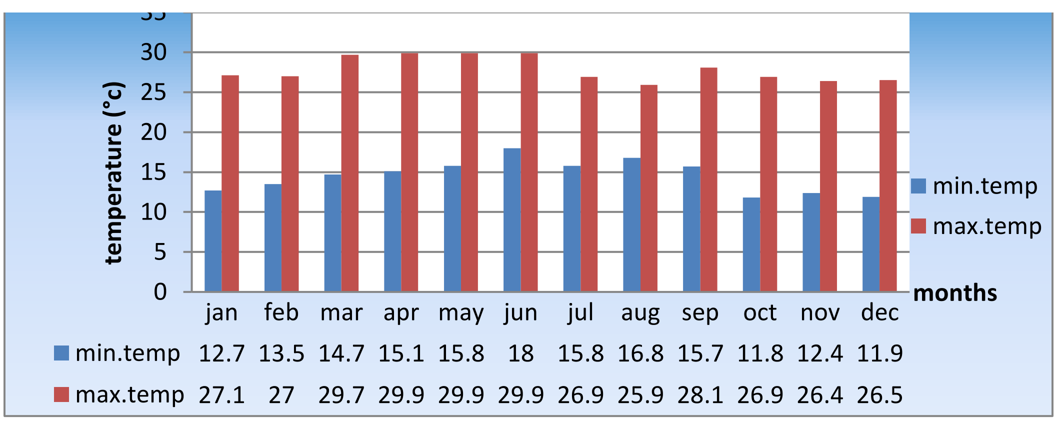

Figure 3: *Monthly average minimum and maximum temperature (1984-2017) (Source: National Meteorological Agency of Ethiopia, Adama Branch office Directorate)*

2.3.Topography and Drainage Pattern

The study area is situated in graben which is bounded by fault escarpments in western and eastern directions. The major part of the study area is gentle to flat lying land and altitude is between 1500m and 2000m above sea level (Figure 4).Geological structures and geomorphology of the study area dictated the system of streams. All the streams flow into the depression bounded by fault. There is no perennial river andthe peak discharge is attained during summer. During rainy season runoff from the escarpment, cones and ridges drain into the depression area filled by sediments and form deep gullies in different parts of the town. In general, the presence of numerous gullies and seasonal ponds in the center of the town has an effect on land use planning of the town.

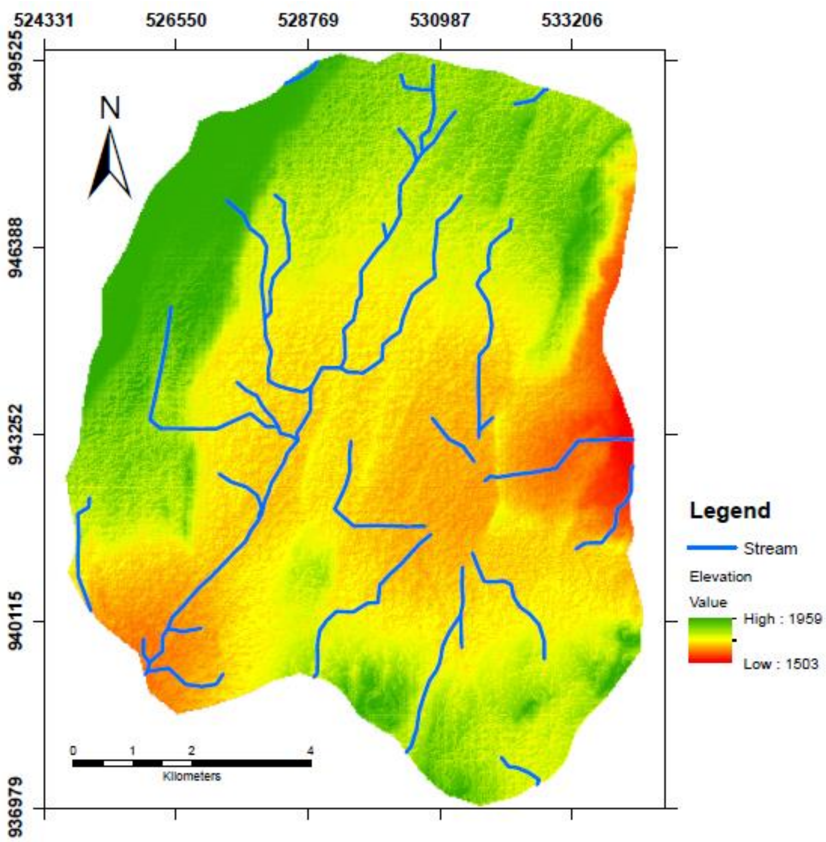

***Figure 4**: Drainage map of the study area*

3. LITERATURE REVIEW

3.1. Site Investigations

Site investigation is the process by which relevant information which might affect the construction or performance of a civil engineering or building project is acquired. This information shall include ground conditions, geology, geomorphology, seismicity, hydrology and other related information (BS 5930:1999). Geotechnical/engineering geological investigations for towns are also conducted to know the characteristics of the foundation materials on which the engineering structures of the town like buildings, roads, etc. are constructed. Geotechnical investigation includes surface and subsurface investigation and preliminary and design (detail) investigation. The investigation shall be proceed in stage from simple to complex and cheap to expensive (ES EN 1997-2:2015).Preliminary investigation enables to assess the general suitability of the site and environment for proposed work and the level of risks, while detail investigation provides data necessary for the design of structure.

Design of foundations, method of construction and solving geological problems begins with the determination of the rock and soil properties (Das, 2006). In Ethiopia, engineering geological investigation for towns is not well known and most towns of the country founded without knowing the engineering geology of the area. Currently, the country is developing at high rate and many civil engineering structures especially multi-story buildings are under construction in different towns of the country. At present, the flow of foreign investors and local community to different towns of the country is increasing. So, engineering geological investigation, medium to large scale geological and engineering geological maps are very important for towns.

3.2. Description and Formation of Soil

The term soil has different meanings under different profession. In soil engineering, soil is defined as an unconsolidated material composed of solid particle produced by disintegration of rock that can be separated by gentle mechanical means such as agitation in water (Arora, 2003; Das, 2006). It forms by mechanical/chemical weathering of rocksinfluenced by external factors such as climate, topography, and living organisms operating simultaneously over time (Arora, 2003).

In the weathering process, the parent rock and rock minerals break down, releasing internal energy and forming soils of lower internal energy that are stable. The three major weathering processes are physical, chemical and biological processes (Arora, 2003). Physical weathering causes disintegration of the rocks into smaller particle sizes by agents including freezing and thawing, temperature changes, erosion, and activity of plants and animals including man, whereas chemical weathering decomposes the minerals in the rock by agents of oxidation, reduction, carbonation and other chemical processes. Physical processes increase surface area and fractures so that chemical attack takes place where as biological phenomena include both of them. The physical properties of soil materials depend up on the minerals that constitute the soil particles and, hence, the properties of the rock materials which they are derived from (Das, 2006)

3.2.1. Types of Soil

According to their mode of origin, soils can be divided into residual soils and transported soils (Murthy, 1990).Soil is said to be residual soil, if the present location of the soil is that in which the original weathering of the parent rock occurred, otherwise, the soil is referred to as transported. An important characteristic of residual soil is the gradation of particle size. Fine grained soil is found at the surface, and the grain size increases with depth. At greater depths, angular rock fragments may also be found (Arora, 2003).The transporting agencies of transported soils are water, wind, glaciers and gravity. These soils are in turn classified into alluvial, colluvial, lacustrine, Aeolian and glacial. The engineering properties of transported soils are entirely different from the properties of the rock at the place of deposition (Singh and Chowdhary, 1994).

According to predominant grain size, soils are classified as fine grain (silt and clay) and coarse grain (cobbles, gravel and sans) soil. Grains having diameters greater than 76.2mm are called cobbles, grains having diameters in the range of 4.75mm to 76.2mm are called gravel. If the grains are visible to the naked eye, but are less than about 4.75mm in size the soil is described as sand. The lower limit of visibility of grains for the naked eyes is about 0.075mm. Soil grains ranging from 0.075mm to 0.002mm are termed as silt and those that are finer than 0.002mm as clay. This classification is purely based on size which does not indicate the properties of fine grained materials (Murthy, 1990). A classification between silt and clay can be based on the presence or lack of plasticity, dilatancy, and dry strength (Das, 2006).

3.2.2. Engineering Characterization of Soil

Soils are characterized by their index and engineering (design) properties. The main engineering properties of soils are permeability, shear strength and compressibility. However, the tests required to determine the engineering properties are expensive and time consuming (Arora, 2003). Hence, it is common to approximately assess the engineering properties of soil from index properties after conducting classification. Index properties are the properties of soil which serve mainly for identification and classification of soil. They are water content, grain size analysis, Atterberg limits, free swell and specific gravity.

3.2.2.1. Water/Moisture Content

The water content of a soil mass is defined as the ratio of the mass of water in the voids to the mass of solids. The water content, which is usually expressed as a percentage, can range from zero (dry soil) to several hundred percent (Murthy, 1990). The value depends on the mineralogical composition, grain size and the season of sampling. Moisture content can affect the engineering properties of the soils such as compressibility, shear strength and compaction properties. It also affects the shrink/swelling potential of expansive soils.

3.2.2.2. Specific Gravity

The specific gravity of a given material is defined as the ratio of the weight of a given volume of the material to the weight of an equal volume of distilled water. The specific gravity of soil solids is an important parameter for calculation of the weight-volume relationship (Das, 2006).It is also useful in computing the unit weight of the soil under different conditions, identification of minerals and also in the determination of particle size by hydrometer analysis.

3.2.2.3. Grain Size Distribution/Particle size analysis

Particle size analysis is a method of separation of soils into different fractions based on the particle size (Arora, 2003). Two methods generally are used to find the particle-size distribution of soil: (1) sieve analysis-for particle sizes larger than 0.075mm in diameter (coarse-grained soils), and (2) hydrometer analysis-for particle sizes smaller than 0.075 mm in diameter (fine-grained soils). The grain size result obtained from sieve and hydrometer analyses is generally presented graphically on grain size distribution curve.

3.2.2.4.Atterberg Limits/Consistency limits

Atterberg limits are defined as the water content at which the soil changes from one state to the other states. They are used to indicate the degree of firmness of a soil and are very important index properties for fine grained soils (Arora, 2003).Consistency of a soil is indicated by such terms as soft, firm and hard. As the water content of a fine-grained soil is increased gradually, it goes through different consistencies, namely solid, semi-solid, plastic and liquid states.Tests of Atterberg limits are used to check visual descriptions of soil. They are performed on fine grained soils (clays, silts) to determine the amount of water necessary to achieve a range of behavioral states and generally, used for classification of fine grained soils (Das, 2003; Murthy, 1990).The atterberg limits include: liquid limit (LL), plastic limit (PL) and shrinkage limit (SL). The plasticity index (PI) which is difference between the liquid limit and plastic limit and represents the range of moisture within which the soil is plastic. It is important in classifying the fine-grained soils. Generally, the greater the plasticity index meaning that the soil is more plastic, compressible and the greater volume change characteristic.

3.2.2.5. Free Swell

The free swell of soil is defined as the ratio of the increase in volume of the soil from a loose dry powder form to the equilibrium sediment when it is poured into water, expressed as the percentage of the original volume (Chen, 1975). Free swell test is obtained by placing a known volume of dry soil passing through 425 µm sieve in water and recording the swelled volume after the material settles, without any surcharge, to the bottom of a graduated cylinder. The difference between the final and initial volume, expressed as a percentage of initial volume, is the free swell value (Chen, 1975).The degree of swelling are known to be dependent on the type of clay minerals present in the soil. Among clay minerals montimorillonite influence the magnitude of swelling maximally as compared to illites and kaolinites (Das, 2006).

3.2.3. Engineering Classification of Soil

In order to make communication between different professionals involved in certain projects and for the sake of the identification of certain soil properties and behavior, it is important to groupsoils in to different classes based on simple laboratory test results.Although many different classification systems are used in different disciplines, their application for engineering purposes are limited, since they are purely based on particle-size. For engineering purpose, the classifications commonlyinvolve a combination of particle size and Atterberg limits (Murthy, 1990; Arora, 2003; Das, 2006). Two classification systems are widely used in our country for engineering applications. These are the: American Association of State Highway and Transportation Officials (AASHTO) classification system and Unified Soil Classification system (USCS). Both systems take into consideration the particle size distribution and Atterberg limits.

Unified Soil Classification System (USCS) system is more preferred to be used by geotechnical engineer (Das, 2006) as it is general and can be used for different engineering application. The system classified coarse-grained soils that are gravelly and sandy in nature with less than 50% passing through the No.200 sieve. The group symbols are GW, GP, GM, GC, SW, SP, SM and SC. The symbols that started with a prefix G stands for gravel or gravelly soil and symbol that started with S are sand or sandy soil. The other symbols used are W for well graded soil and P for poorly graded soil. Fine-grained soils are 50% or more passing through the No.200 sieve with symbols of M, which represent inorganic silt, C for inorganic clay, or O for organic silts and clay (Das, 2006).

According to American Association of State Highway and Transportation Officials (AASHTO) classification system, soil is classified into seven major groups: A-1 through A-7. Soils classified under groups A-1, A-2, and A-3 are granular materials of which 35% or less of the particles pass through the No. 200 (0.075mm) sieve. Soils with more than 35% pass through the No. 200 (0.075mm) sieve are classified under groups A-4, A-5, A-6 and A-7. These soils are mostly silt and clay-type materials.The classification system is widely used by highway and transportation engineers for selection of sub grade materials (Das, 2006). Soils with low group number is more suitable for subgrade material than those with higher group number.

3.3. Engineering Characterization and Classification of Rocks

Rock is a natural aggregate of minerals that cannot be readily broken by hand and will no disintegrate on its first drying and wetting cycle. Based on mode of origin rocks are classified into three major groups: a) Igneous rock, b) Sedimentary rock and c) metamorphic rock. Although this classification is only based on mode of origin, genetic class representsdifferent engineering propertiesbecause of their mode of origin, mineralogical composition, textural structure and presence of primary structures in the rock(Bell, 2007). For engineering uses, rocks are broadly grouped into two more generic subdivision: intact rock (rock material) and rock mass. The former include block of rocks that do not contain mechanical discontinuities and do have tensile strength. It is described by color, grain size, compressive strength and rock type (Bell, 2007). Rock mass is a mass of rock interrupted by discontinuity, with each constituent discrete block having intact rock properties. In the evaluation of the engineering properties of a rock mass, the intact rock properties, the occurrence and nature of discontinuities and the degree and extent of chemical weathering need to be considered.

Various rock mass classification methods are available. The commonly adopted methods are:-Terzaghi (1946), Deere and Miller (1966), Bieniawski (1989), Barton et al (1976) and ISRM (1981). From these methods, the classification system proposed by International Society for Rock Mechanics (ISRM, 1981)is used in this work. This classification system is based on:rock generic name, discontinuity spacing, and Uniaxial Compressive Strength (UCS) of intact rock.

3.4. Concept of Engineering Geological Mapping

Engineering geological mapping began to be developed with the first steps towards co-operation between geologists and engineers (Bell, 2007) in the building of the larger engineering works such as tunnels, dams and railways. The engineering geological maps intended to show some properties important to civil engineers and land use planners. It shows the distribution of rocks and soils including their physical and mechanical state, geomorphological, geodynamic phenomena, etc. that affect engineering use of different areas.

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 (UNESCO Press, 1976).Themap units are most distinctively engineering character and behavior that expected to have uniform engineering design characteristics.In engineering geological mapping context, the term soil is generally used for all material which can be excavated without the use of explosives or equipment for loosening or ripping.Many civil engineering structures are constructed on and/or within the top few meters of surficial deposits. According to UNESCO Press (1976), an area is mapped as a soil unit if the soil thickness exceeds 1 m. But, if the soil thickness is less than 1 m, the area is mapped as the underlying bedrock. The thickness of 1 m is chosen for two reasons. First, the surface morphology of the underlying bedrock is usually recognizable through the overlying soil "blanket" if its thickness is less than 1 m and not recognizable when the thickness exceeds 1 m. Second, the engineering geological importance of a soil cover with a thickness less than 1 m is limited. In the current work, the presentation of geological and engineering geological soil/rock units on both geological and engineering geological maps respectively are done according to the above mentioned way of mapping of soils and/ or underlying bedrocks.

3.5. Regional Geology and Tectonic setup

A large number of researches on the geology and volcano- tectonic development of the Main Ethiopian Rift (MER) in general, on the central sector in particular, have been conducted in the past. MER which is part of the East African Rift System (EARS) started to develop in Miocene time and comprises a series of rift zones extending over a distance of about 1000 kilometers from the Afar Triple Junction (Boccaletti et al., 1999). Geographically it is sub-divided in to three main sectors: northern, central and southern sectors (Wolde Gabriel et al, 1990) and bordered by Ethiopian plateau to the west and Somalia plateau to the east.

A north-south striking Miocene-Quaternary age rifting in NMER suggested to be a southward propagation of the Afar rift and it is characterized as volcano-tectonically active part of the East African Rift System. The NMER starts in the north from the southern termination of the Afar rift (Chernet et al., 1998; Corti, 2009) where as in the south it is structurally continuous down to the south of Adama (Agostini et al., 2011; Corti et al.,2009; Erbello et al., 2016). Keir et al.(2015) suggests the rift extends in the south further down to the north of Meki based on seismic feature and Moho crustal thickness characteristics. Considering volcanic intensity variation and tectonic activities, this part of the rift is classified as a progressed rifting towards rift maturation (Keir et al., 2015). The region contain several volcanic eruptive centers which resulted both mafic and silicic products (Abebe et al., 2007). Some of the main eruptive centers such as:Fentale, Gedemissa and Corbiti are located in this part of the rift and inferred to have been developed due to reactivation of pre-existing week zones (Acocella et al., 2002; Wilks et al., 2017).

Structurally, the rift comprises rift initiated, longer and high displacement marginal faults and relatively recent, and shorter axial faults called Wonji Fault Belt (Abebe et al., 2007). These main structural domains show variable geometrical features in the different parts of the rift and also within a particular sector of the rift (Agostini et al.,2011; Corti et al., 2009). These geometrical features of the faults developed a change in extensional stress directions(Bonini et al.,2005) or a steady state stress direction with the support of pre-existing pervasive basement fabric (Corti et al., 2009; Agostini et al.,2011; Erbello et al., 2016). Long term Nubia-Somalian plate motion geodetic and seismic study constrained an average extension between N 90° E and N 105° E (Keir at al.,2006). Locally minor deflected extension of N 112° E direction was also determined from fault plane measurement data around Adama area (Asfaw Erbello and Hassen Shube, 2019).

Geologically, the region is mainly covered by bimodal composition volcanic products. Volcanic centers arrangement in the NMER and specifically around Adama followed domains of structural features (Morton et al., 1979). The dominating volcanic stratigraphy outcropping in the Nazreth-Dera area subdivided into eight units(Boccaletti et al., 1999). Out of these main volcano-stratigraphic units, five units outcropped in and around the study area. These are Nazreth, Boku-Tede, Bofa, Dera-Sodere, and Woniji units from bottom to top, respectively (Figure5).

Nazreth Unit

The Nazreth unit comprises paleosoil interbeded ignimbrite sheet layers. These strongly welded ignimbrite containing unit becomes less welded at the top of the unit. The intensity of welding well manifested by stretched glass shards. Upward decrease in welding of the unit also revealed by less and shorter stretched glass shards. The unit well exposed in the western escarpment of the Adama fault(Erbello et al., 2018). The Pleistocene in age (1.7 Ma to 1.5 Ma) rhyolithic volcanic unit extends in the north and south (Boccaletti et al., 1999).

Boku-Tede Unit

Highly fractured lava domes with associated obsidian layer, pyroclastic fall deposits and surge deposits represent the Boku-Tede unit. This layer underlies the Bofa Unit. It exposed along the part remnant of the Boku caldera. Radiometric age of this unit range from 0.833Ma to 0.51 Ma (Morton et al., 1979).

Bofa Unit

Fissure eruptive volcanic product of the Bofa unit overlies the Boku-Tede unit and compositionally characterized as transitional basalt with subordinate alkaline basalt. The unit mainly pinch out in the in the southwest of the map area. Calculated radiometric age of the unit ranges from 0.61Ma to 0.4 Ma (Mortton et al., 1979).

Dera-Sodere Unit

Dera-Sodere unit is the most widely exposed ignimbrite volcano-stratigraphic unit. The unit distinguished from others by containing unwelded to poorly welded brown ash with scattered pumic lithic fragments. Mainly outcropped in the southwest of the Adama town. The exposure of this unit reveals a variable stratigraphic thickness in different outcropping sections.

Wonji Unit

These group is the younger and confined to Wonji fault belt (WFB).Systematically distributed spatter cones and cinder cones associated with alkali basaltic lava flows represent the Woniji units. Even though the unit also exposed in the southwest of Adama town but dominantly outcropped in the east along the Adama-Asela main road. Compositionally, the unit contains highly oxidized basaltic products of morphologically cone shaped (Asfaw Erbelo and Hassen Shube, 2019).

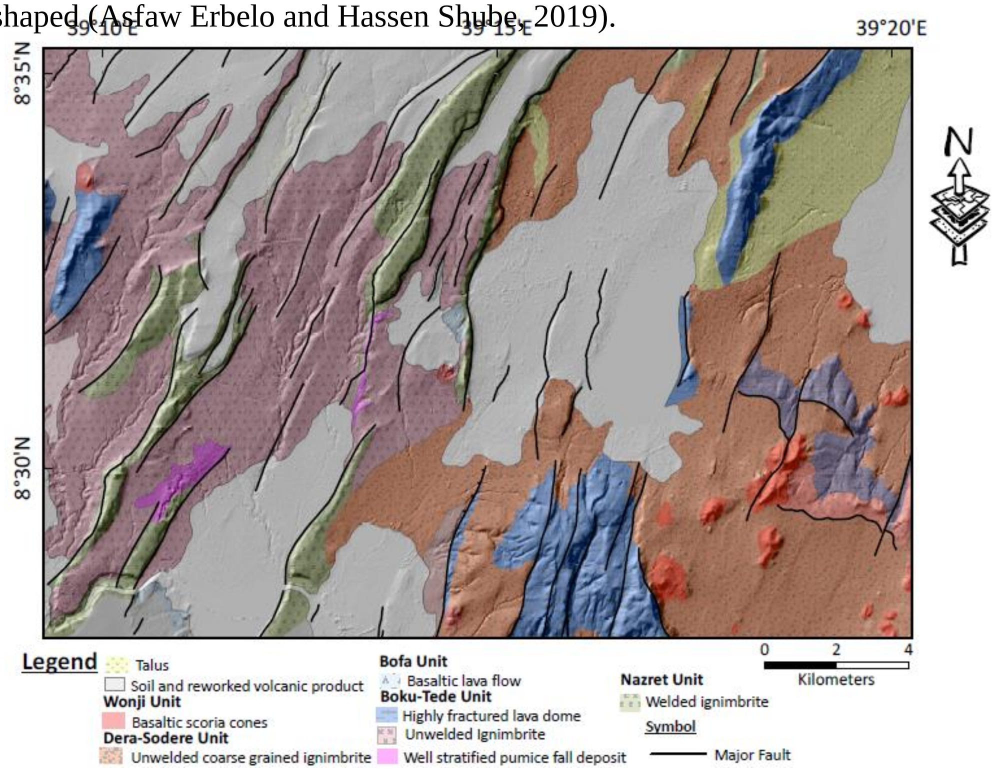

Figure 5 *: Regional geological map of the study area (modified from Morton et al., 1979)*

4. METHODOLOGY

4.1. Introduction

In order to achieve the objectives of the research work successfully, the following methodology have been carried out by applying different systematic procedures and materials. This chapter concerned with the general procedure and methodology followed during desk study, detailed field survey, laboratory test, data processing and analyses. After systematic literature review was undertaken, secondary data was collected from different organization. During detailed field investigation, representative and fresh samples were collected from test pits in selected location based on reconnaissance survey, in-situ geotechnical tests and geophysical survey were carried out.In laboratory work, the index property testes were done on the soil samples. To do in-situ and laboratory tests on soil and rock,different test standard such as American Association of State Highway and TransportationOfficials (AASHTO), International Society for Rock Mechanics (ISRM) and American Societyfor Testing and Materials (ASTM) was followed. The step followed to perform each of themethod was broadly described as follows.

4.2. Desk study and reconnaissance survey

Exhaustive and thorough systematic literature review with regard to site investigation, description and classification of soil and rock for engineering purposes, procedures for engineering geological mapping, similar and related works in the world, Ethiopia and particularly in the study area was done. Similarly, a review on unpublished and published geological map and geodynamic processes was done. Later conceptual frame work and general methodology was developed from the knowledge acquired through literature review. In order to acquire the general conditions of the study area such as topography, soil distribution, land slide manifestations, information was gathered and field reconnaissance survey was undertaken. The first reconnaissance field survey was held from May08/2017 to July 5/2017 and during this field survey, some preliminary geological mapping, geomorphological and land form assessment and soil distribution identified were done.

4.3. Detailed Field Survey and Data Collection

In this stage, detailed field description of rock and soils, in-situ geotechnical tests, soil sampling and geophysical survey carried out which are described in the following paragraphs.

Different traverses were made along rock and soil exposures in different parts of the study area for identification and mapping of lithological units. Surface mapping of geological structures was undertaken by measuring orientations (dip and dip directions) of discontinuities using Brunton compass. Similarly, conditions of discontinuity such as joint roughness, aperture, infill and weathering conditions were visually estimated on the field. In selected rock outcrops, the unconfined compressive rock strength (UCS) was estimated by using a digital Schmidt hammer (N-type). A minimum of twelve Schmidt hammer rebound value was applied perpendicularly on fresh exposed rock surface and joint wall at each rock outcrops (Figure6). The test was conducted according to the standard suggested by Barton and Choubey (1977) and ISRM (1978)as follow: Schmidt hammer rebound value on fresh and un-weathered rock surface was recorded, the rebound value ordered in ascending order and then discard the first four lower values and take the average of higher value.

Figure 6: *Field description of rock outcrop, discontinuity orientation measurement (Left) and strength measurement using digital Schmidt hammer (Right)*

For collection of soil samples, 16 test pits (Figure 8) were excavated up to three meter depth (Figure7) in different parts of the town and visual description and soil sampling were carried out at two different depths (1.5 m and 3 m). Due to the nature of the soil, only disturbed soil samples (30 samples) were taken for laboratory tests. The soil samples were kept in plastic immediately after sampling to keep their natural moisture content and then brought to laboratory.

***Figure 7**: Taking soil sample by digging test pit*

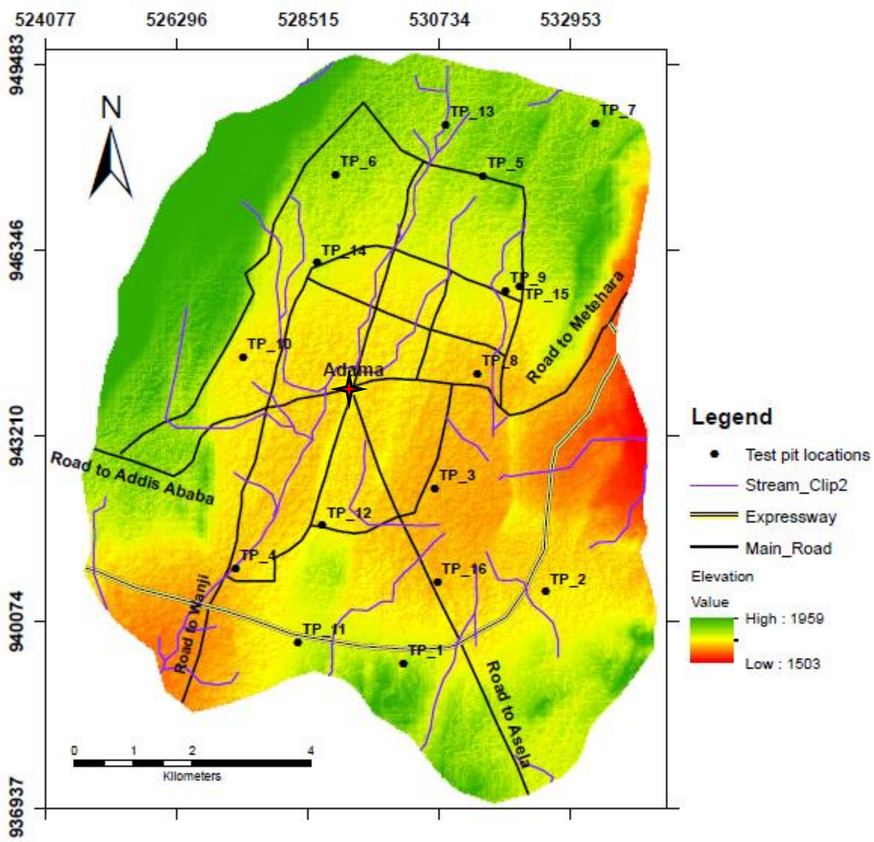

***Figure 8**: Test pit locations*

Dynamic Cone Penetration (DCP) test was performed in side test pits at a depth of 1.5 m using light weight TRL (Transport Research Laboratory, UK) DCP apparatus (8kg hammer weight, 575mm drop height, 60°apex cone) to estimate in-situ soil density. A total number of 14 DPC tests were performed in test pits in different parts of the town. During the measurement, the DCP set up (Figure9) was held vertically at desired test location and the hammer was lifted and dropped from specified height to initiate the test. Following each blows of hammer, the depth of penetration was measured and recorded as D-value(mm/blow).

Figure 9: *DCPT testing at 1.5 m depth in the north-eastern part of the town*

Geophysical technique involving Vertical Electrical Sounding (VES) was also implemented to obtain indirect information about the subsurface condition.Accordingly, the Vertical Electrical Sounding (VES) survey was conducted using the Schlumberger array with a maximum electrode separation AB/2 of 150m using Syscal Resistivity Meter.It is automatic instrument which directly gives resistivity of subsurface from input current and voltage. Schlumberger electrode array is shown in Figure 4.8in which an electrical current (I) is injected into the ground through two current electrodeswhile the resulting potential difference is measured by another pair of potentialelectrodes.The soundings are conducted at63 VES locations in different parts of the town, a parts of which are aligned on the relatively the same lineto produce three nearly east – west oriented resistivity sections. The rest VES locations (Figure 10) are distributed in different parts of the area to produce the iso-resistivity maps at different depths.

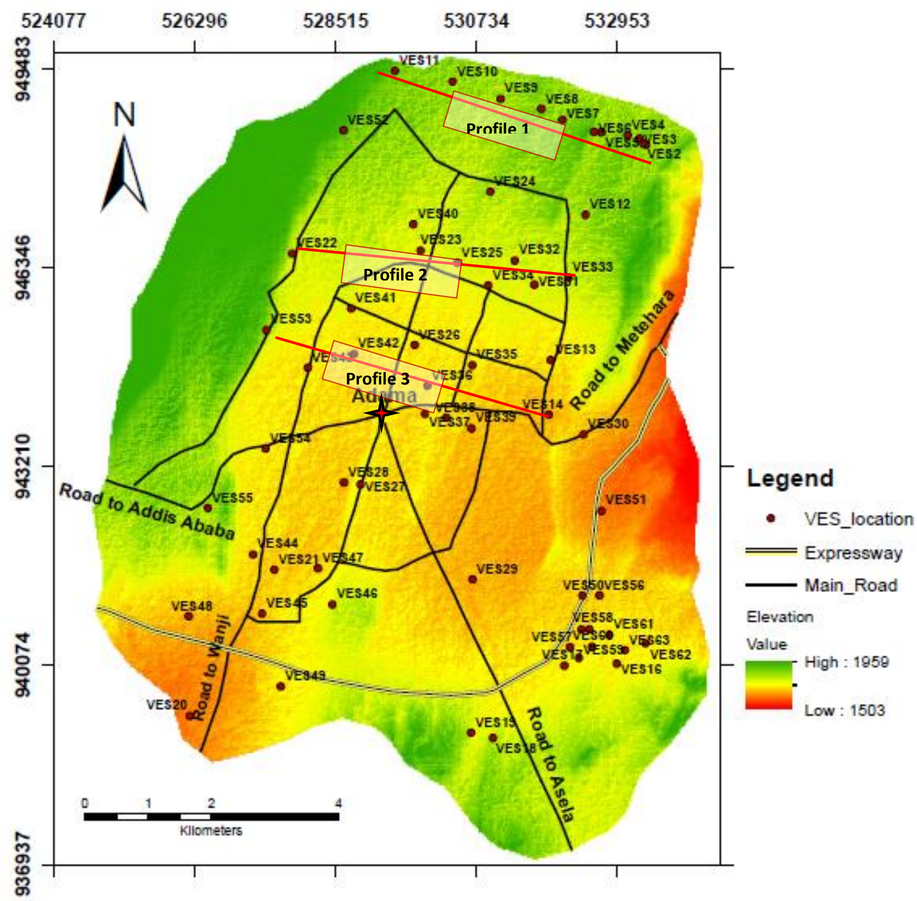

Figure 10: *VES locations and east-west oriented profile sections*

4.4. Laboratory test and data analysis

Laboratory test was conducted to determine index properties of soil such as Atterberg limit (liquid limit, plastic limit and plasticity index) and soil gradation and other parameters of soils (moisture content, specific gravity, free swelling, pH). The tests were conducted on disturbed samplesbecause the silty sandor sandy nature of the soil makes recovering of undisturbed sample difficult. Laboratory tests were done according to ASTM and AASHTO standards as summarized in Table 1 in ASTU geotechnical laboratory.

Table 1: Laboratory tests and standards

Laboratory testtype	Number of samples	Standard
Moisture content	30	ASTM D-2216
Sieve analysis	30	ASTM D-421
Liquid limit (LL)	30	ASTM D 4318
Plastic limit (PL)	30	ASTM D 4318
Free swell	30	ASTM D-4546
Specific gravity(SG)	30	ASTM D-854
pH	16	ASTM D-4972
Shear strength	14	ASTM D 3080

The natural moisture content of the soil was determined using oven drying method. Samples were taken to the laboratory by sealing with plastic paper to minimize moisture loss. The weight of the moisture can and the weight of can with moist soil was measured. Then the sample put it in to drying oven at a temperature of 105°c for 24 hours. Then after, the natural moisture content (i.e. the ratio of mass of water to dry soil mass) was determined.

Casagrande method was used for determination of liquid limit according to ASTM D 4318 - Standard Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soil. Taking 200gm of air dried soil passing 0.425mm sieve, considerable amount of water was added to moist the soil grains and placed for hours. Water contents were determined by separating the blows number in to four parts from 15 to 35. The soil mix at each blow number were taken and oven dried for 24 hours from which water contents were calculated. The plot (flow chart) was drawn as the moisture content as ordinate (natural scale) and number of blows as abscissa (log scale). From the plot, the liquid limit was determined by locating the water content at 25 blows.For determination of plastic limit, from the 200gm mixed soil two ball like are rolled in 3mm tread on glass plate. The thread is rolled until the soil crumbled when it reached 3mm diameter. At this stage the soil is taken and oven dried for 24 hours and water content is measured. Then the average value of the water contents from two trails taken as plastic limit.

The specific gravity is determined as per ASTM D-854 standard. About 25gm of oven dried soil specimenpassing 0.425mm (No. 10) sieve is poured into the pycnometer using funnel. Then water is added until the water level is ½ of the depth of the main body of the pycnometer. It is well mixed until slurry is formed. Using vacuum entrapped air is removed. Water is added to the air free slurry up to the mark of the pycnometer. Then the slurry with the pycnometer is weighted. The slurry is then removed and pycnometer is cleaned and dried andthen filled with clean water up to the mark of the pycnometer and weighted.

Grain size analysis provides the grain size distribution of soil mass, and it is required in classifying the soil. The distribution of particle sizes larger than 75 µm (retained on the No. 200 sieve) is determined by sieving, while the distribution of particle sizes smaller than 75 µm is determined by a sedimentation process, using a hydrometer test.A representative 500 gram air dried soil was sieved through set of sieve and the weight retained on each sieve record. Since % finer (smaller than 75 µm)for all soil samples are less than 25%, hydrometer analysis was not conducted in this study.

To determine the free swell test as per ASTM D-4546, a 10cm^3(V_i) dry soil passing thorough a No.40 (425micron) sieve is poured into a 100cm^3 graduated cylinders filled with water. The volume of settled soil is measured after 24 hours which gives the value of V_f; The ratio of the increase in volume to its initial((V_f-V_i)/V_i)expressed in %, is taken as the free swell

Direct shear test of soil under study area is performed according to ASTM D 3080. The tests were conducted on remolded soil samples at optimum moisture content (OMC). The optimum moisture content of the soils are determined from standard proctor compaction test in which a soil at a selected water content was placed in three layers into a mold of given dimensions, with each layer compacted by 25 blows. The procedure was repeated for sufficient number of water contents to establish a relationship between the dry unit weight and the water content (compaction curve) form which OMC determined.

The resistivity data were analyzed using computer software program specifically known as IPI2win resist software.During data processing, iterations (the model layer resistivity and thickness of the subsurface electrical layers beneath the sounding point) continued until best fitting was attained between the practical and theoretical curves, and in this case until RMS (Root Mean Square) error of less than 5% was achieved. Then the values were used to construct the geo-electric sections and based on which data interpretations were made. Generally, good correlation between the field data and the interpreted model sections are obtained (Figure 11). Several reinterpretations for modeled soundings curves were performed to get better model parameters and the iteration process was finalized when the root mean square (RMS) errors was less than 5%.

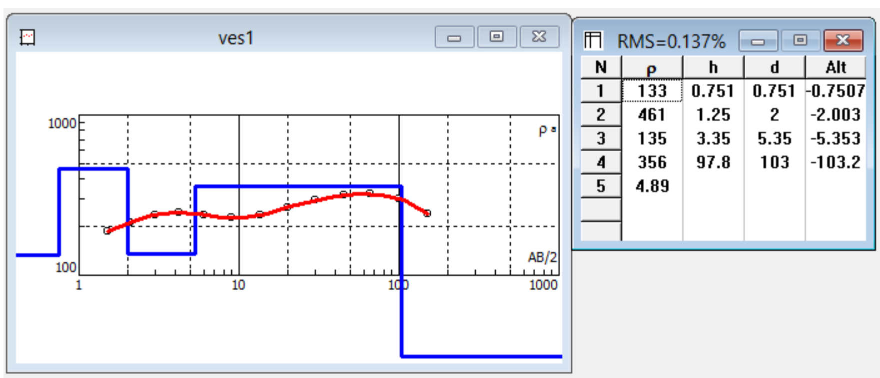

Figure11: *Typical sounding curve for VES 1*

5. RESULT AND DISCUSSIONS

5.1. Geomorphological Condition and Geo-hazard in the Study Area

5.1.1. Geomorphologic characteristics

Geomorphologic characteristics of a given town can control the expansion and land use planning of the town. Additionally, it can be the cause for the vulnerability of a given town to geo-hazards like flood, landslide, erosion that can damage the town infrastructures. According to Coats (1976), geomorphology is the science of the study of landforms and processes that create them and is useful in evaluating geologic hazards (such as landslide, flooding, etc.) and other environmental planning and management.

Adama town is located in the Main Ethiopian Rift (MER) where there is a series of parallel normal faults indicating the lengthening of the earth's crust. Different landforms of the study area are formed as a result of volcanism (cones and ridges), tectonic activity (faulting), erosion (gullies) and deposition. These different landforms of the study area were interpreted from Landsat image, hill shade image, topographic map and field surveys. The main goal of describing landscapes of the study area are to identify the area susceptible to flood, landslide, erosion and siltation that affect the town infrastructures and land use planning.

5.1.1.1. Landform and Relief

The study area is characterized by different type of landforms such as graben, horst, gullies, ridges, volcanic cones and escarpment (fault) (Figure 12). The relief of the study area is 250m, i.e. the difference between high elevation (1850m) and low elevation (1600m). The tope of horsts (high lands) are relatively flat and covered by rock fragments, thin overburden, and vegetation mainly grass and shrubs. The graben part is mainly plain and filled by thick overburden.

The slope, which refers to the angle of inclination of the ground surface, expressed in degrees or as a percentage (Huggett, 2007). The study area is characterized by flat to gently slope which ranges from 0° to 64° (Figure 13).

Figure 12: *Different landforms in the study area*

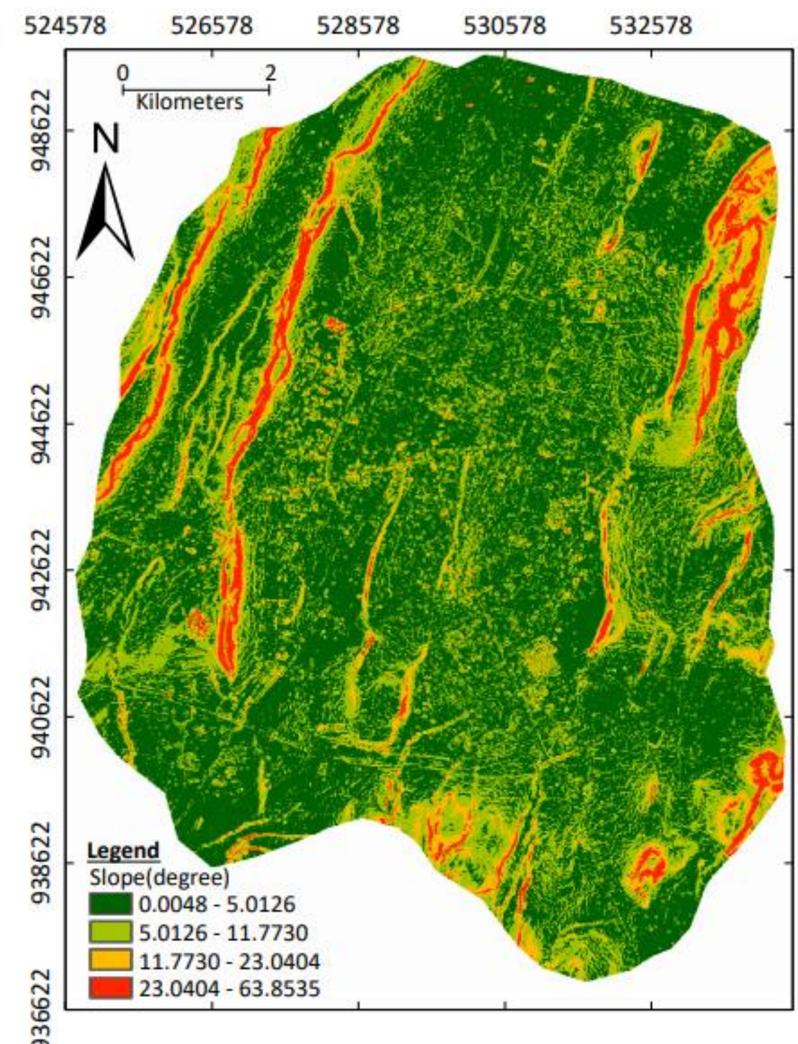

Figure 13: *Slope map of the study area*

5.1.1.2 Geomorphological processes

There are a number of geomorphic processes responsible for the formation of the various geomorphological units. These are weathering, erosion, landslide, volcanism and tectonic structures. Among these, erosion, volcanism and tectonic structures are the major and common geomorphologic processes identified in the study area.

5.1.1.2.1. Erosion

Erosion is the detachment and removal of soil and rock by the action of running water, wind, flowing ice, and mass movement and the relationships between the factors which influence erosion is extremely complex (Selby, 1993).It is the function of erosivity (what factor causes erosion) and material erodibility (the susceptibility of geological material to erosion).The hard material can resist erosion while the soft formation are vulnerable to erosion.The velocity of runoff and erosion power increases as the steepness of slope increasing. In general, the soil tolerance against erosion is dependent on several factors like slope steepness, soil erodability, slope length, cover and support practices.

Figure14: *Partial view of active gully erosional features in different part of the town*

The main causes of erosion in the study area are: the presence of steep slope (fault escarpment and volcanic ridges), seasonal intense rainfall and soft geologic materials (like volcanic ashes and alluvial soil deposit).The runoff from high land erode the soil from top of ridge and slope (sheet erosion) and spread the sediment on flat land. The other common types of erosion in the study areaisgully erosion. It formed deep gorges (gully) along drainage lineby eroding loos soil and ash deposits. It posed major problem on land use of the town bychanging the surficial features (Figure5.14).Construction of cheek dams and gabions can considerably reduce the erodabilty and further increase of width of gully.

5.1.2.2. Volcanism and Geological Structures

The common types of landforms formed by volcanismin the study area are volcanic ridge andsystematically distributed scoria cones and cliff (steep slope).The Main Ethiopia Rift (MER) which started to develop in Miocene time is part of the East African Rift System (EARS) and comprises a series of rift zones extending over a distance of about 1000 kilometers from the Afar Triple Junction (Boccaletti et al., 2000).As part of the MER, the topography of the study area is affected by the NNE-SSW running fault sets, which are responsible for the formation of the different landforms, especially for the NNE-SSW trending cliff (escarpment), horst and graben. The section is also characterized by complex extensional tectonics features manifested with associated quaternary volcanic outpourings.

5.1.3. Geo-hazards in the study area

Geological hazards can be responsible for devastating large areas of the land surface and so can pose serious constraints on development (Bell, 2007).However, geological processes such as volcanic eruptions, earthquakes, landslides and floods cause disasters only when they impinge upon people or their activities.Geologic hazards are there to stay and some of them cannot be avoided, but if we can identify where these hazards will probably occur then it will be very easy for the local government units to establish control or mitigating measures to lessen the effect of such hazards.Therefore, the establishment of land use zoning considering geo-hazards is very important to protect people and their properties. Earthquake, landslide and flooding are some of the geological hazards observed or expected in the study area.

5.1.3.1. Earthquake

An earthquake is the vibration of Earth produced by the rapid release of energy and it is the most devastating earth process.According to Bolt (1988), the important step in geological assessment of earthquake hazard of a site is the location and mapping of all geological structures and ascertainment of whether they are active or not.The study shall also include the assessment of soil condition and likelihood of landslides, subsidence, and liquefaction.Concerning the location, the study area is locatedin the southern extreme of the active volcano-tectonic segment of the northern MER. Some of the earthquakes that were recorded within the Ethiopian rift valley and caused serious damage on property and human life are:the Kara kore earthquake of 1961 that completely damaged the town of Majete and severely destroyed Kara kore town, the Serdo earthquake of 1969 with a magnitude of 6.3 that were killed people, Dobi graben earthquake of 1989 (Magnitude = 6.5) which destroyed several bridges on the highway connecting the port of Asseb to Addis Ababa and the Hawassa earthquake of 2016 with a magnitude of 4.3 that caused building crack and injuries.

The study area also dominated by NNE-SSW striking extensional related normal faulting. The geomorphological features of the fault scarpsreveals the normal faults in the study area are active (Asfaw Erbelo and Hassen Shube, 2019) requiring due attention when evaluating seismicity. Historical earthquake could reoccur with high ground acceleration in the area due to slip along one of the nearby faults.

Liquefaction is the loss of strength of saturated loos cohessionless soils due to pore water pressure build-up during earthquake shaking. Liquefaction commonly occur in loos coarse grained (cohessionless) soil and at depth shallower than 15 m (i.e. shallow ground water). Even though the soil of the study area is dominantly coarse grained soil (silty sand and sand), which is susceptible to liquefaction, liquefaction hazard in the study area is less probable as the groundwater table located at a great depth (> 150 m).

The weathered rock fragments accumulation along the slope of the fault planes especially in the east of the town can result landslide even by a smaller magnitude of earthquake occurrence.From the safety point of view, it is, therefore, recommended to avoid settlement and construction in such areas.

Ethiopian building code standard (EBCS, 1995) is seismic hazard mapproduced by the state building codes standard which recommends the engineering precaution to be taken in each rank of hazard in the maps.According to the map (Figure 15), the country is divided into zones of approximately equal seismic risks depending on the known distribution of the past damaging earthquake ranging from less damaging zones (zone 1 and 2) to zones of major damaging (zone 4). Adama is located in zone 4 of the seismic hazard map (Figure5.4).Adama is located in high risk zone where earthquake with Modified Mercali (MM) intensity of VI to IX is expected to occur in 100 years return period. The design ground acceleration chosenfor each seismic zone,which is important parameter for the design of engineering structures, are given in Table2.Hence, the ground acceleration value for the study area (zone 4) is considered to be 0.1g for 100 year return period.

Earthquake cannot be avoided and we cannot control it, however the effect can be mitigated. Designing earthquake resistant building to resist earthquake force is important in seismically active areas. The design of any engineering structure in the town shall, therefore, meet all necessary seismic resistant design parameters before its construction.

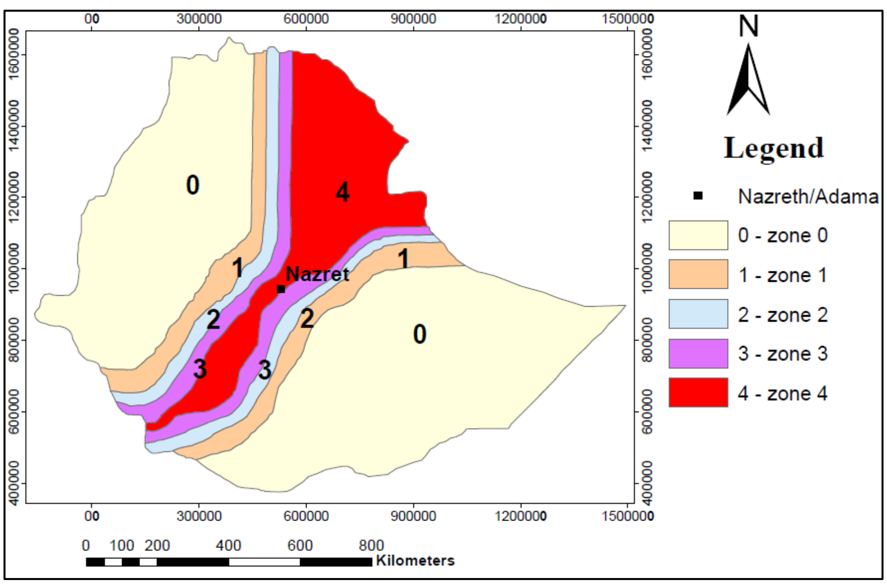

Figure 15: *Map that shows study area (Adama/Nazret) on seismic hazard zone map of Ethiopia (Source: Ethiopian Building Code Standard (1995))*

Table 2: Bed rock acceleration ratio: α0 = zone the bed rock acceleration ratio for the site and depends on the seismic zone

Zone	4	3	2	1
α_0	0.10	0.07	0.05	0.03

5.1.3.2. Landslide

5.1.3.2.1. General

Landslides represent the rapid downward and outward movement of slope-forming materials (Bell, 2007). The movement taking place by falling, sliding or flowing or by some combination of these factors. It can cause a great damage to farmlands, forest stands, communications and other civil engineering structures (roads, dams, buildings, etc.) resulting in serious economic problems and social damage.The process of sliding of earth material may be triggered by natural or by artificial processes. The natural processes include earthquake loading, toe erosion by stream and pore water developed in rock discontinuities. The artificial processes involve steep slope cutting for natural resource extraction or for road, slope surcharge due to civil engineering structure, blasting activity, etc. The aim of this topic is not to describe and classify the landslide in detail but it is to mention the type of landslide present in the study area and their effect on the town infrastructures like roads, dwelling houses, etc.In general, the most common triggering factor of landslide in the study area is human interference and erosion.

5.1.3.2.2. Types of Land slide in the study area

Slope movement can be classified based on mode and rate of movement, the shape of sliding plane, type of sliding material and other criteria (Bell, 2007). Basically landslides are associated to three main types of movements, material that fall, slides and flows. According to the types of movement of materials (rocks and soils) the following types of landslides were identified in the study area.

a) **Fall**: It is the movement of rocks or soil material from a steep slope without a continuous contact with failure plane. That mean the material travels mostly through the air by free fall. These falls are classified into rock fall and soil fall depending on the material.

Rock falls: It is an abrupt movement of rock blocks loosened by weathering and discontinuity (Bell, 1987) and are very rapid as a result of free fall. This type of landslide was observed on slightly to medium weathered and fractured ignimbrite, rhyolite and basalt forming steep to very steep slopes in different part of the study area (Figure16). Fallen blocks of these materials are found at the foot of steep slope/cliff. This type of landslide affected asphalt road and residential area.

Figure 16: *Rock fall in the eastern (left) and south western (right) part of the study area*

Soil falls. In the study area these types of landslides occur in limited area along streams/river channel/gullies. It is commonly observed in unconsolidated materials like volcanic ashes and alluvial deposits (Figure17). The causative factors is undercutting of the toe or face of a slope by a river during raining season. Construction of gabions can considerably reduce the further gully undercutting that cause landslide.

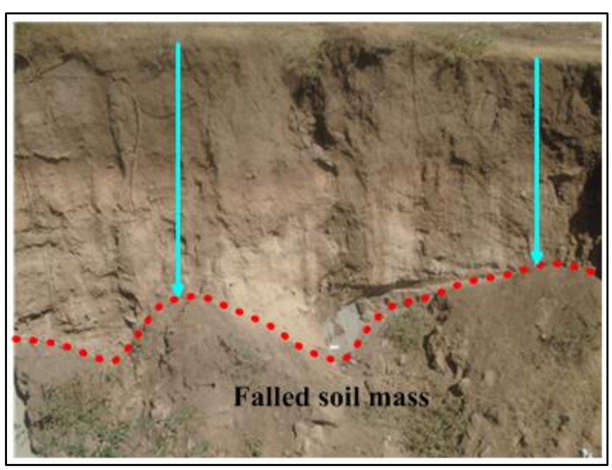

Figure 17: *Soil mass fall along gully*

b) **Sliding**: It occurs when the materials move along defined shear surface by making continuous contact with failure plane. Debris slide is observed in the north-east part of the study area on the fault scarp and ridge (Figure18) in which fragmented rock (debris) slide down slope. Intense fracturing and weathering and human interference (quarrying at the base of ridge) are causative factors.

Figure 18: *Land (debris) slide in the North-East part of the study area*

5.3.3. Flood

Floods represent one of the most threatening types of natural hazards. However, the likelihood of flooding is more predictable than some other types of geological hazards such as earthquakes, volcanic eruption and landslides (Bell, 2007). The geomorphological characteristics (presence of numerous steep slope faults scarp andvolcanic ridges) make the Adama town vulnerable to flooding hazard during rainy season.Flooding in Adama town is an after effect of high precipitation (which is more common during summer), clogged canals (due to improper waste disposal), and poor drainage.

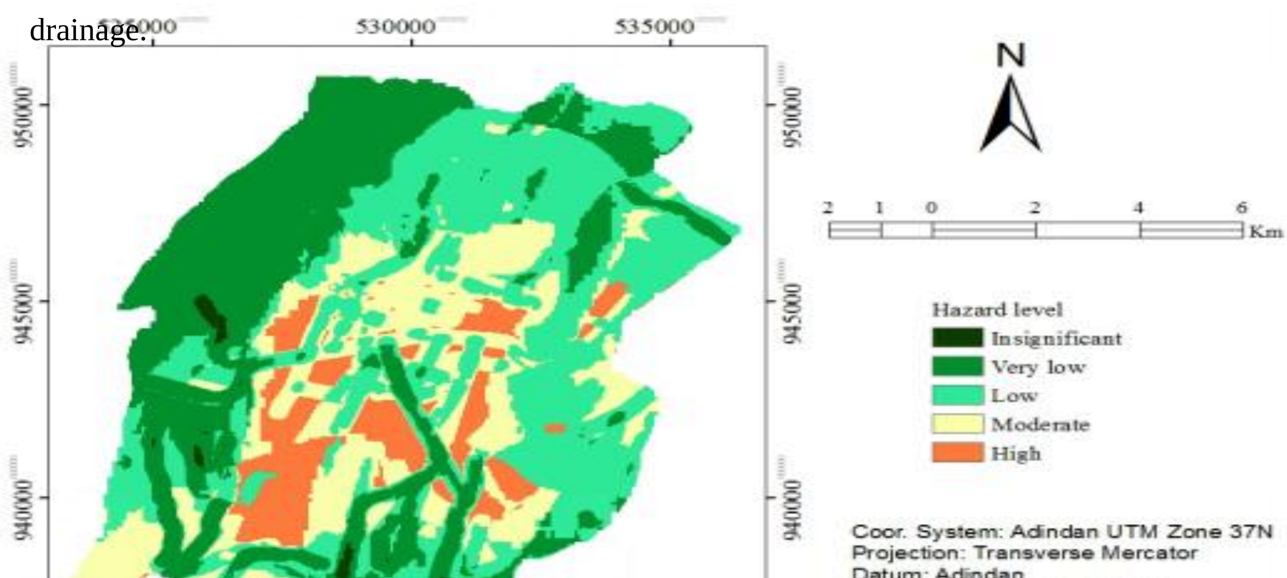

***Figure 19:** Flood hazard zones map of Adama town (after Dejene Tesema et al., 2017)*

The central and southern part of the Adama town is vulnerable to flooding Hazard.According to Dejene Tesema et al. (2017), 10.4% of total area of the town, whichcomposed of different urban land uses,lies within high flood hazard zone (Figure19).In addition,32,670 residents are living in flood risk zone and 867.6 ha of land functioning for different land uses (176.1 ha industrial, 571.1 ha residential, 120.4 ha mixed built up, and 1.8km paved road) located in high flood risk zone.

5.2. Geology of the area

The study area is covered by Quaternary sediments and various types of volcanic rocks which includes, Scoria, Rhyolite, Basalt, Volcanic ashes, Pumice and Ignimbrite. They are described below from young to old.

5.2.1. Quaternary deposits

The recent sediments in the study area consist of alluvial, colluvials and residual soils.The residual deposit are common along the gentle slopes on the top of the ridges. These residual soils are derived from in-situ weathering of volcanic rocks such as ignimbrite, basalt and volcanic ashes with pumice.The thicknesses of these units vary from about 0.5 to 0.8meter, so for the current purpose it is mapped as a bedrock. Colluvial deposits are common along foot of steep slopes (east and west of the town) and are not mapable. Alluvial deposit is widespread and mainly exposed in the central, northern and southern part of the town (Figure 20 and 27). It islight gray to brown in color, loose to dense and in some places it is stratified. The major components are sand and silt, with few clay and gravel.

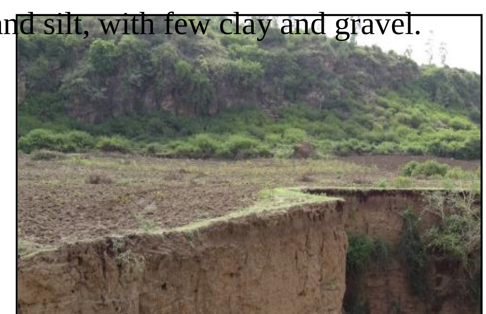

Figure 20: *Exposure of alluvial deposit in the southern part of the study area overlying rhyolite (left) and ash unit (right)*

5.2.2. Scoria

The scoria rock unit is exposed in south-eastern part of the study area (Figure 5.16) as systematically distributed scoria cone. It is highly vesicular and has porous and very rough surface. The nature of exposure of scoria cones varied from place to place where it is mainly vesicular and red in color (Figure 21). But in some places it exposed as gray in color. This variation in exposure color could be related with oxidation reaction intensity of the rock with the available atmospheric oxygen.

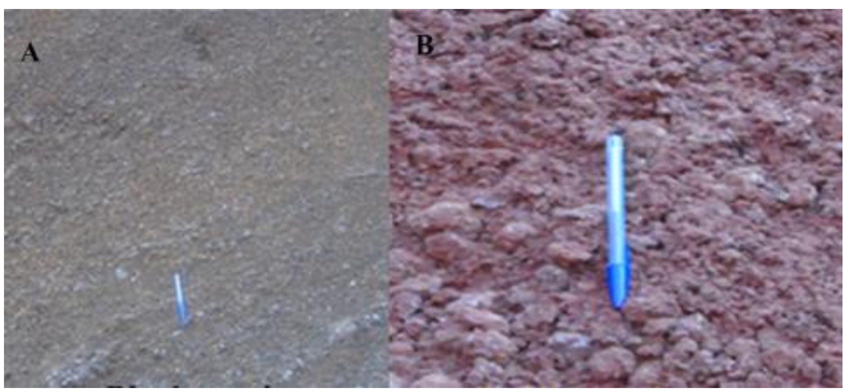

Figure 21: *Scoria exposure: Gray scoria (A) and reddish scoria (B)*

5.2.3. Rhyolite

The rhyolite rock unit is one of the fine grained extrusive volcanic rocks. It is exposed in the south-east and south-west part of the study area as a volcanic ridge (Figure27). It is fresh to slightly weathered and at some places it is interlayered with obsidian. It is felsic in composition and light in color. Thisrock unit is fracturedby two sets of joints (NE and SE striking), which are dominantly vertical, and fault.

Figure 5-22: *Rhyolite ridge (left) and outcrop along fault scarp*

5.2.4. Basalt

This rock unit is another type of extrusive volcanic rock and texturally fine grained and vesicular. The fine grained basalt is exposed in the north-west part of the study area. While the vesicular basalt is exposed at south-western and central part of the study area (Figure 23). It is mafic in composition and light gray in color. It is slightly to medium weathered. It is fractured and jointed (both horizontally and vertically). It is exposed as steep cliff along fault scarp. Some of the vesicles of vesicular basalt are filled by secondary materials (silica or calcite).

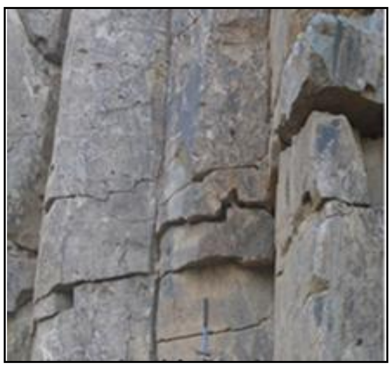

Figure 23: *Fine grained (left) and vesicular (right) basalts exposed on fault scarp*

5.2.5. Volcanic Ashes

This rock unit is a type of pyroclastic rock (pyroclastic fall) and covered large part of the study area (Figure 27). The volcanic ashes rock unit is loose, fine to coarse grained and found at eastern, northern, north-western, southern and south-western sides of the study area. It is well exposed along deep stream/river cut gullies (Figure 24). It is light brown in color. An alternating thin layer of pumice is common in this lithological unit. At some places it is very difficult to differentiate this deposit from alluvial soil.

Figure 24: *Asha deposit with layer of pumice clasts*

5.2.6. Ignimbrite

This rock unit is found dominantly in the eastern and western part of the study area along a fault scarp (Figure5.26). In some places it is interbedded with paleosol layers, indicating frequent breaks in the volcanic activity.It is characterized by stretched glassy 'fiamme', showing a pantelleritic composition (Figure25) and by abundant basaltic lithic fragments. It is felsic in composition and the color varies from brownish to greenish. It is jointed both horizontally and vertically.

Figure 25: *Ignimbrite rock outcrop along fault scarp (left) and ignimbrite texture (right)*

5.2.7. Geological Structures

Geological structure affects the stability of civil engineering structures that constructed on discontinuous rock masses. It makes the rocks weaker and permeable.Thus, it is very vital to consider and study the nature and type of geological structures in any civil engineering projects. In Engineering geological/Geotechnical investigation these geological structures are considered as discontinuity or plane of weakness. The geological structures of the study area are identified both from desk study using Landsat image, DEM and followed by later field checks.The dominant geological structures found in the study area are brittle type structures such as faults and joints.

5.2.7.1. Fault

The study area is located within most active region of the MER which is affected by a series of parallel normal fault.Specifically, the Adama town is found in Wonji Fault Belt, which is rift floor concentrated younger fault.The Landsat image and DEM image show that the faults found in the study area are parallel to each other. In the field the fault is identified from physiographic features such as sharp cliffs which face towards the rift. In the west and south of the town, it forms narrow horest and graben structures. The overall orientation of the fault in the study area ranges from N-S to NNE-SSW strike (Figure 27) and mainly vertical.

Ground fissure is also common in the study arealike the other rift section of Ethiopia. The average orientation of the cracks is N 10-15° E which is parallel to the local faults patternand most commonly form during rainy season.More recently (in 2016), ground fissurewas occurred after heavy rain fall at the vicinity of the southern part of the study area (Figure26). It extends from the bottom of Boku ridge in the south-west to the Dera scoria cone, Wagillo and Dabe Ridge in the south-east and it crosses the main asphalt road from Adama to Awash-Dera-Asella. It is 3 to 4km in length and has a width ranging from 3-30m. The opening of the crack is wider at the middle in the soft formation and become narrow towards the ridges containing hard rock.From the geometrical feature of this crack (width and orientation) and season it formed, we can predict that the ground fissure in the study area may happened as a consequence of two processes: due to breaking of solid rocks in the basement of the rift floor by internal tectonic activity and subsequent subsurface erosion of loose material overlying the bedrock.

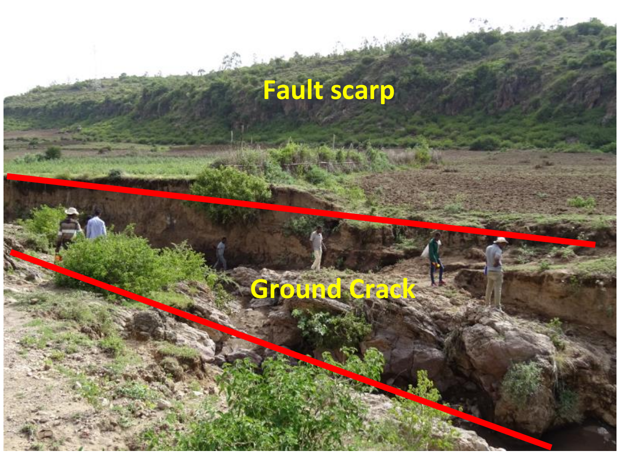

Figure 26: *Ground crack parallel to fault (left) and recent (2016) ground crack crossing Adama-Asella road*

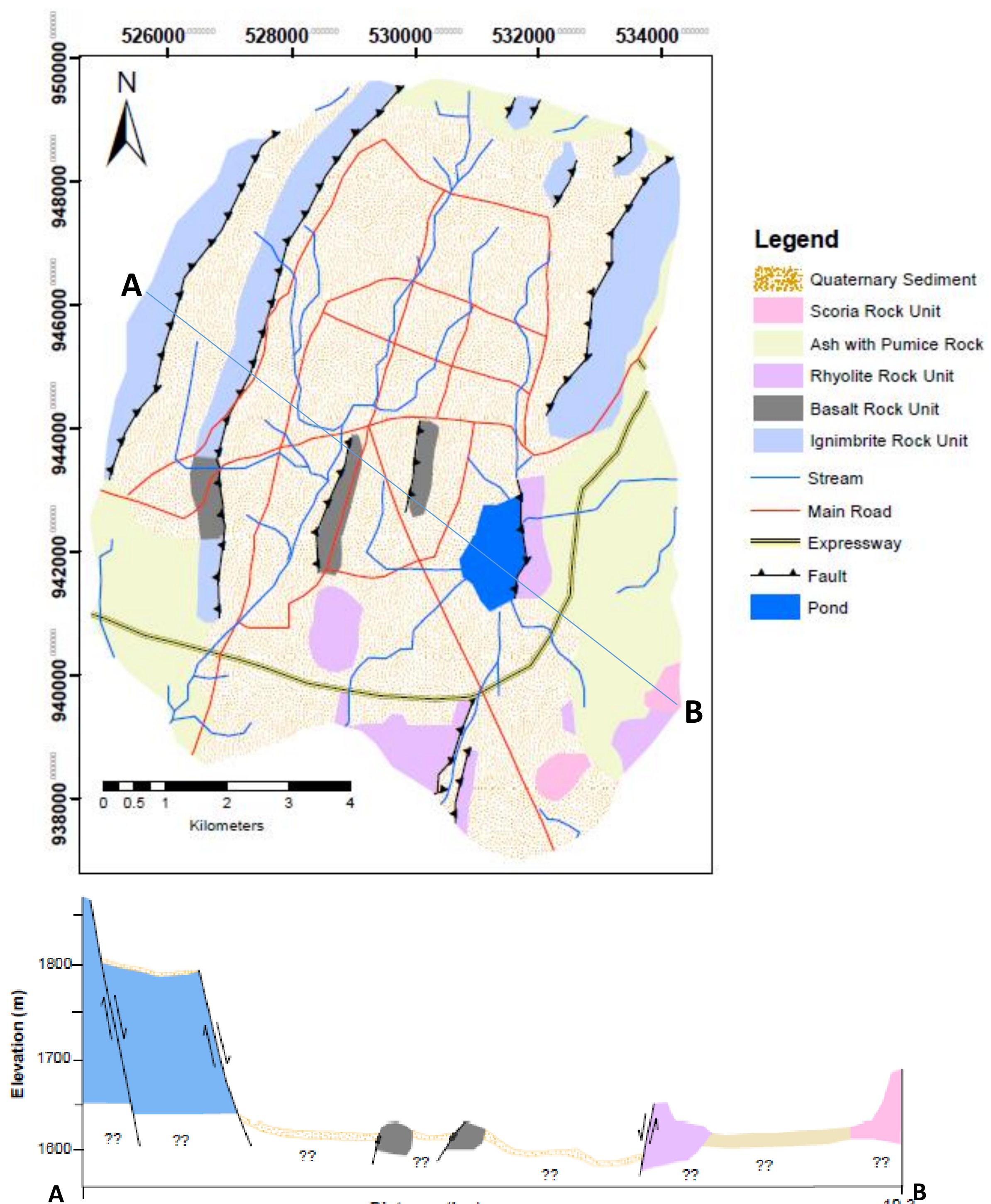

Figure 27: *Geological map of the study area (Note: the scale reduced from 1:10000)*

5.2.7.2.Joint

The joints are the second common geological structure observed on all types of rocks found in the study area except volcanic ashes/pumice and scoria. About 117 joint orientation measurements and characterization are conducted at different part of the study area for the regularly oriented joint systems (Annex B-1). Most of the joints are vertical (steeply dipping) and parallel to the local faults.The major joint sets observed are N to NE strike. Not only this common range of structural orientations, but also there are some exceptional NW and E-W striking joints as shown on rose diagram (Figure28).

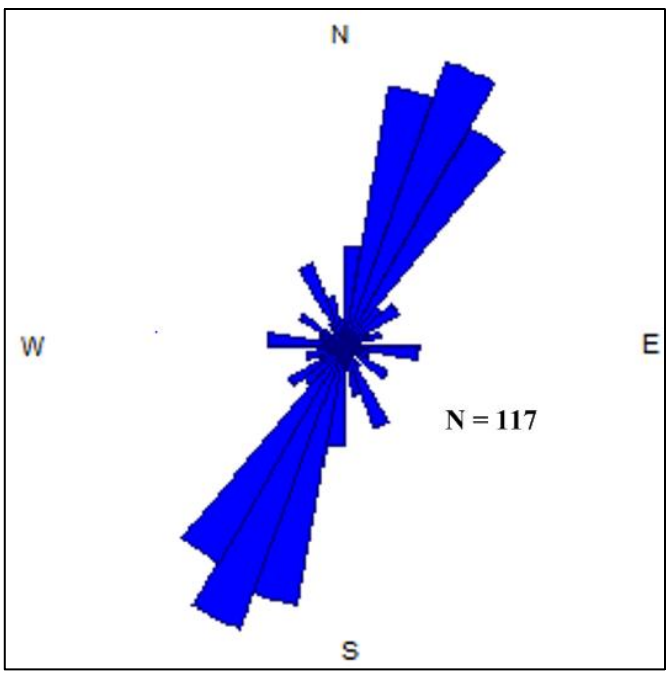

Figure 28: *Rose Diagram of joints*

5.3. Engineering Geological and Geotechnical Characterization

5.3.1. Engineering Geological and Geotechnical Characterization of soil

5.3.1.1. General

The soils of the study areabroadly categorized into residual and transported soils. Residual soils are those soils that remain in position at the place of origin while transported soils are soils moved from their place of origin by different transporting agents. The residual deposit are common along the gentle slopes on the top of the ridges and the thickness ranges from 0.4 to 0.8 meter, so considered as unmapable. Depending on their transporting agent, alluvial and colluvial soils are common types of transported soils in the study area.However, the area coverage of colluvial soilis very small, whilelarge part of the town is covered by alluvial soil which has a thickness more than 10 meter in most places.For engineering purpose, soil unit is mappable if its thickness is greater than one meter. Hence, in the current study, sample collection, characterization and engineering descriptions have been conducted only on alluvial soils.

5.3.1.2. Index Properties

5.3.1.2.1. Natural Moisture Content (NMC)

The natural water content is the ratio of the mass of water to the mass of dry solid.For the soils of the study area, it ranges from 6.34% to 25.2% (Table3). The result imply, the soil of the study area dominantly has low water holding capacity as the coarse fraction is dominant grain size. Such soils are expected to exhibit lower volume change (swelling and shrinkage) in association with moisture content variation.

5.3.1.2.2. Specific Gravity (SG)

Specific gravity is the ratio of the mass of unit volume of soil at a stated temperature to the mass of the same volume of gas-free distilled water at a stated temperature. It is used in computing other soil properties, such as unit weight, void ratio and soil particle size determination by means of hydrometer.The laboratory result shows that the specific gravity of the soils of the study area ranges from 2.0 to 2.67 (Table3). The lower value for some soils is due to the presence of pumice grain in the soil.

5.3.1.2.3. Grain Size Analysis

The grain size analysis is used to determine the percentage of different grain sizes contained within a soils which in turn is useful for classification and evaluating the engineering characteristics. The percentages of different particle size for the 30 soil samples collected from 16 test pits are summarized in Table3. The result shows that the predominant size of soil particle in the research area is coarse-grained soils, which have the gravel content is ranging from 3.2-32.4%, sand fraction 62.8-93.1% and fine fraction(silt + clay) is ranging from 2.9-26.4%.

Table 3: Natural Moisture Content, Specific gravity and Grain Size Analysis results

Sample Designation	Depth (m)	NMC (%)	SG	% grain fraction		
				Gravel	Sand	Fines (silt & clay)
TP-1-1	1.41	18.72	2.14	10	82.4	12.6
TP-1-2	3.00	14.80	2.33	8.8	83.2	8.0
TP-2-1	1.50	6.43	2.50	10	82.6	7.4
TP-2-2	3.00	11.47	2.33	10	82.8	7.2
TP-3-1	1.50	12.75	2.50	18.6	67.4	14
TP-3-2	3.00	15.61	2.12	32.4	63.6	4.0
TP-4-1	1.30	12.07	2.33	16.6	76.8	6.6
TP-4-2	1.70	11.47	2.33	13.6	77.6	8.8
TP-5-1	1.40	11.36	2.00	28.8	62.8	8.4
TP-5-2	3.00	11.64	2.00	20.8	71.2	8.0
TP-6-1	1.20	10.35	2.33	12.2	77.2	10.6
TP-6-2	3.00	11.31	2.33	5.8	89.4	4.8
TP-7-1	1.51	16.72	2.14	12.2	77.2	10.6
TP-7-2	3.00	13.48	2.14	5.8	89.6	4.6
TP-8-1	1.30	12.46	2.54	5.8	89.6	4.6
TP-8-2	3.00	6.34	2.57	24.8	64.0	11.2
TP-9-1	1.35	11.02	2.54	20.68	66.72	12.6
TP-9-2	3.00	18.31	2.55	4.0	90.1	5.9
TP-10-1	1.48	17.1	2.58	13	77.6	9.4
TP-10-2	3.00	25.2	2.61	13.38	74.02	12.6
TP-11-1	1.50	14.82	2.50	7	70.4	22.6
TP-11-2	3.00	22.93	2.14	3.4	70.2	26.4

TP-12-1	1.45	13.36	2.35	6.2	75.2	18.6
TP-12-2	3.00	15.37	2.14	3.2	81.8	15
TP-13-1	1.50	22.32	2.14	3.2	91.2	5.6
TP-13-2	3.00	15.69	2.29	17.6	72	10.4
TP-14-1	1.42	21.03	2.29	12.4	71.8	15.8
TP-14-2	3.00	20.51	2.33	14.2	81	4.8
TP-15	3.2	-	2.37	4.0	93.1	2.9
TP-16	2.6	-	2.67	4.9	91.2	3.9

5.3.1.2.4. Consistency or Atterberg Limits

The Consistency limits or Atterberg Limits of the soils of the study area are summarized in Table4.From the results, we can observe that the liquid limit of a soil of the study area ranges from 26.06% – 49%, plastic limit ranges from 7.5% – 40.83% and plastic index ranges from 2.22% – 23%.According to Chen (1975), as he classified swelling potential based on plasticity index, about 86.7% of the soil samples fall in low and about 15.3% soil samples fall in medium swelling potential.The larger the plasticity index, the greater will be the engineering problems associated with using the soil as an engineering material, such as foundation support for residential building and road sub grades (Bowles, 1992).

5.3.1.2.5. Free Swell

Free swell test results of the soil of the study area are summarized in the Table4. From the test result, we can see that the free swell value of the soil of the study area ranges from 0 % to 40 %. According to free swell classification of soils, the soil which has free swell value less than 50% is non-expansive, 50-100% is marginal and greater than 100% is expansive (BIS – 1498). Accordingly, the soils of the study area have a free swell value below 50% which is considered as low in degree of expansion and expected not to pose significant damage on engineering structures.

Table 4: Atterberg limits and swelling results of soils of the study area

SampleDesignation	Liquid Limit (%)	Plastic Limit (%)	PlasticityIndex (%)	Free Swell (%)
TP-1-1	26.06	23.81	2.25	10
TP-1-2	34.44	29.83	4.61	0
TP-2-1	28.59	23.47	5.12	10

TP-2-2	28.04	20.13	7.91	10
TP-3-1	32.68	28.89	3.79	10
TP-3-2	27.50	22.22	5.27	20
TP-4-1	31.39	24.24	7.15	20
TP-4-2	35.00	32.30	2.70	30
TP-5-1	31.75	28.04	3.70	10
TP-5-2	26.46	21.48	4.97	20
TP-6-1	31.35	27.59	3.76	10
TP-6-2	28.6	23.21	5.39	30
TP-7-1	45.14	40.83	4.31	0
TP-7-2	28.05	22.71	5.34	5
TP-8-1	49.05	37.82	11.23	10
TP-8-2	36.01	33.80	2.22	10
TP-9-1	41.14	31.4	9.74	17
TP-9-2	34.84	29.04	5.8	19
TP-10-1	34.2	25.8	8.4	28
TP-10-2	33.64	26.11	7.53	39
TP-11-1	36.94	27.42	9.51	18.2
TP-11-2	43.79	29.81	13.98	8.3
TP-12-1	43.98	32.78	11.2	22.7
TP-12-2	38.41	15.57	22.84	25
TP-13-1	30.37	7.5	22.87	16.7
TP-13-2	37.24	29.41	7.83	9.1
TP-14-1	41.14	31.4	9.74	8.3
TP-14-2	42.25	29.41	12.83	9
TP-15	31.35	27.59	3.76	
TP-16	30.15	26.49	3.66	16

5.3.1.3. pH of the soils

The knowledge of chemistry of soil, such as pH, is essential to determine the aggressiveness of the soil to the engineering structure. Dissolution reaction is higher at acidic and alkaline pH condition that can deteriorate(corrode)concrete of engineering structure. According to laboratory results(Table5), the pH values of soils of the study area vary from 4.48(acidic) to 6.7(weak acidic) indicating their corrosive nature. Further chemical test such as EC (electrical conductivity) and sulphate content shall be conductedto assess the constituents that cause concrete to deteriorate.

Table 5: pH value of selected soils

Sample	Depth(m)	pH value

TP1	1.41	5.56
TP2	1.50	5.2
TP3	1.50	4.48
TP4	1.30	6.2
TP5	1.40	6.7
TP6	1.20	5.62
TP7	1.51	5.4
TP8	1.30	6.5
TP9	1.35	5.3
TP10	1.48	5.8
TP-11	1.50	6.0
TP-12	1.50	5.5
TP-13	1.45	6.5
TP-14	1.50	5.5
TP-15	1.50	6.0
TP-16	1.42	6.4

5.3.1.4. Dynamic Cone Penetrometer (DCP) Test

The DCP test is a useful tool to measure the resistance of the foundation ground to penetration and density of soil. The higher the resistance to penetration, the higher the load bearing capacity of foundation material. The details of DCP test resultsat a depth of 1.5 m (No. of blows and penetration in mm)are presented in Annex A-2. Penetration Index (DPI) which is expressed in mm/blow was calculated from the recorded DCP data (Table6).This information can be converted into SPT (Standard Penetration Test) N-30 (i.e. number of blows required to penetrate 30cm during the Standard Penetration Test)using the correlation developed byTransport Research Laboratory Overseas Road Note 9 (OSRN9) – “Design of Small Bridges”.To ease calculation and to allow some extrapolation, the relationship given in OSRN9 between DCP and N-30 was curve-fitted using Excel giving the following equation:

SPT ‘N’ value = 240.98 $X^{-0.97}$ where X = DCP in mm/blow

A summary of the result of DCP value (mm/blow)and the equivalent SPT value (N-30)are presented in Table 4.5.The SPT value ranges between 11 and 37 indicating that the soilsare medium dense to dense.

Table 6: DCP value and equivalent SPT value

Location	Average DCPI value (mm/ blow)	SPT value (blows/300mm)	Relative density (Peck et al., 1974)

Boku	8	32.6±1	Dense
Migira	24	11.4±1	Medium dense
105	12	22.1±1	Medium dense
Kebele 03	21	12.9±1	Medium dense
Dembela (059	17	15.8±1	Medium dense
Ganda Hara	7	37.1±1	Dense
Dabe	9	29.1±1	Medium dense
Kebele 05	17	15.8±1	Medium dense
Dhaka Adi	8	32.6±1	Dense
Around ASTU	13	20.5±1	Medium dense
Sole	19	14.2±1	Medium dense
Doro Eribata	21	12.9±1	Medium dense
Dibibisa	17	15.8±1	Medium dense
Municipal	11	24.0±1	Medium dense

5.3.1.5. Shear strength

Shear strength is one of the most important engineering properties of soils. The results of the shear strength parameters of soils of the study area is summarized in Table7.The results showed that cohesion ranges from 3.1 to 15.9kPa and angle of internal friction ranges from 16° to 30.7°. According to Bell (2003), the internal shearing resistance of a coarse soil is generated by friction when the grains in the zone of shearing are caused to slide, roll and rotate against each other. Generally, the angle of shearing resistance is influenced by the grain size distribution (i.e. well or poorly graded) and grain shape (i.e. angular or rounded). The more angular the grains are, the greater the frictional resistance to their relative movement, since they interlock more thoroughly than do rounded ones. Therefore, they produce a larger angle of shearing resistance. While the cohesion is due to inter-particle attraction by surface force which is common in fine grained soils. The soil of the study area possess both cohesion and friction as the soil contains both coarse and fine fraction.

Table 7: Shear strength parameter of selected soils

Test pit designation	Depth (m)	Cohesion (C) (KN/m^2)	Friction angle (Φ) (°)
TP1	3.0	3.08	28.7
TP2	3.0	13.2	27.70
TP3	3.0	15.52	29.20

TP4	3.0	15.9	25.3
TP5	3.0	14.6	30.7
TP6	3.0	8.6	26.98
TP7	3.0	9	25
TP8	3.0	7	26
TP9	3.0	15	16
TP10	3.0	11.95	26.9
TP11	3.0	12.10	29.08
TP12	3.0	16	23
TP13	3.0	7	25
TP14	3.0	1.4	28.6

5.3.1.6. Classification of Soil for Engineering Purpose

Engineering classification of soils in short means the arrangement of soils into different groups and subgroups according to their engineering behavior.Its main purpose is for preliminary assessment of the engineering behaviors of soils using simple tests. Among the different classification system, Unified Soil Classification System (USCS) is used in this study as it is the popular system for use in all types of engineering problems involving soils (Arora, 1997). It considers textures and plasticity and classifies soils into two broad categories: coarse and fine grain.

The laboratory grain size analysis result revealed that the percentage passing No. 200 sieve size for all studied soils is <30% (Table 3).As per this classification system, the soils of the study area are coarse grained soils with percentage finer than 75 µm is less than 50%.Based on plasticity and percentage of fine fraction, the soils were further classified into different groups (classes). Coefficient of gradations (Cu and Cc) were used for classifying soils that have percentage finer less than ≤5% as well graded (W) or poorly graded (P), whereas for soils with percentage of fine fraction >5%, plasticity chart was used.Accordingly, the soils of the study area were classified as: SM, SW-SM, SP-SM, SP-SC, SC, SW, and SP (Table8).According to general engineering suitability of the soils(Arora; 2003), most of the soils of the study area characterized by negligible to low compressibility, good to excellent shear strength and good to excellent in engineering workability. The resultsindicate that they are not problematic soils for engineering application with lower swelling-shrinkage potential.

Table 8: Classifications of Soils of the study area based on unified soil classification

Sample Designation	Percent of particle size			LL (%)	PI (%)	Group symbol	Group name
	Gravel	Sand	Fine				
TP-1-1	5	82.4	12.6	26.06	2.25	SM	Silty Sand
TP-1-2	8.8	83.2	8.0	34.44	4.61	SP-SM	Poorly graded sand with silt
TP-2-1	10	82.6	7.4	28.59	5.12	SW-SM	Well graded sand with silt
TP-2-2	10	82.8	7.2	28.04	7.91	SP-SC	Poorly graded sand with clay
TP-3-1	18.6	67.4	14	32.68	3.79	SM	Silty Sand with gravel
TP-3-2	32.4	63.6	4.0	27.5	5.27	SP	Poorly graded sand with gravel
TP-4-1	16.6	76.8	6.6	31.39	7.15	SP-SM	Poorly graded sand with silt and gravel
TP-4-2	13.6	77.6	8.8	35.00	2.70	SW-SM	Well graded sand with silt
TP-5-1	28.8	62.8	8.4	31.75	3.70	SP-SM	Poorly graded sand with silt and gravel
TP-5-2	20.8	71.2	8.0	26.46	4.97	SW-SC	Well graded sand with clay and gravel
TP-6-1	12.2	77.2	10.6	31.35	3.76	SP-SM	Poorly graded sand with silt
TP-6-2	5.8	89.4	4.8	28.6	5.39	SW	Well graded sand
TP-7-1	12.2	77.2	10.6	45.14	4.31	SP-SM	Poorly graded sand with silt
TP-7-2	5.8	89.6	4.6	28.05	5.34	SW	Well graded sand
TP-8-1	5.8	81.6	12.6	49.05	11.23	SM	Silty sand
TP-8-2	22.8	64.0	13.2	36.01	2.22	SM	Silty Sand with gravel
TP-9-1	20.68	66.72	12.6	41.14	9.74	SM	Silty sand with gravel
TP-9-2	4.0	90.1	5.9	34.84	5.8	SP-SM	Poorly graded sand with silt
TP-10-1	13	77.6	9.4	34.2	8.4	SP-SM	Poorly graded sand with silt
TP-10-2	13.38	74.02	12.6	33.64	7.53	SM	Silty sand
TP-11-1	7	70.4	22.6	42.25	12.83	SM	Silty sand
TP-11-2	3.4	70.2	26.4	43.79	13.97	SM	Silty sand
TP-12-1	6.2	75.2	18.6	37.24	7.83	SM	Silty sand

TP-12-2	3.2	81.8	15	30.37	22.84	SC	Clayey sand
TP-13-1	3.2	91.2	5.6	38.41	22.87	SP-SC	Poorly graded sand with clay
TP-13-2	17.6	72	10.4	43.98	11.2	SP-SM	Poorly graded sand with silt and gravel
TP-14-1	12.4	71.8	15.8	41.14	9.74	SM	Silty sand
TP-14-2	14.2	81	4.8	36.94	9.51	SW	Well graded sand
TP-15	4.0	93.1	2.9	-	-	SP	Poorly graded sand
TP-16	4.9	91.2	3.9	30.15	3.66	SP	Poorly graded sand

5.3.2. Engineering Geological and Geotechnical Characterization of Rocks of the study area

5.3.2.1. General

Description is the initial step in any engineering assessment of rocks and rock masses (Bell, 2007). The description of rock involves: determination of the rock names i.e. the lithological rock name, description of the properties of the rock material (texture, color, strength and state of weathering) and description of the additional properties necessary to describe the features of the rock mass (discontinuities surface condition and infilling materials).Engineering uses of rocks require subdividing rocks into two groups: rock mass and intact rock. Rock mass is a mass of rock interrupted by discontinuity, with each constituent discrete block having intact rock properties. Intact rock is the term applied to rock containing no discontinuities such as joints and bedding.

The rocks of the study area were classified according to international society of rock mechanics (ISRM, 1981). To estimate the engineering properties of the rock masses found in the study area, Schmidt hammer rebound test at thirty seven (37) locations (See Appendix) were conducted to estimate unconfined compressive strength of intact rock in addition to visual description and estimation of their weathering grade and discontinuity surface conditions. Based on the strength (unconfined compressive strength) of intact rock; rock of the study area are classified into three major engineering geological subunits: Low Strength rock mass units, Medium Strength rock mass units and High

Strength rock mass units. During the time of investigation, the groundwater conditions of all the joints were dry for all outcrops.

5.3.2.2. Low Strength Rock Mass Unit

The strength of this unit is very low to measure using Schmidt hammer. Even though it is not the weathering product, similar to engineering soil it can be excavated using simple hand tools. It includes scoria and volcanic ashes.

5.3.2.2.1. Scoria

This rock unit covers limited area in the south-eastern part of the study area (Figure 5.28) in the form of volcanic cone. Its color varies from dark to red color depending on the degree of weathering. Texturally it is vesicular/highly porous and fragmented due to explosive mode of eruption. The fragmented grains are not cemented together. The individual grains are characterized by rough surface and sub rounded.

5.3.2.2.2. Volcanic ash

This rock unit covered large part of the study area (Figure 29) and at some places it contains layers of pumice. It is fine to coarse grained in texture and brownish in color. It is loose and unconsolidated deposit, as a result it is easily eroded.As stated in Bell (2007), ashes are often highly permeable and frequently prone to sliding.

5.3.2.3. Medium Strength Rock Mass unit

These engineering geological subunits include slight to moderately weathered ignimbrite, basalt and rhyolite.

5.3.2.3.1. Moderately Weathered Ignimbrite

Medium strength ignimbrite rock unit is found in the northern, western, south-western and north-western part of the study area (Figure 5.28) along the fault scarp. It is light brown and greenish in color. Texturally it is porphyritic in texture (i.e. clasts and ground mass) and moderately weathered. The strength of the rock material ranges from 25.7 to 58 MPa. Three sets of joints(strike NW, N-S and NE) are dominant which are steeply dipping and medium to widely spaced (21cm to 2m). The joint surface is both rough and smooth and planar. The aperture is variable and ranges from open to very wide (6mm to 3cm). The aperture is partially filled with fine materials and rock fragments.

5.3.2.3.2. Moderately Weathered Rhyolite

Medium strength rhyolite rock subunit is found at the south-eastern part of the town around Adama industrial park and south-west (boku ridge) (Figure 29). It is light brown in color. It is fine grained and moderately weathered. The strength of the rock material varies between 36 to 54.2 MPa. Two sets joints(NE and SE) are dominant which are vertical. The joint is medium to widely spaced (20cm to 82cm). The joint surface is rough and planar. The aperture is open and partially filled with rock fragments.

5.3.2.3.3. Slightly to Moderately Weathered Basalt

The basalt rock unit covers limited area in the western and centralpart of the town (Figure 29). It is light gray to light dark in color, fine grained, vesicular and slightly to moderately weathered. The strength of rock material varies from 33 to 58 MPa. Three sets of joints (E-W, SW and NE) are dominant. Most of the joints are vertical. The joints are medium to widely spaced (20.5cm to 1.34m). The aperture varies from tight to very wide (0.2mm to 2.1cm). The joint wall or surface is planar and rough. Some joints in fine grained basalt are partially and completely filled with fine soil material. The vesicles of vesicular basalt are filled by secondary materials (quartz/silica).

5.3.2.4. High Strength Rock Mass Unit

This engineering geological subunit includesfresh to slightly weathered high strength ignimbrite and rhyolite.

5.3.2.4.1. Slightly Weathered Ignimbrite

High strength ignimbrite rock subunit is found on the faults that bound the town at the east, northeast and southwest direction (Figure 29) and it forms steep cliff. The strength of rock material varies from 62.5 to 80.6 MPa. The joints are medium to widely spaced (22cm to 1.53m). Two sets of joints; (striking NW and SE) are dominant. The joint surface is both smooth and rough and planar. The aperture varies from partly open to moderately wide (0.5mm to 8mm). The aperture is open and partially filled with fine material.

5.3.2.4.2. Fresh to Slightly Weathered Rhyolite

High strength rhyolite rock subunit is mainly found at the south-west and south-east part of the town (Figure 29). It is light gray in color. It is fine-grained and fresh to slightly weathered. The strength of the rock material varies between 64 to 79 MPa. Three sets of joints(striking NW, NE and SE) are dominant which are vertical. The joint is medium to widely spaced (22cm to 86cm). The joint surfaces are rough and planar. The aperture is variable and ranges from open to very wide. Some joints are filled with fine materials and the other is partly filled with rock fragments.

5.4. Ground Water

The term ground water is usually refers to water that occurs beneath the water table in soils and geologic formations that are fully saturated. It is affects the stability and safe function of engineering structures. The properties of rock and soil are often changed by groundwater as it facilitates chemical weathering. Groundwater may influence excavation and construction methods by flowing into excavations, by producing seepage forces and uplift pressures and by its corrosive action (UNESCO, 1976).

As observed from the ground water wells data from different part of the town, the depth of static water level found at depth greater than 190 m (see Appendix). Therefore, the influence of groundwater to the foundations could not be critical in the town.

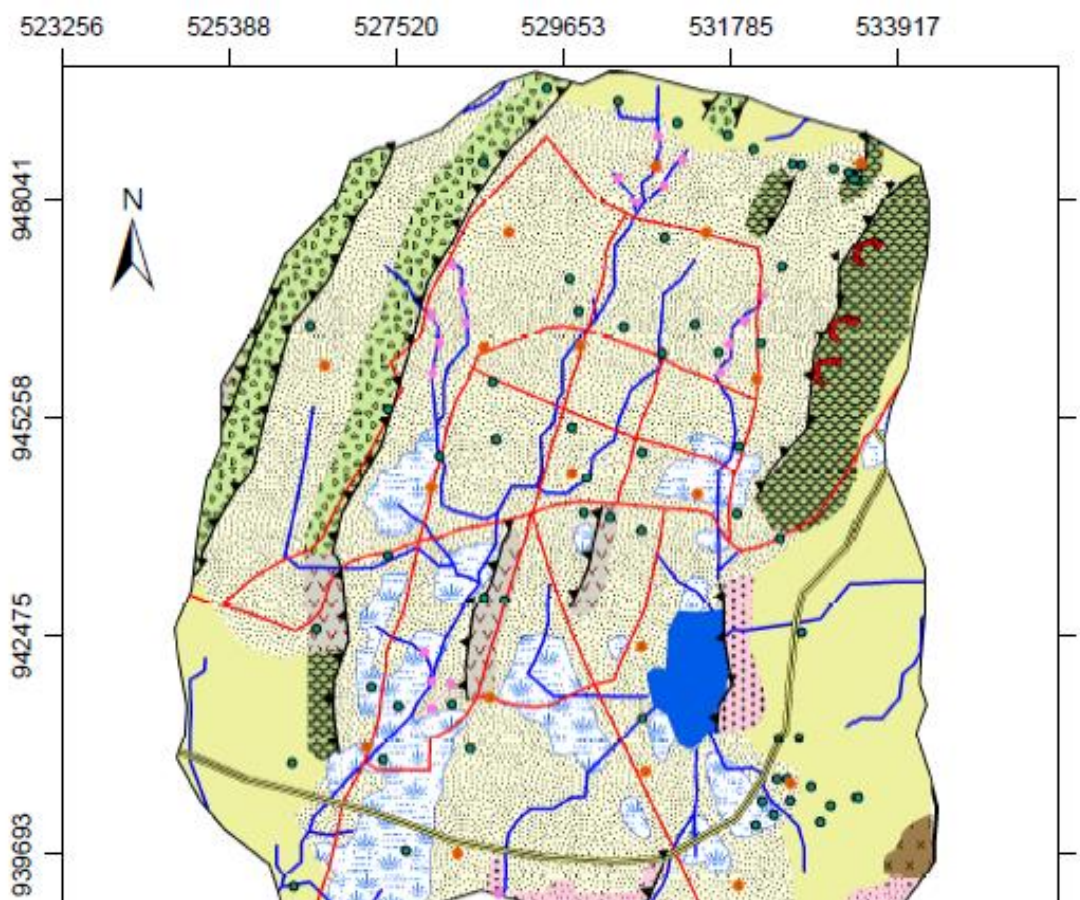

Figure 29: *Multipurpose large scale (1:10000) engineering geological map of the study area*

5.5.Geophysical survey

In complement to the geological and engineering geological assessment of rock and soilson the bases of fielddescription, in-situ geotechnical test and laboratory analysis, electrical resistivity method of geophysical prospecting using Vertical Electrical Sounding (VES)technique was utilized to map the subsurface condition. The survey was conducted at sixty threelocation in different part of the study area as shown in Figure29. The VES data were collected for two purpose: to produce geo-electric section and isoresistivity map of the townto assist in the assessment of geological sub-surface conditions.

5.5.1. Interpretation of resistivity layers

There are different ways in which geophysical data can be interpreted such as correlating with borehole data and regional geological cross sections. Even though, the former is more ideal, there is limited number of borehole drilled in study area for groundwater well. Therefore, interpretation of most of the VES results are mainly based on information fromregional geology, except for the VES near to ground water bore well.

The individual VES are interpreted to get the layer parameters (resistivity and thickness of the subsurface layers) using Ipi2win software.The interpreted result of each VESwith model layer resistivity and thickness dataand representative VES model curve for each VES point is depicted in the appendix C-1 and C-2. Using resistivity value of each model curve, probable geologic layers is revealed and possible interpretation of each layer is also made. The descriptions may not be necessarily representing the actual formations that will be encountered during drilling due to some resistivity overlapping for different geologic formation. Four to five resistivity subsurface layers were identified which may represent different lithological units, i.e. top soil, ash and pumice/alluvial/lacustrine deposit, Ignimbrite, basalt, rhyolite, etc. with different degree of fracturing and weathering.

5.5.2. Geoelectric section

5.5.2.1. Profile section one

The geo-electric section is constructed in the East-West direction (Profile-1) perpendicular to the regional rift direction to show subsurface variation. About 4 kmprofile section is produced using ten VES data (VES1 to VES 10)at the northern side of the study area. The topography along this profile line is undulating due to the presence of small graben and horst formed by parallel step faults.

As shown on the geo-electric section constructed by Ipi2win (Figure30), the variation of subsurface electrical resistivity value laterally and vertically is very higher. It ranges between 4 Ω.m and 8224Ω.m. In the present work, it is grouped into two geo-electric layers: low resistivity layer (<100 Ω.m) and high resistivity layer (>100 Ω.m) (Figure31) based on correlation with borehole data. The low resistivity layer observed almost through the entire profile near the ground surface, except at eastern part beneath VES 1and VES 6 where ignimbrite bed rock exposed on the surface. It is relatively thinner beneath the horest(VES 5 to VES 6) and the thickness increases from east towards the main graben. It is relatively very thick beneath VES 7 to VES 9.Asthe correlation with the lithology log of a borehole drilled for the ground water well near VES 9 (Appendix

D-1) suggests, the low resistivity layer represent geologic subsurface layer comprising top soil, alluvial/lacustrine ash and pumice deposits and weathered basalt, which are considered as unconsolidated overburden material for engineering purposes. The high resistivity layer, on the other hand, may correlated with bed rock of vesicular basalt, ignimbrite,and rhyolite. The lower resistivity layer beneath the bed rock could be volcanic ash intercalation and/or highly fractured and weathered bed rock.

Figure 30: *Geo-electric section of profile one (constructed by Ipi2win)*

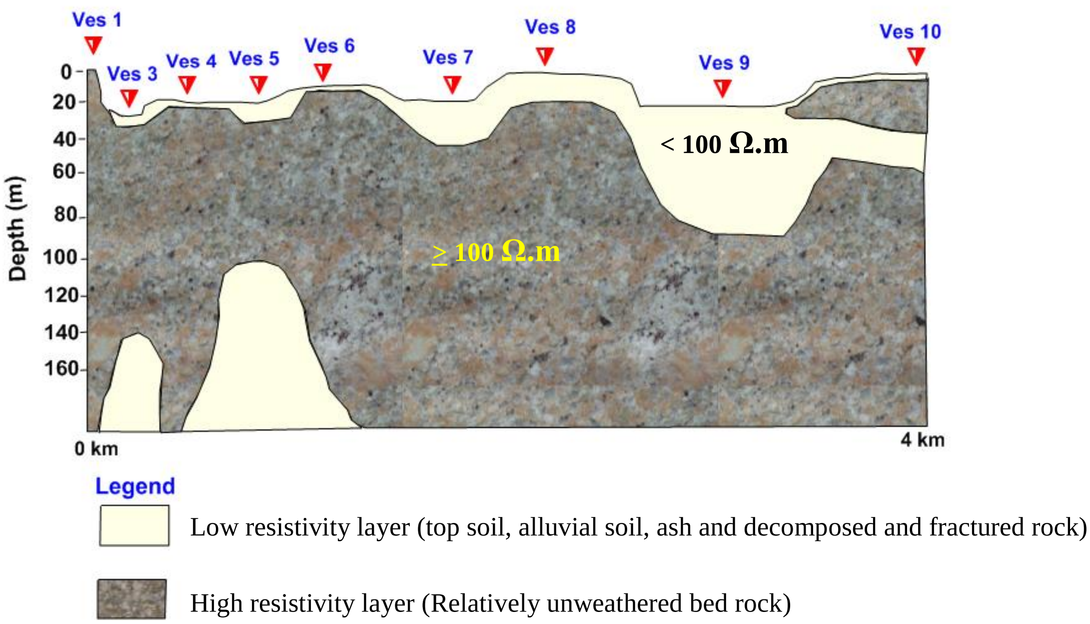

Figure 31: *Profile section one*

5.5.2.2. Profile section two

The geo-electric section of Profile-2 is obtained from the interpreted layer parameters (i.e. layer thickness and resistivity) of VES 31, VES 32, VES 25 and VES 23 as shown in Figure32.Similar to section one, this profile is also more or less oriented in East-West direction perpendicular to the rift system.This section also showed very wide range of electrical resistivity (from 4.9to 1689Ω.m). The low resistivity layer (<100Ω.m)found almost through the entire profile near the ground surface and relatively thinner beneath VES 31 to VES 32 and thicker beneath VES 25 to VES 23 (in the main graben). Generally, the thickness of the low resistivity layer increases from east to west (Figure 33).

The data are interpreted by comparing withlithology log of a borehole drilled for the ground water well in Adama Science and Technology University (near VES 31) (Appendix D-2). Similar to profile section one, the lower resistivity layer is correlated with geologic subsurface layer comprising top soil, alluvial/lacustrine/ash and pumice/ sandy soil deposits and the higher resistivity layer (> 100Ω.m)is correlated with moderately weathered and massive ignimbrite and basalts. The former is considered as overburden material, while the later as bed rock.

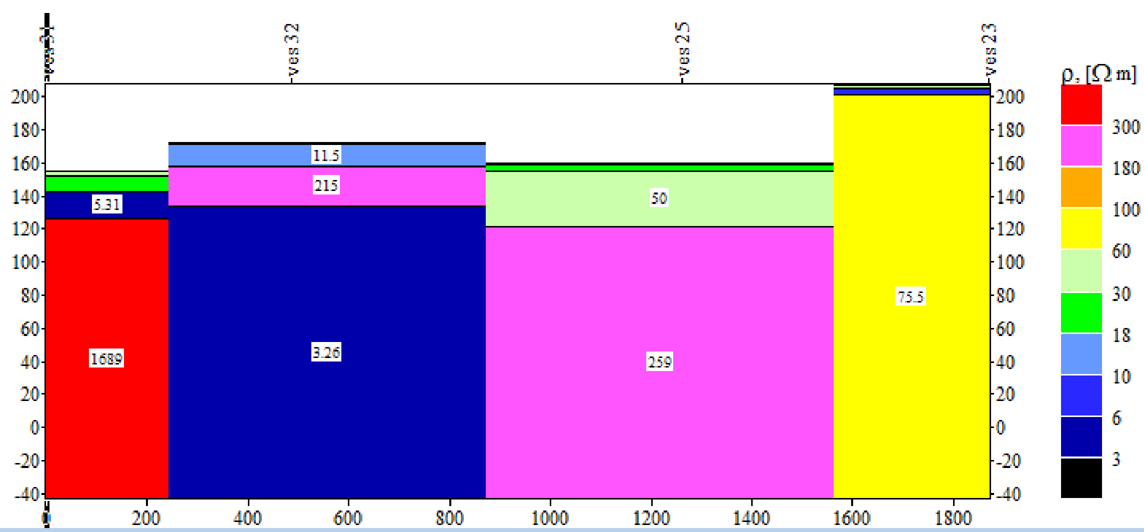

Figure 32: *Geo-electric section of profile one (constructed by Ipi2win)*

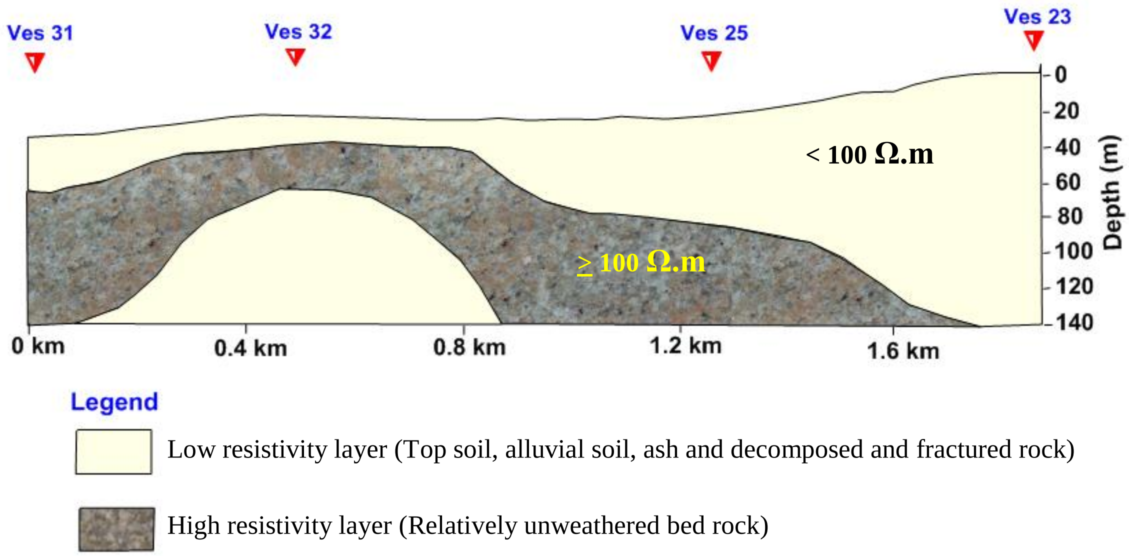

Figure 33: *Profile section two*

5.5.2.3. Profile section three

The geo-electric section of Profile-3 is obtained from the interpreted layer parameters (i.e. layer thickness and resistivity) of VES 30, VES 14 and VES 26 as shown in Figure34.The alignment is more or less similar to the profile one and two and carried out in the central part of the town. The resistivity value of the subsurface material ranges between 4Ω.m and 1500Ω.m. Similar to the previous two sections, the thickness of the lower resistivity layer (<100Ω.m) increases from east to west (Figure 35). This low layer may be inte[illegible]strine /ash and pumice deposit, while the higher resistivity layer can be interpreted as moderately weathered to unweathered ignimbrite/basalt/rhyolite like the previous two sections.

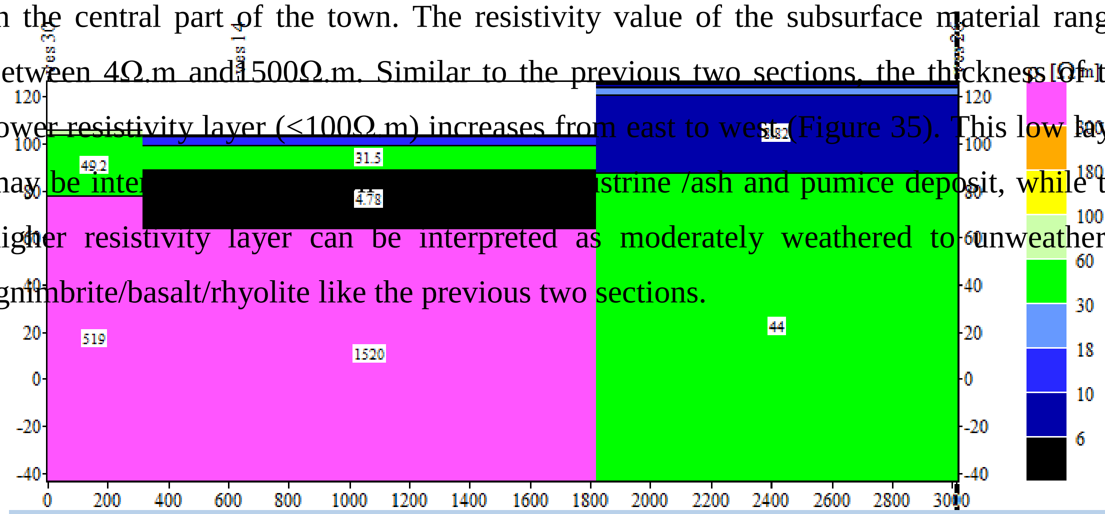

__Figure 34:__ Geo-electric section of profile one (constructed by Ipi2win)

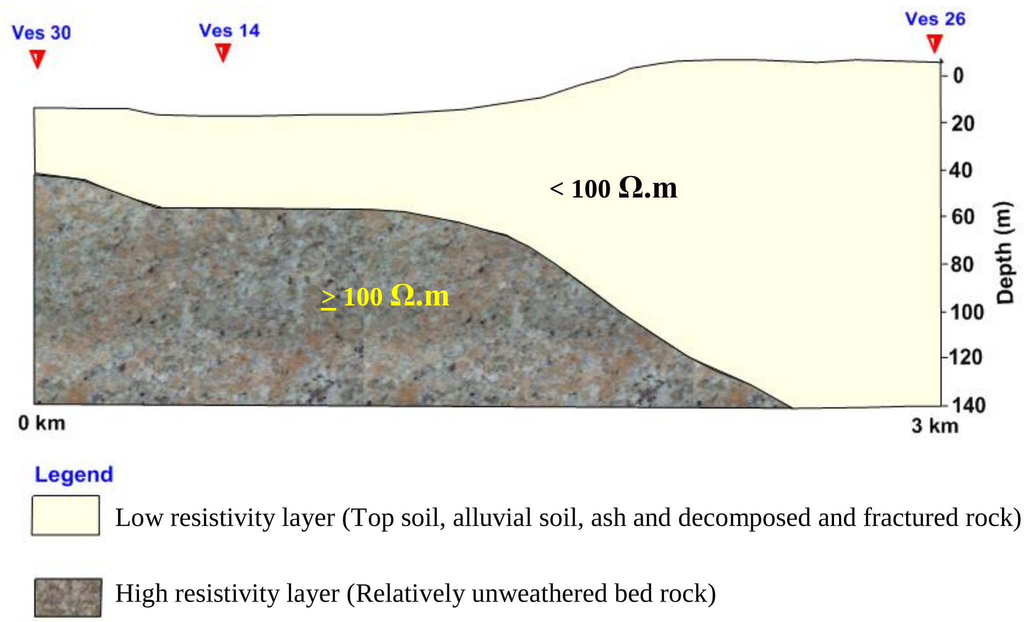

__Figure 35:__ Profile section three

5.5.3. The Isoresistivity Maps

In complement to profile section, the isoresistivity couture maps of the study area were produced to show the resistivity variation both with depth and spatially. Isoresistivity maps were generated using Surfer 8 Software for different depths (3 m, 6 m, 13.5 m, 44 m, 66 m and 100 m) (Figure36and 37).

At shallower depth (3 m, 6 m, 13.5 m, and 45 m), the dominant parts (>75%) of the area (central, northern, south western and eastern parts) are characterized by relatively lower resistivity value (<100Ω.m).The north eastern, north western and southern parts, which accounts less than 25% of the study area, are characterized by relatively higher resistivity.At relatively greater depth (66 m and 100 m), the south western, southern and part of central town are covered by relatively lower resistivity layer. North western, north eastern, eastern, western, south eastern and parts of central part are covered by relatively higher resistivity layer.The low resistivity zones are probably represents areas underlain by unconsolidated overburden material such as top soil, alluvial/lacustrine deposit and volcanic ash and pumice layer, while the higher resistivity zones represents bed rocks such as ignimbrite, basalt and rhyolites based on the borehole data.

From these results we can deduce that the depth to bed rock in most of the central, southern and south western part of the town is located at relatively greater depth (> 100 m),while in north eastern and north western part, the bed rock founds at shallower depth (< 6 m). The landscape of the area appears to plays a role on theobserved variation of overburden thickness.Geomorphological features of the area are the result of different geological structural finger prints and volcanic products pileups. It is intensively divided by a number of minor and major normal faults running almost parallel to each other in a NNE-SSW direction and is usually arranged in “enechelon” fashions and form graben-horst structures. The high resistivity layer oriented in N-S direction which is similar to the orientation of MER and coincides with the horest location in the study area indicatingthe occurrence of shallower bed rock on the horest. On the other hand, the material eroded from elevated surrounding areas (horest) are deposited in the low lying area as a result the overburden material is thicker in the graben.

It is well recognized that damage due to seismic hazard is much higher on the unconsolidated soils than on solid rocks. The town is situated in the graben over thick overburden material, which may be susceptible to ground motion amplification, hence structures constructed in the town may suffer severe damage even due to moderate earth quake.

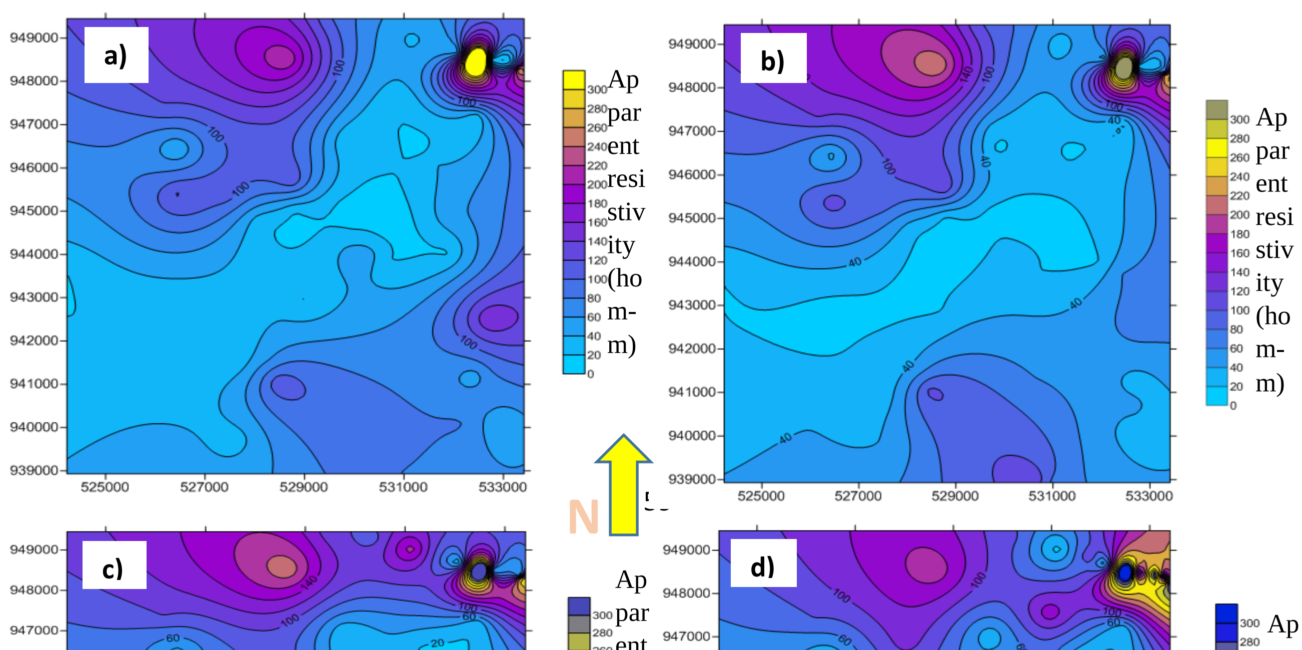

Figure 36: *Iso-apparent electric resistivity map at different investigation depths (a) AB/2 = 3m, b) AB/2 = 6m, c) AB/2 = 13.5m, d) AB/2 = 45m, e) AB/2 = 66 m and f) AB/2 = 100m)*

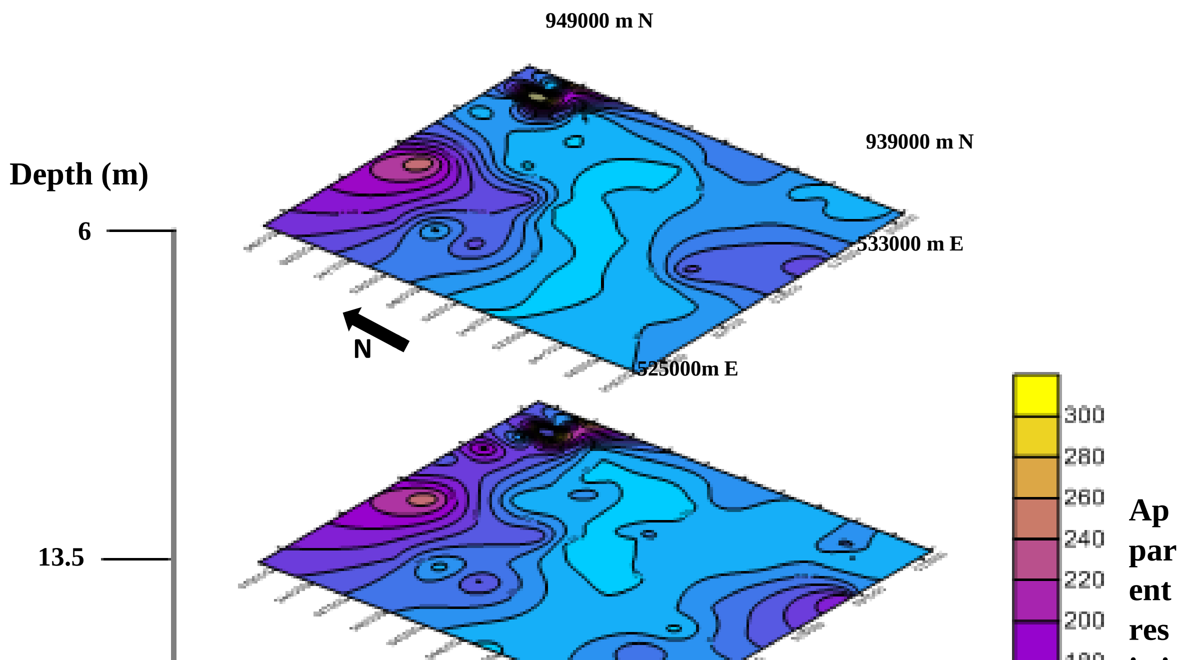

Figure 37: *Layer stacking of iso-apparent resistivity maps*

6. CONCLUSION AND RECOMMENDATION

6.1. Conclusion

The main mapable soil units in the study area are alluvial soils. From grain size analysis, the soils are dominantly coarse grain with the content of gravel range from 3.2% to 22.8%, sand 62.8% to 93.1% and fines (silt and clay) 2.9% to 26.4%. The natural moisture content varies from 6.34% to 25.2%, indicating the water holding capacity of the soils is very low. The liquid limits in percentage range from 26.06% – 49.05%, plastic limit 7.5% – 40.83%, plasticity index 2.22% – 22.84%. According to range of plasticity index, most of the soils (87%) of the study area are characterized as low plastic and low compressible soil. The potential expansion behavior or swelling nature of the soils is found to below with free swell value ranges from 0 to 40%. The soil of the study area has a pH value of less than 7 (varies from 4.48-6.7) which is acidic (weak acidic) in compositionand can deteriorate(corrode)concrete of engineering structure. The shear strength parameter, cohesion(C) and angle of internal friction (Φ) of the soils of the study area range from 3 kN/m^2– 15.9 kN/m^2 and 16°-29.2°, respectively. According to Unified Soil Classification System (USCS), the soils are dominantly sand and silty sand and characterized by good to excellent engineering workability and don't pose significant damage on engineering structures.Large scale (1:10000) geological and engineering geological map of the town were produced.The main lithological rock units exposed in the study area are ignimbrite, rhyolite, basalt, scoria and volcanic ashes with pumice. These lithological rock units are classified into three major engineering geological subunits: rocks with low mass strength which include loose pyroclastic deposits (volcanic ashes with pumice and scoria), rocks with medium mass strength (medium strength ignimbrite, basalt and rhyolite) and rocks with high mass strength (high strength ignimbrite and rhyolite). The depth to bedrock is highly varies within the study area and generally, it is relatively higher in the graben in the central and southern part.The study area is exposed to multiple geo-hazards such as flooding, gully erosion, ground fissure and earthquake.

5.2. Recommendation

Based on the findings of current work, the following recommendations are forwarded:

- Flooding is one of the threatening natural hazards in the southern and central part of the town and caused by seasonal heavy rainfall. Food control remedial measures, such asconstructing drainage network and diversion canals, proper waste management and increasing size of canals, shall be carried out to minimize the risk.
- Gully erosion affected large area in the town and it is expanding and modifying the land form and land use development. Therefore, effective and preventive remedial measures should be taken to control the erosion of stream bank.Construction of cheek dams and gabions are recommended to considerably reduce the erodabilty and further increase of width of gully.

- It is well recognized that Adama is located in most seismically active region of the country. Therefore, design of any engineering structure in the town shall meet all necessary seismic resistant design parameters as per national Building Code. Moreover, the town is situated over thick overburden material that has a potential to amplify ground motion and cause severe damage. Hence, to mitigate seismic hazard due to local soil condition, it is necessary to carry out detail study and prepare seismic microzonation map of the area.There should be also a trend of construction towards low rise buildings with reinforcement ofthe existing ones to resist earthquake damage.

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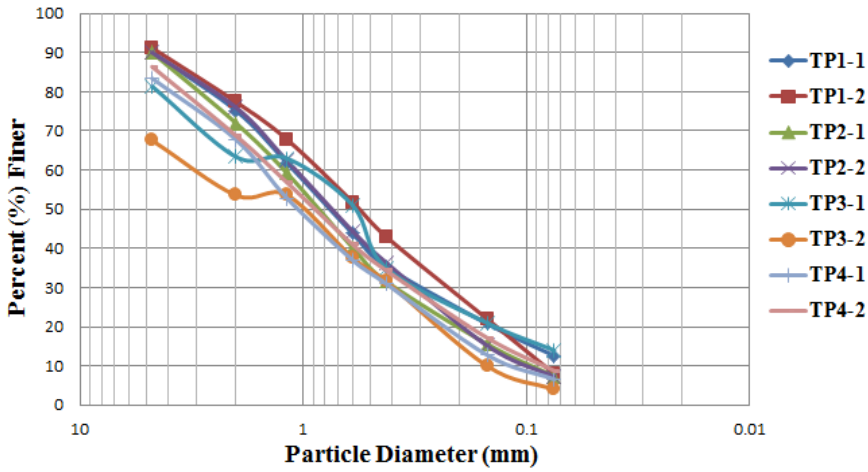
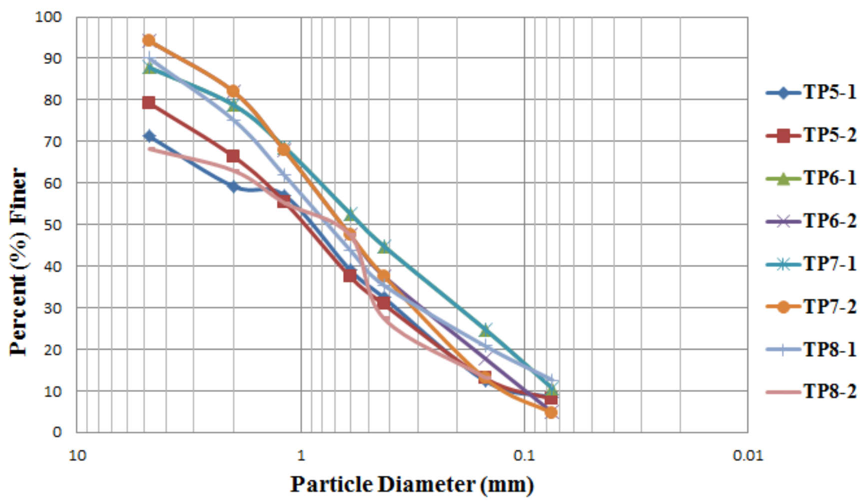
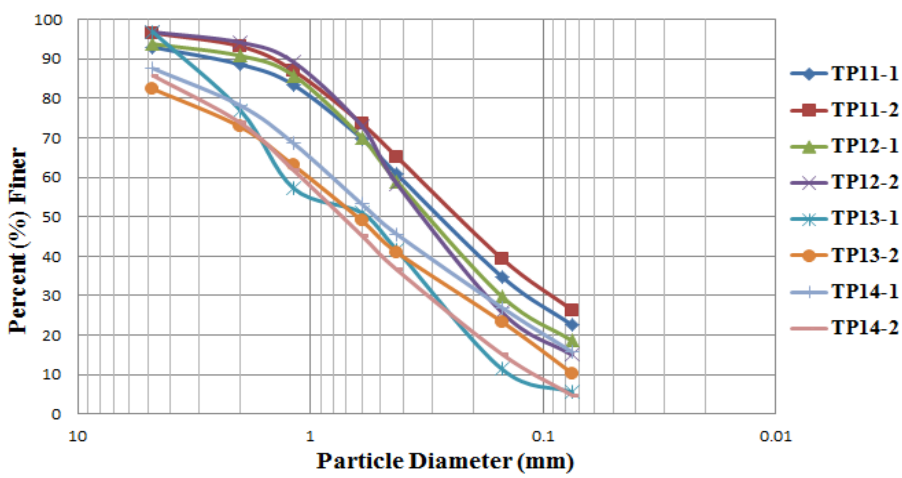
Appendix A: Laboratory soil test result

Appendix A-1: Grain Size Distribution curve (TP 1 – 14)







Appendix A-2: DCP graph of selected samples

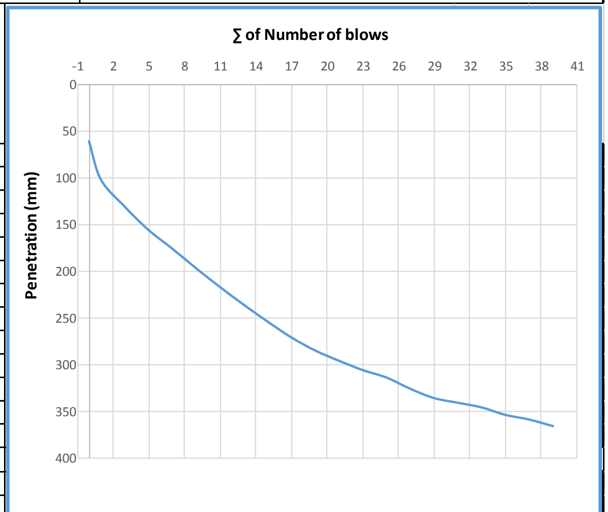
DYNAMIC CONE PENTROMETER TEST READINGS AND GRAPH

Location: Boku
Test performed in Test Pit at 2m depth

DCP EQUIPMENT : TRL TYPE (8kg hammer, 575mm drop height, 60mm con

Ground water Level: Dry

No. of Blows	∑of blows	DCP reading (mm)	Penetration Index (DPI) (mm/blow)
0	0	60	0
1	1	101	41
2	3	130	15
3	5	155	13
4	7	175	10
5	9	196	11
6	11	216	10
7	13	235	10
8	15	253	9
9	17	270	9
10	19	284	7
11	21	295	6
12	23	**305**	5
13	25	**313**	4
14	27	**325**	6
15	29	335	5
16	31	340	3
17	33	345	3
18	35	353	4
19	37	358	3
20	39	365	4
Average			8



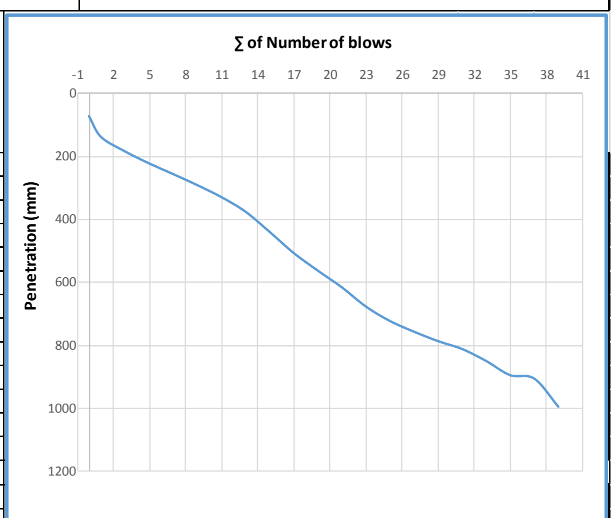
DYNAMIC CONE PENTROMETER TEST READINGS AND GRAPH

Location: Migira
Test performed in Test Pit at 2m depth

DCP EQUIPMENT : TRL TYPE (8kg hammer, 575mm drop height, 60mm con

Ground water Level: Dry

No. of Blows	∑of blows	DCP reading (mm)	Penetration Index (DPI) (mm/blow)
0	0	73	0
1	1	139	66
2	3	185	23
3	5	223	19
4	7	257	17
5	9	292	18
6	11	330	19
7	13	376	23
8	15	440	32
9	17	507	34
10	19	563	28
11	21	616	27
12	23	677	31
13	25	723	23
14	27	757	17
15	29	787	15
16	31	812	13
17	33	850	19
18	35	895	23
19	37	906	6
20	39	995	45
Average			24



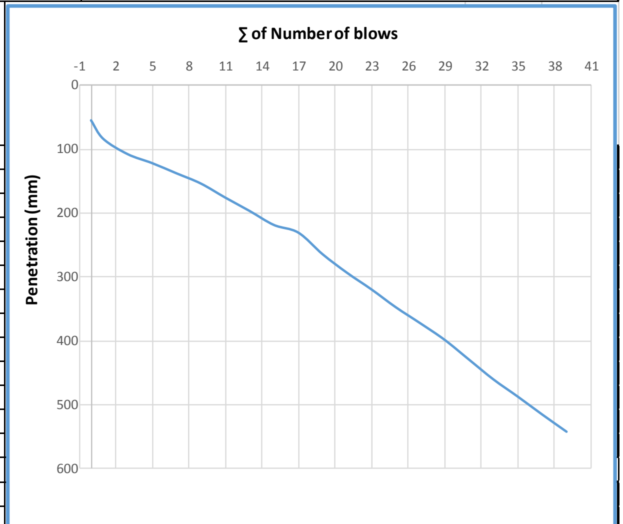
DYNAMIC CONE PENTROMETER TEST READINGS AND GRAPH

Location: 105
Test performed in Test Pit at 2m depth

DCP EQUIPMENT : TRL TYPE (8kg hammer, 575mm drop height, 60mm con

Ground water Level: Dry

No. of Blows	∑of blows	DCP reading (mm)	Penetration Index (DPI) (mm/blow)
0	0	54	0
1	1	83	29
2	3	107	12
3	5	121	7
4	7	137	8
5	9	153	8
6	11	175	11
7	13	196	11
8	15	218	11
9	17	230	6
10	19	264	17
11	21	293	15
12	23	319	13
13	25	347	14
14	27	372	13
15	29	398	13
16	31	429	16
17	33	460	16
18	35	487	14
19	37	515	14
20	39	542	14
Average			12



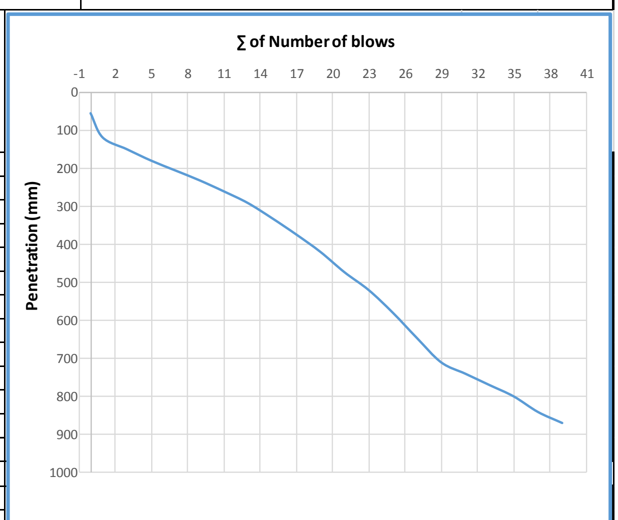
DYNAMIC CONE PENTROMETER TEST READINGS AND GRAPH

Location: Kebele 03
Test performed in Test Pit at 2m depth

DCP EQUIPMENT : TRL TYPE (8kg hammer, 575mm drop height, 60mm con

Ground water Level: Dry

No. of Blows	∑of blows	DCP reading (mm)	Penetration Index (DPI) (mm/blow)
0	0	53	0
1	1	117	64
2	3	148	16
3	5	178	15
4	7	204	13
5	9	230	13
6	11	259	15
7	13	290	16
8	15	330	20
9	17	373	22
10	19	419	23
11	21	473	27
12	23	520	24
13	25	580	30
14	27	647	34
15	29	711	32
16	31	741	15
17	33	771	15
18	35	801	15
19	37	842	21
20	39	871	15
Average			21



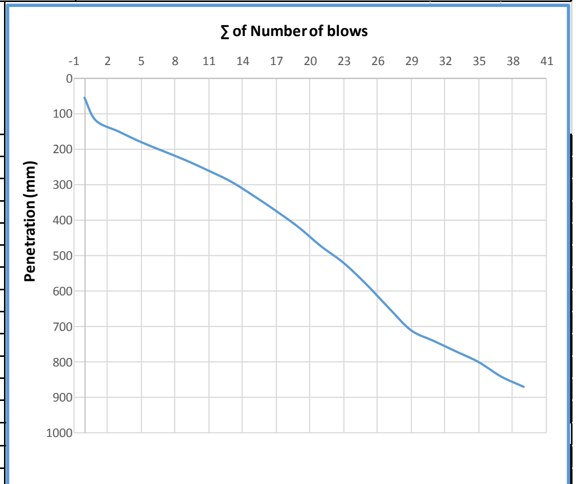
DYNAMIC CONE PENTROMETER TEST READINGS AND GRAPH

Location: Dembela 09
Test performed in Test Pit at 2m depth

DCP EQUIPMENT : TRL TYPE (8kg hammer, 575mm drop height, 60mm con

Ground water Level: Dry

No. of Blows	∑of blows	DCP reading (mm)	Penetration Index (DPI) (mm/blow)
0	0	63	0
1	1	117	54
2	3	155	19
3	5	194	20
4	7	233	20
5	9	276	22
6	11	316	20
7	13	347	16
8	15	376	15
9	17	403	14
10	19	432	15
11	21	460	14
12	23	495	18
13	25	525	15
14	27	545	10
15	29	572	14
16	31	597	13
17	33	624	14
18	35	652	14
19	37	679	14
20	39	707	14
Average			17



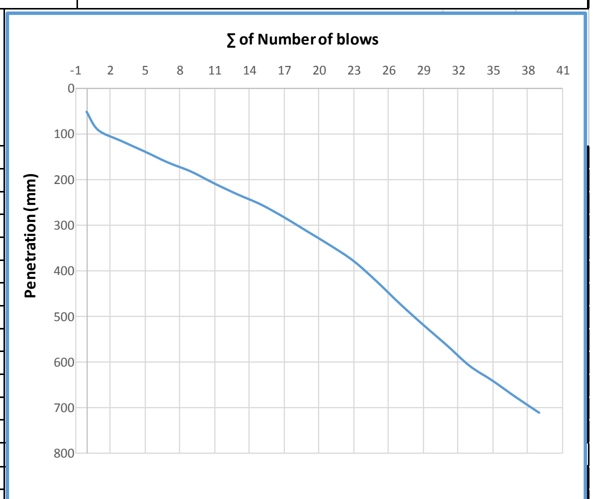
DYNAMIC CONE PENTROMETER TEST READINGS AND GRAPH

Location: Kebele 05
Test performed in Test Pit at 2m depth

DCP EQUIPMENT : TRL TYPE (8kg hammer, 575mm drop height, 60mm con

Ground water Level: Dry

No. of Blows	∑of blows	DCP reading (mm)	Penetration Index (DPI) (mm/blow)
0	0	50	0
1	1	90	40
2	3	114	12
3	5	137	12
4	7	161	12
5	9	181	10
6	11	207	13
7	13	231	12
8	15	253	11
9	17	281	14
10	19	312	16
11	21	343	16
12	23	377	17
13	25	422	23
14	27	471	25
15	29	517	23
16	31	561	22
17	33	607	23
18	35	640	17
19	37	676	18
20	39	710	17
Average			17



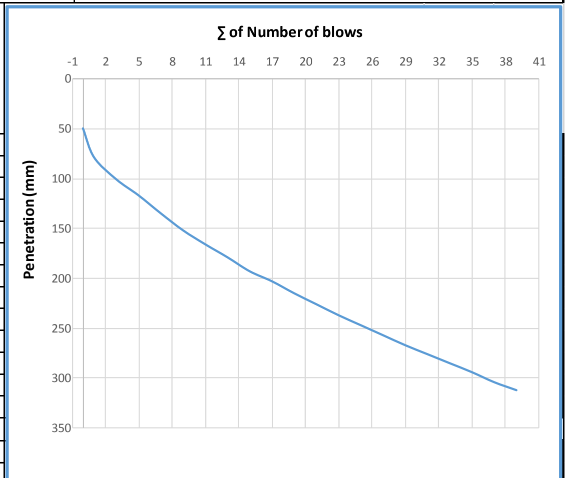
DYNAMIC CONE PENTROMETER TEST READINGS AND GRAPH

DCP EQUIPMENT : TRL TYPE (8kg hammer, 575mm drop height, 60mm con

Location: Ganda hara
Test performed in Test Pit at 2m depth

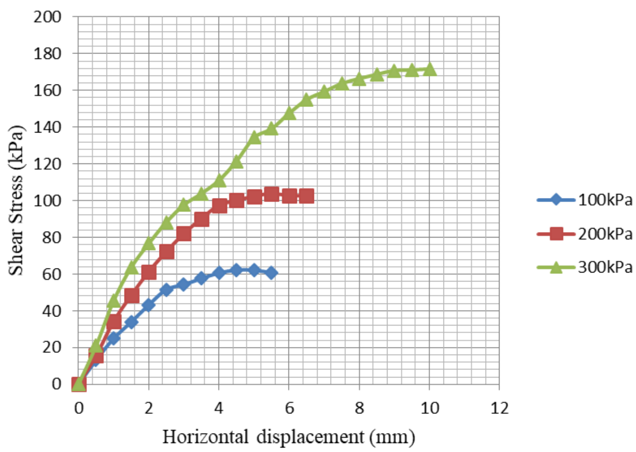
Ground water Level: Dry

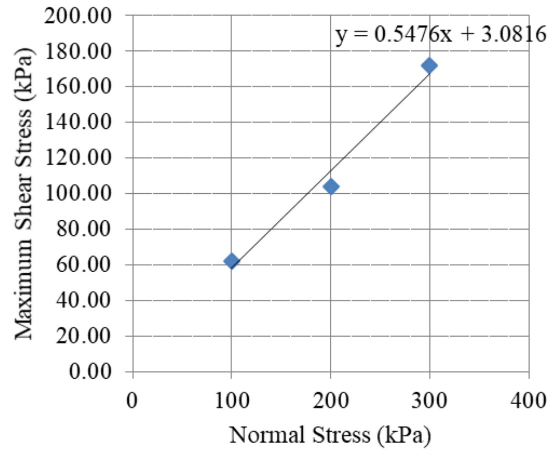
No. of Blows	∑of blows	DCP reading (mm)	Penetration Index (DPI) (mm/blow)
0	0	50	0
1	1	79	29
2	3	101	11
3	5	117	8
4	7	135	9
5	9	152	9
6	11	166	7
7	13	179	7
8	15	193	7
9	17	203	5
10	19	215	6
11	21	226	6
12	23	237	6
13	25	247	5
14	27	257	5
15	29	267	5
16	31	276	5
17	33	285	5
18	35	294	5
19	37	304	5
20	39	312	4
Average			7



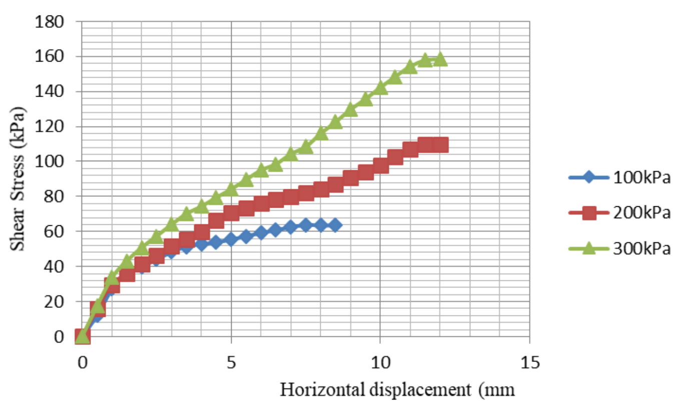
Appendix A-3: Direct shear strength data of selected sample

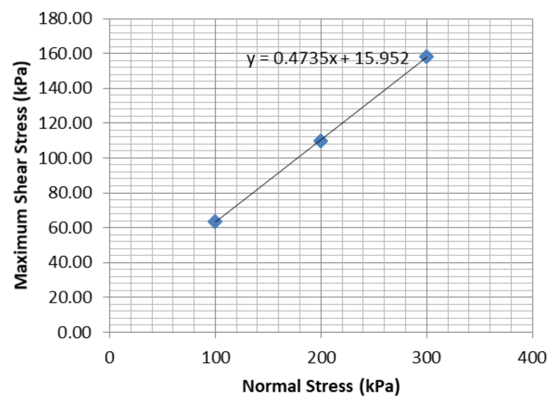
TP-1 3 m depth



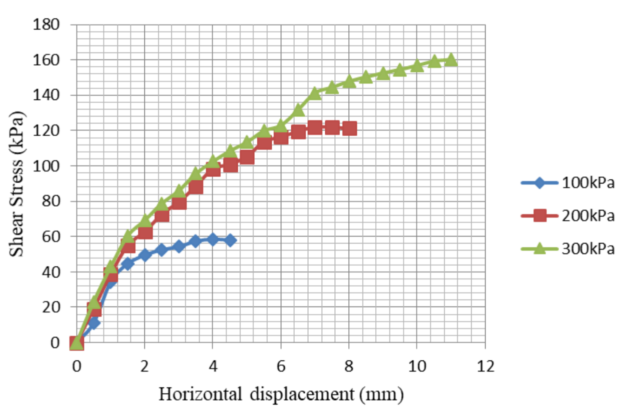


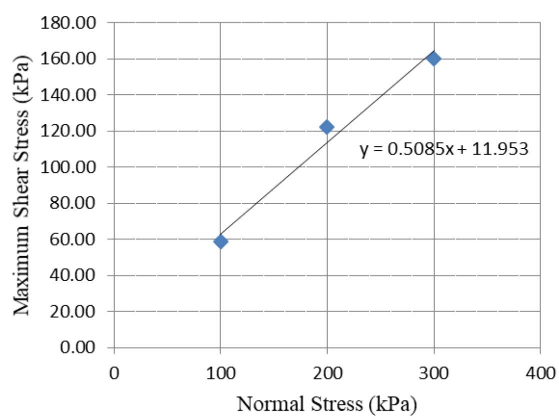
TP-4 3m depth



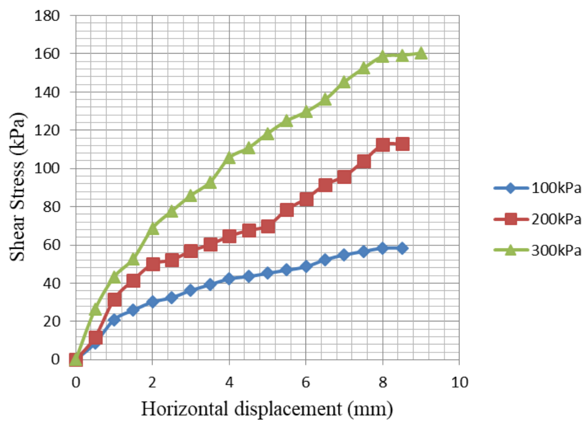


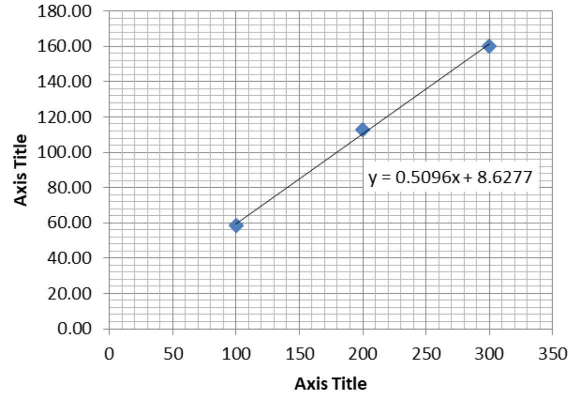
TP-10 3 m depth



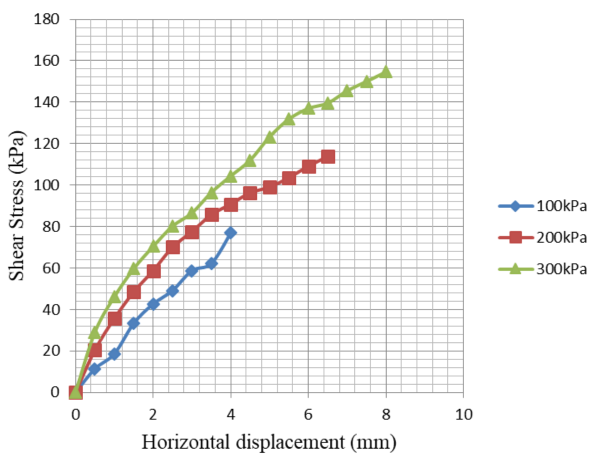


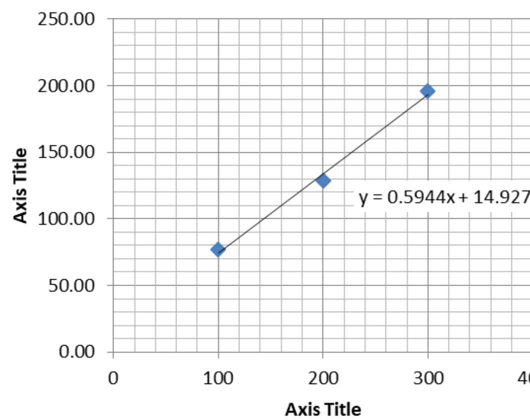
TP-6 3 m depth



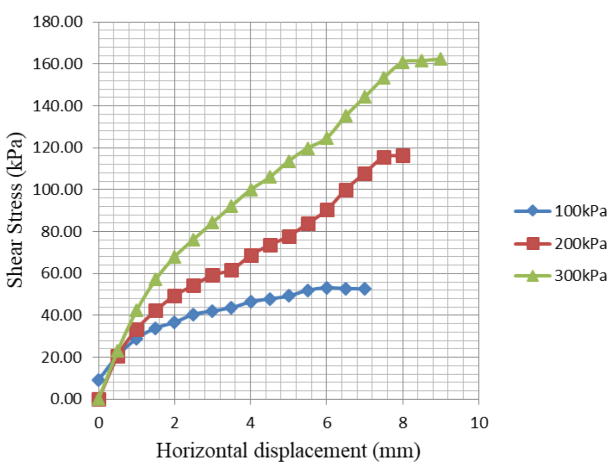


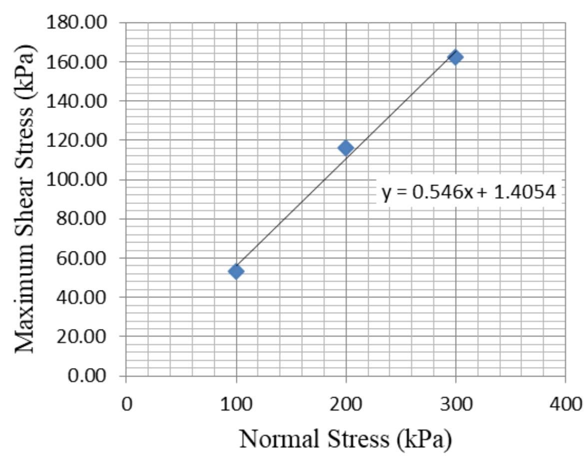
TP-5 3 m depth





TP-14 3 m depth





Appendix B: Data for rock samples and discontinuities

Appendix B-1: Orientations of Joints (Strike and Dip)

S.No	Strike (Bearing or Quadrant)	Strike (Azimuth)	Dip
1	N52^{0}W	308	82^0 NE
2	N26^{0}E	26	84^0 NE
3	N18^{0}W	342	80^0 NE
4	S44^{0}W	224	88^0 NE
5	N22^{0}W	338	84^0 NE
6	N72^{0}W	288	85^0 NE
7	N60^{0}W	300	80^0 NE
8	N04^{0}W	356	90^0
9	N60^{0}W	300	90^0
10	S86^{0}E	94	80^{0}NE
11	S74^{0}E	106	86^{0}NE
12	N38^{0}W	322	78^{0}NE
13	N60^{0}W	300	88^{0}NE
14	S72^{0}W	252	82^{0}SE
15	S30^{0}W	210	34^{0}SE
16	S80^{0}W	260	72^{0}NW
17	E-W	270	58^{0}NE
18	N50^{0}W	310	88^{0}NE
19	S18^{0}W	198	84^{0}NW
20	S62^{0}W	242	86^{0}NW
21	S40^{0}E	140	88^{0}NE
22	N72^{0}E	72	78^{0}SE
23	N06^{0}E	6	76^{0}SE
24	N14^{0}E	14	90^0
25	N12^{0}E	12	90^0
26	N24^{0}E	24	90^0
27	N-S	180	62^{0}NE
28	N12^{0}E	12	53^{0}NE
29	S22^{0}E	158	72^{0}NE
30	N66^{0}W	294	72^{0}SE
31	N22^{0}E	22	90^0
32	N98^{0}E	98	90^0
33	N58^{0}E	58	86^{0}SE
34	N-S	180	60^{0}NE
35	N10^{0}E	10	62^{0}NE
36	N12^{0}E	12	58^{0}NE
37	N24^{0}E	24	90^0
38	N12^{0}E	12	90^0
39	N14^{0}E	14	90^0
40	N12^{0}E	12	90^0
41	N24^{0}E	24	90^0
42	N30^{0}E	30	90^0
43	N28^{0}E	28	90^0
44	N32^{0}E	32	85^{0}NE

45	$N32^0E$	32	88^0NE
46	$N30^0E$	30	90^0
47	$N26^0E$	26	90^0
48	$N29^0E$	29	90^0
49	E-W	90	90^0
50	$N70^0E$	70	90^0
51	$N32^0E$	32	42^0NE
52	$N34^0E$	34	72^0NE
53	$N60^0E$	60	86^0NE
54	E-W	90	78^0NE
55	$N31^0E$	31	70^0NE
56	$N34^0E$	34	82^0SE
57	$N28^0E$	28	90^0
58	$N27^0E$	27	85^0SE
59	$N29^0E$	29	90^0
60	N-S	180	60^0NE
61	$N10^0E$	10	62^0NE
62	$N12^0W$	348	58^0NE
63	$N24^0E$	24	90^0
64	$N12^0E$	12	90^0
65	$N14^0E$	14	90^0
66	$N12^0E$	12	90^0
67	$N24^0E$	24	90^0
68	$N30^0E$	30	90^0
69	$N28^0E$	28	90^0
70	$N32^0E$	32	85^0NE
71	$N32^0E$	32	88^0NE
72	$N30^0W$	330	90^0
73	$N26^0W$	334	90^0
74	$N29^0W$	331	90^0
75	E-W	90	90^0
76	$N70^0W$	290	90^0
77	$N23^0E$	23	70^0NE
78	$N27^0E$	27	68^0NE
79	$N26^0E$	26	69^0NE
80	$N30^0E$	30	73^0NE
81	$N34^0E$	34	72^0NE
82	$N37^0E$	37	71^0NE
83	$N09^0E$	9	75^0NE
84	N-S	180	70^0NE
85	$N11^0E$	11	68^0NE
86	$N14^0E$	14	61^0NE
87	$N20^0E$	20	58^0NE
88	$N21^0E$	21	53^0SE
89	$N27^0E$	27	49^0NE
90	$N30^0E$	30	62^0NE
91	$N32^0E$	32	63^0NE
92	$N15^0E$	15	68^0NE
93	$N17^0E$	17	66^0NE
94	$N23^0E$	23	65^0NE

95	N15^{0}W	345	67^{0}NE
96	N18^{0}W	342	65^{0}NE
97	N07^{0}W	353	61^{0}SE
98	N56^{0}E	56	59^{0}NE
99	N46^{0}E	46	58^{0}NE
100	N09^{0}E	09	89^{0}NE
101	N25^{0}W	335	90^0
102	N15^{0}E	15	88^{0}NE
103	N18^{0}E	18	86^{0}SE
104	N30^{0}W	330	89^{0}NE
105	N29^{0}E	29	84^{0}NE
106	N33^{0}E	33	85^{0}NE
107	N33^{0}E	33	86^{0}NE
108	N23^{0}E	23	87^{0}NE
109	S11^{0}W	191	89^{0}NE
110	S23^{0}W	203	90^0
111	N40^{0}E	40	70^{0}NE
112	S10^{0}W	190	70^{0}NE
113	N42^{0}E	42	68^{0}NE
114	N54^{0}E	54	79^{0}NE
115	N56^{0}E	56	69^{0}NE
116	N36^{0}E	36	68^{0}NE
117	N53^{0}E	53	77^{0}NE

Appendix B-2: Schmidt hammer test result

GPS Location	Lithological unit	Average UCS (MPa)

Easting (m)	Northing (m)	Elevation (m)		
531970	949496	1714	rhyolite	36.3
533537	938646	1683	rhyolite	54.2
532899	945304	1674	ignimbrite	57.2
533359	948252	1705	ignimbrite	75.7
532515	948289	1728	Ignimbrite	80.1
529412	949395	1758	Ignimbrite	49.7
528220	947585	1720	Ignimbrite	51
525073	945488	1800	Basalt	33
525343	945707	1822	Basalt	57.6
530714	938049	1675	Rhyolite	75.9
528872	939502	1655	Rhyolite	74.8
528836	939458	1667	Rhyolite	77.2
533091	944125	1600	Ignimbrite	80.6
533799	939304	1700	Ignimbrite	64.2
526743	940889	1617	Ignimbrite	63.4
532099	941891	1616	Rhyolite	72.1
529128	937471	1780	Rhyolite	59.6
532301	938008	1658	Scoria	-
525578	947051	1808	Ignimbrite	25.7
525476	944472	1701	ignimbrite	52.6
527347	948622	1644	ignimbrite	57.4
524551	943218	1735	Ignimbrite	75.5
526510	942725	1692	Basalt	54.9
533846	939709	1704	Scoria	-
532424	938419	1680	Scoria	-0
530703	938156	1699	Rhyolite	74.3
528422	941137	1629	Rhyolite	56.9
528846	938597	1702	Rhyolite	52.7
533639	947832	1705	Ignimbrite	73.6
533409	948273	1724	Ignimbrite	72.4
526738	943595	1653	Basalt	25.1
533581	949199	1724	Ignimbrite	75.6
524560	943121	1723	Ignimbrite	28.2
531109	935768	1826	Rhyolite	48.4
528566	942320	1613	Basalt	23.6
532500	939428	1671	Rhyolite	55.2
533246	946756	1667	Ignimbrite	74.3

Appendix c: Electrical resistivity data and curve fitting models

Appendix C-1: Possible Interpretation of collected VES data

VES	No. of layer	Resistivity (Oh.m)	Thickness (m)	Depth (m)	Possible Interpretation	Remarks
1	1	133	0.75	0.75	Highly to slightly weathered and fractured ignimbrite	Considered as overburden material
	2	461	1.25	2	Slightly frqctured Ignimbrite	Expected bedrock
	3	135	3.35	5.35	Moderately fractured Ignimbrites	
	4	356	97.8	103	Slightly fractured Ignimbrites or Rhyolites	
	5	4.89	∞	∞	Highly fractured and weathered Ignimbrites	Saturated
2	1	262	1	1	SHighly weathered and fractured ignimbrite	Considered as Overburden material
	2	629	0.75	1.75	Slightly weathered and fractured ignimbrite	Expected bedrock
	3	248	11.4	13.5	Moderately fractured Ignimbrites	
	4	151	59.1	72.2	Moderately to highly fractured Ignimbrites	
	5	3862	∞	∞	Massive Ignimbrites or Rhyolites	
3	1	161	2.66	2.66	Dry top soil	Considered as overburden material
	2	20.5	19.8	22.4	Alluvial soil and reworked volcanic ash	
	3	566	20.1	42.5	Slightly fractured Ignimbrites or Rhyolites	Expected bedrock
	4	1.64	∞	∞	Highly fractured Ignimbrites or Rhyolites	Saturated
4	1	42.7	1.15	1.15	Considerably dry top soil	Considered as overburden material
	2	9.56	1.41	2.57	Considerably moist top soil	
	3	1264	2.45	5.02	Slightly fractured Ignimbrites or Rhyolites	Expected bedrock
	4	81	13.2	18.2	Moderately to highly fractured Ignimbrites or Rhyolites	
	5	61202	∞	∞	Massive bed rock/Ignimbrites/rhyolites	
5	1	20.7	4.3	4.3	Considerably moist top soil	Considered as overburden material
	2	34.3	16.4	20.7	Moderately fractured Ignimbrites or Rhyolites	
	3	69.1	∞	∞	Highly fractured Ignimbrites or Rhyolites/other rocks	Expected bedrock
6	1	1242	1	1	Massive ignimbrite	Expected bedrock
	2	2174	3.6	4.6	Massive ignimbrite	
	3	895	∞	∞	Slightly fractured Ignimbrites or Rhyolites/other rocks	
7	1	51.2	2.23	2.23	Top soil	Considered as overburden material
	2	13.5	28.5	30.7	Thick alluvial soil and reworked volcanic ash	
	3	242	∞	∞	Moderately fractured Ignimbrites or Rhyolites/other rocks	Expected bedrock
8	1	31.8	0.75	0.75	Top soil	Considered as overburden material

	2	65.9	12.3	13.1	Moderately to highly fractured Ignimbrites or Rhyolites/other rocks	Expected bedrock
	3	112	∞	∞	Moderately fractured Ignimbrites or Rhyolites/other rocks	
9	1	46.7	3.53	3.53	Top soil	Considered as overburden material; Saturated
	2	10	50.2	53.8	Thick alluvial soil and reworked volcanic ash	
	3	197	∞	∞	Highly fractured Ignimbrites or Rhyolites/other rocks	Expected bedrock
10	1	40.4	0.75	0.75	Top soil	Considered as overburden material
	2	86.3	13.6	14.4	Dry top soil	
	3	71.1	88.1	102	Highly fractured and weathered Ignimbrites or Rhyolites/other rocks	Expected bedrock
	4	2098	∞	∞	Massive Ignimbrites or Rhyolites/other rocks	
11	1	72.6	0.75	0.75	Moist top soil	Considered as overburden material
	2	121	13.6	14.3	Highly to moderately fractured Ignimbrites or Rhyolites/other rocks	Expected bedrock
	3	166	30.5	44.8	Moderately fractured Ignimbrites or Rhyolites/other rocks	
	4	21.2	∞	∞	Highly fractured Ignimbrites or Rhyolites/other rocks	Saturated
12	1	42.9	1.53	1.53	Top soil	Considered as overburden material
	2	14.6	34.7	36.3	Moist top soil	
	3	954	∞	∞	Slightly fractured Ignimbrites or Rhyolites/other rocks	Expected bedrock
13	1	46	3.2	3.2	Top soil	Considered as overburden material
	2	4.48	45.4	48.6	Moist top soil	
	3	1536	∞	∞	Slightly fractured to fresh Ignimbrites or Rhyolites/other rocks	Expected bedrock
14	1	26.2	0.9	0.93	Top soil	Considered as overburden material
	2	13.7	4.37	5.3	Moist top soil	
	3	47.8	6.0	11.3	Reworked volcanic ash unit	
	4	2.41	14	25.2	Moist Reworked volcanic ash	
	5	381	∞	∞	Moderately fractured Ignimbrites or Rhyolites/other rocks	Expected bedrock
15	1	89.7	1.9	1.9	Top soil	Considerable overburden material
	2	36	5.6	7.6	Sandy top soil	
	3	575	19.1	26.7	Slightly fractured basalt/rhyolites	Expected bedrock
	4	8.3	∞	∞	Highly fractured basalt/rhyolites	

16	1	82.7	1.2	1.2	Top soil	Considerable overburden material
	2	22.4	3.5	4.7	Highly fractured Ignimbrites or Rhyolites/other rocks	
	3	39.9	27.2	31.9	Moderately to Highly fractured basalt or Rhyolites	Expected bedrock
	4	342	∞	∞	Moderately fractured basalt or rhyolites	
17	1	72.9	3	3	Top soil	Considerable overburden material
	2	19.4	41	44	Moist reworked volcanic ash and alluvial soil	
	3	218	∞	∞	Moderately to Highly fractured Ignimbrites or Rhyolites/other rocks	Expected bedrock
18	1	53.8	0.75	0.75	Top soil	Considerable overburden material
	2	98.8	2.85	3.6	Relatively more moist top soil	
	3	46.2	127	130	Saturated and highly fractured basalt/rhyolites	Expected bedrock
	4	707	∞	∞	Slightly fractured basalt/ Ignimbrites	
19	1	45.6	0.75	0.75	Top soil	Considerable overburden material
	2	131	7.97	8.72	Moderately fractured Ignimbrites or Rhyolites	Expected bedrock
	3	393	12.7	21.4	Moderately Ignimbrites or Rhyolites	
	4	41.7	33.4	54.8	Highly fractured Ignimbrites or Rhyolites/other rocks	Saturated
	5	972	∞	∞	Slightly fractured Ignimbrites or Rhyolites	
20	1	67.5	1.8	1.8	Top soil	Considerable overburden material
	2	36.5	7.5	9.3	Moist top soil	
	3	9.46	83.6	92.9	Thick and saturated alluvial and reworked volcanic ash	
	4	967	∞	∞	Slightly fractured Ignimbrites or Rhyolites/other rocks	Expected bedrock
21	1	13.6	1.8	1.8	Top soil	Considerable overburden material
	2	34	12.6	14.5	Alluvial and reworked volcanic ash	
	3	426	∞	∞	Highly fractured Ignimbrites or Rhyolites	Expected bedrock
22	1	39.1	9.5	9.51	Top soil	Considerable overburden material
	2	5.1	13.8	23.4	Alluvial, colluvial and reworked volcanic ash	
	3	154	29.1	52.4	Slightly fractured Ignimbrites or Rhyolites	Expected bedrock
	4	0.96	∞	∞	Highly fractured and weathered Ignimbrites or Rhyolites/other rocks	Saturated
23	1	39.6	0.75	0.75	Top soil	Considerable overburden material
	2	17.7	2.35	3.1	Moist top soil	
	3	6.6	2.7	5.8	Alluvial, colluvial and reworked volcanic ash	
	4	74	∞	∞	Highly fractured Ignimbrites or Rhyolites/other rocks	Expected bedrock

24	1	76.1	0.75	0.75	Top soil	Considerable overburden material
	2	6.5	0.9	1.7	Moist top soil	
	3	129	14.6	16.3	Slightly fractured Ignimbrites or Rhyolites/other rocks	Expected bedrock
	4	959	20.1	36.4	Fresh to slightly fractured Ignimbrites or Rhyolites/other rocks	
	5	10.8	∞	∞	Highly fractured Ignimbrites or Rhyolites/other rocks	
25	1	56.3	0.85	0.85	Top soil	Considerable overburden material
	2	20.4	1.1	2	Moist top soil	
	3	38.8	24.9	26.8	Highly fractured Ignimbrites or Rhyolite	Expected bedrock
	4	200	∞	∞	Moderately fractured Ignimbrites or Rhyolite	
26	1	45.4	0.9	0.9	Top soil	Considerable overburden material
	2	5.5	1.2	2.1	Moist top soil	
	3	51.7	2.1	4.3	Dense top soil	
	4	7.5	41	45.1	Alluvial soil and reworked volcanic ash	
		202	∞	∞	Moderately fractured Ignimbrites or Rhyolite	Expected bedrock
27	1	9.8	1.1	1.1	Top soil	Considerable overburden material
	2	59.9	1.3	2.4	Top soil	
	3	26.3	12.1	14.5	Highly to moderately fractured basalt	Expected bedrock
	4	535	∞	∞	Slightly fractured basalt	
28	1	111	0.75	0.75	Dry top soil	Considerable overburden material
	2	35.5	1.5	2.2	Top soil	
	3	9.2	7.6	9.8	Reworked volcanic ash	
	4	23.5	∞	∞	Highly fractured Ignimbrites or Rhyolites/other rocks	Expected bedrock
29	1	70.3	3.1	3.1	Top soil	Considerable overburden material
	2	38.9	8.1	11.2	Alluvial soil	
	3	11.6	37.3	48.5	Alluvial soil and reworked volcanic ash	
	4	1234	∞	∞	Fresh bedrock	Expected bedrock
30	1	77.7	0.75	0.75	Top soil	Considerable overburden material
	2	61.2	7.28	8.0	Highly fractured Ignimbrites or Rhyolites	Expected bedrock
	3	34	14.3	22.3	Highly fractured Ignimbrites or Rhyolites; Saturated	
	4	527	∞	∞	Slightly fractured Ignimbrites or Rhyolites	
31	1	38.4	5.2	5.2	Top soil	Considerable overburden material
	2	10.3	35.8	41	Highly fractured Ignimbrites or Rhyolites; Saturated	

	3	928	∞	∞	Slightly fractured Ignimbrites or Rhyolites/other rocks	
32	1	13.5	15.7	15.7	Top soil	Considerable overburden material
	2	62	52.7	68.4	Highly fractured Ignimbrites or Rhyolites	
	3	18.1	∞	∞	Slightly fractured Ignimbrites or Rhyolites/other rocks	
33	1	323	0.84	0.84	Top soil	Considerable overburden material
	2	120	9.3	10.1	Alluvial soil and reworked volcanic ash	
	3	530	10.5	28.6	Slightly fractured Ignimbrites or Rhyolites/other rocks	Expected bedrock
	4	14.8	44.5	73.1	Highly fractured Ignimbrites or Rhyolites/other rocks	
	5	1800	∞	∞	Fresh to slightly fractured Ignimbrites or Rhyolites	
34	1	10.8	1.3	1.3	Top soil	Considerable overburden material
	2	57.8	13.7	15	Alluvial soil and reworked volcanic ash	
	3	328	∞	∞	Slightly fractured Ignimbrites or Rhyolites/other rocks	Expected bedrock
35	1	6.1	13.7	13.7	Top soil	Considerable overburden material
	2	4574	∞	∞	Highly fractured Ignimbrites or Rhyolites	
36	1	30.7	1.2	1.2	Top soil	Considerable overburden material
	2	21.8	23.8	25	Alluvial soil and reworked volcanic ash	
	3	1839	∞	∞	Slightly fractured ignimbrites or rhyolites	Expected bedrock
37	1	60.4	2.15	2.15	Top soil	Considerable overburden material
	2	5.1	1.25	3.14	Moist top soil	
	3	72	9.39	12.8	Alluvial soil and reworked volcanic ash	
	4	18.5	∞	∞	Highly fractured Ignimbrites or Rhyolites; saturated	Expected bedrock
38	1	649	0.5	0.47	Dry top soil	Considerable overburden material
	2	65.4	1.2	1.7	Moist top soil	
	3	33.1	8.3	10	Alluvial soil and reworked volcanic ash	
	4	311	∞	∞	Slightly fractured Ignimbrites or Rhyolites	Expected bedrock
39	1	15.4	17.4	17.4	Top soil	Considerable overburden material
	2	2526	∞	∞	Slightly fractured Ignimbrites or Rhyolites	Expected bedrock
40	1	63.8	1.7	1.7	Top soil	Considerable
	2	12.8	1.7	3.4	Moist top soil	
	3	91.7	2.3	5.6	Hard top soil	

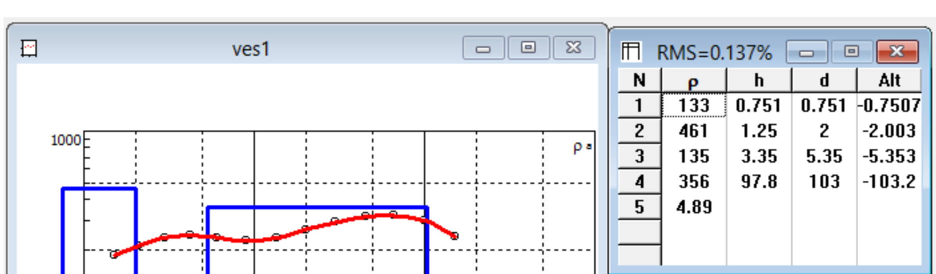
	4	6.54	11.2	16.8	Alluvial soil and reworked volcanic ash	overburden material
		325	∞	∞	Slightly fractured Ignimbrites or Rhyolites/other rocks	Expected bedrock
41	1	113.4	4.5	4.5	Top soil	Considerable overburden material
	2	172.3	4.4	8.9	Fractured Ignimbrites or Rhyolites or other rocks	Expected bedrock
	3	12.6	6.2	15.1	Highly fractured Ignimbrites or Rhyolites/other rocks; Saturated	
	4	191.3	∞	∞	Fractured Ignimbrites or Rhyolites/other rocks	
42	1	23.9	1.8	1.8	Top soil	Considerable overburden material
	2	9.8	7.6	8.4	Alluvial soil and reworked volcanic ash	
	3	2125	20.3	29.7	Massive Ignimbrites or Rhyolites/other rocks	Expected bedrock
	4	20.8	∞	∞	Highly fractured Ignimbrites or Rhyolites/other rocks; Saturated	
43	1	25.1	19.1	19.1	Top soil	Considerable overburden material
	2	461	∞	∞	Slightly fractured Ignimbrites or Rhyolites/other rocks	Expected bedrock
44	1	12.3	0.5	0.5	Top soil	Considerable overburden material
	2	72.5	1.5	2.0	Hard top soil	
	3	12.3	6.8	8.8	Alluvial soil and reworked volcanic ash	
	4	172	24.2	33	Fractured Ignimbrites or Rhyolites/other rocks	Expected bedrock
	5	310	∞	∞	Slightly fractured Ignimbrites or Rhyolites/other rocks	Expected bedrock
45	1	67.5	1.6	1.6	Top soil	Considerable overburden material
	2	12.1	26	27.6	Alluvial soil and reworked volcanic ash	
	3	372	∞	∞	Slightly fractured Ignimbrites or Rhyolites/other rocks	Expected bedrock
46	1	112	6.8	6.8	Top soil	Considerable overburden material
	2	10.1	21.7	28.5	Highly fractured Ignimbrites or Rhyolites/other rocks; saturated	Expected bedrock
	3	3272	∞	∞	Massive Ignimbrites or Rhyolites/other rocks	
47	1	57.4	2.6	2.6	Top soil	Considerable overburden material
	2	33.2	49.6	52.2	Alluvial soil and reworked volcanic ash	
	3	3733	∞	∞	Massive Ignimbrites or Rhyolites/other rocks	Expected bedrock
48	1	27.3	3.55	3.55	Top soil	Considerable overburden material
	2	422	5.4	8.9	Alluvial soil and reworked volcanic ash	

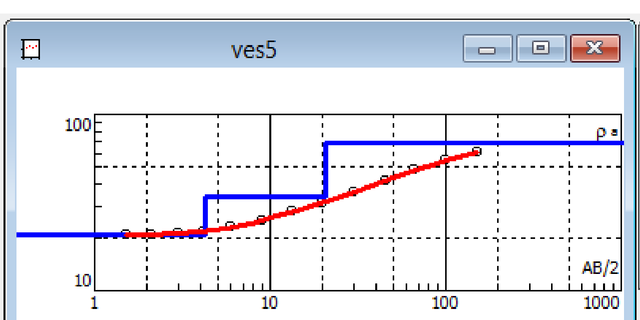
	3	8.5	13.7	22.6	Highly fractured Ignimbrites or Rhyolites or basalt;	Expected bedrock
	4	11021	∞	∞	Massive Ignimbrites or Rhyolites/other rocks	
49	1	27.5	3.7	3.7	Top soil	Considerable overburden material
	2	382	6.6	10.3	Fractured Ignimbrites or Rhyolites/other rocks	Expected bedrock
	3	8.6	18.2	28.5	Highly fractured Ignimbrites or Rhyolites/other rocks	
	4	6342	∞	∞	Massive Ignimbrites or Rhyolites/other rocks	
50	1	19.2	0.52	0.52	Top soil	Considerable overburden material
	2	170	0.45	0.97	Dry top soil	
	3	30.6	59.7	60.7	Highly fractured Ignimbrites or Rhyolites/other rocks; saturated	Expected bedrock
	4	3164	∞	∞	Slightly fractured Ignimbrites or Rhyolites/other rocks	
51	1	73.8	0.42	0.42	Top soil	Considerable overburden material
	2	4.2	0.83	1.24	Moist top soil	
	3	22.1	24.4	25.6	Alluvial soil and reworked volcanic ash	
	4	12663	∞	∞	Massive Ignimbrites or Rhyolites/other rocks	Expected bedrock
52	1	226	9.14	9.14	Top soil	Considerable overburden material
	2	62.7	8.4	17.5	Highly fractured Ignimbrites	Expected bedrock
	3	293	25.1	42.6	Moderately fractured Ignimbrites or Rhyolites/other rocks	
	4	34.7	54.6	97.2	Highly fractured Ignimbrites or Rhyolites/other rocks	
	5	3431	∞	∞	Massive ignimbrite or rhyolite or other rocks	
53	1	65.9	0.97	0.97	Top soil	Considerable overburden material
	2	363	0.77	1.7	Dry top soil	
	3	43.9	33.5	35.3	Slightly fractured Ignimbrites or Rhyolites/other rocks	Expected bedrock
	4	976	31.4	66.7	Moderately to slightly fractured Ignimbrites or Rhyolites/other rocks	
	5	9.8	∞	∞	Highly fractured Ignimbrites or Rhyolites/other rocks; saturated	
54	1	12.5	0.7	0.7	Top soil	Considerable overburden material
	2	14.8	8.5	9.2	Alluvial soil	
	3	3.47	10.7	19.9	Reworked volcanic ash	
	4	58.1	17.9	37.7	Highly fractured Ignimbrites or Rhyolites/other rocks	Expected bedrock
	5	4.5	∞	∞	Saturated and highly fractured Ignimbrites or Rhyolites/other rocks	

55	1	25.4	1.9	1.9	Top soil	Considerable overburden material
	2	5.3	2.3	4.2	Highly fractured Ignimbrites or Rhyolites/other rocks	Expected bedrock .
	3	55.4	34.7	38.9	Highly fractured Ignimbrites or Rhyolites/other rocks	
	4	9867	∞	∞	Massive Ignimbrites or Rhyolites/other rocks	
56	1	73	1.3	1.3	Top soil	Considerable overburden material
	2	34.4	6.3	7.6	Alluvial deposit	
	3	7.6	30.8	38.5	Weathered Scoria, tuff or welded tuffs	Expected bedrock
	4	234.9	91.4	129.8	Slightly weathered and fractured basalt	
	5	353.3	88	217.8	Fresh, hard and Massive basalt	
	6	112.7	∞	∞	Weathered / fractured scoraceous basalt	
57	1	107.8	1	1	Top soil	Considerable overburden material
	2	39.8	4.5	5.5	Alluvial deposit	
	3	24.7	87.1	92.7	Highly weathered ignimbrites, tuffs	Expected bedrock
	4	105.4	95.6	188.2	Weathered / fractured scoraceous basalt	
	5	174.8	53.3	241.5	Slightly weathered or fractured basalt	
	6	122.6	∞	∞	Weathered / fractured scoraceous basalt	
58	1	65.6	1.7	1.7	Top soil	Considerable overburden material
	2	24.4	8.2	9.9	Alluvial deposit	
	3	158.9	27.4	37.3	Slightly weathered/ fractured Scoria, tuff or welded tuffs.	Expected bedrock
	4	35.8	90.3	127.6	Highly weathered and fractured ignimbrites, basalt	
	5	103.5	79.1	206.7	Weathered / fractured scoraceous basalt	
	6	376.6	∞	∞	Fresh and massive basalt	
59	1	83.20	2.0	2.0	Top soil	Considerable overburden material
	2	38	12	14	Alluvial deposit	
	3	12.9	88.8	102.9	Weathered Scoria, tuff or welded tuff	Expected bedrock
	4	68.6	70.9	173.8	Weathered / fractured scoraceous basalt	
	5	216.4	∞	∞	Slightly weathered or fractured basalt	
	6	83.20	2.0	2.0	Top soil	
60	1	63.7	2.2	2.2	Top soil	Considerable overburden material
	2	13.4	5.8	8	Alluvial deposit	
	3	169.2	77.8	85.8	Scoria, hard basalt	Expected bedrock

	4	37.9	85.8	171.6	Weathered ignimbrite, tuff and basalt	
	5	70.1	50.8	222.4	Highly weathered and fractured ignimbrites, basalt	
	6	22.7	∞	∞	Highly Weathered / fractured scoraceous basalt	
61	1	44.8	1.6	1.6	Top soil	Considerable overburden material
	2	26.9	14	15.6	Alluvial deposit	
	3	191.3	63.3	78.9	Moderate to slightly weathered ignimbrite, basalt	Expected bedrock
	4	139.5	89.1	158	Slightly weathered / fractured basalt	
	5	32.8	∞	∞	Weathered / fractured scoraceous basalt	
62	1	98.2	1.4	1.4	Top soil	Considerable overburden material
	2	59.2	9.6	11	Alluvial deposit	
	3	54.5	23.6	34.6	Tuff, highly weathered ignimbrite	Expected bedrock
	4	288.7	51.1	85.7	Moderately to slightly fractured basalt	
	5	85	43.2	128.9	Weathered / fractured scoraceous basalt,	
	6	588.2	∞	∞	Moderately to slightly fractured basalt	
63	1	84.3	1	1	Top soil	Overburden material
	2	36.8	11.2	12.2	Alluvial deposit	
	3	136	70.2	82.4	Slightly weathered / fractured basalt	
	4	96.6	121.6	204	Weathered / fractured scoraceous basalt, probably some aquifer at its base	
	5	317.4			Massive basalt	

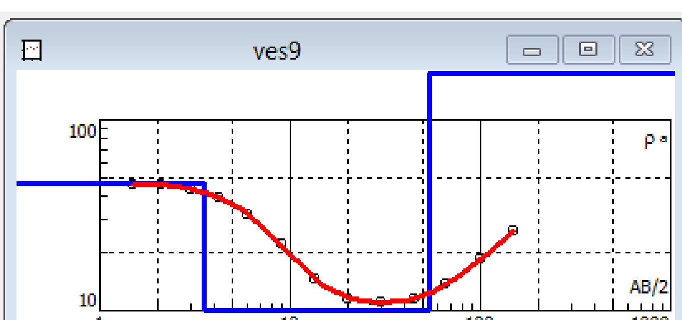
Appendix C-2: VES Model Curves with layer resistivities and thicknessess





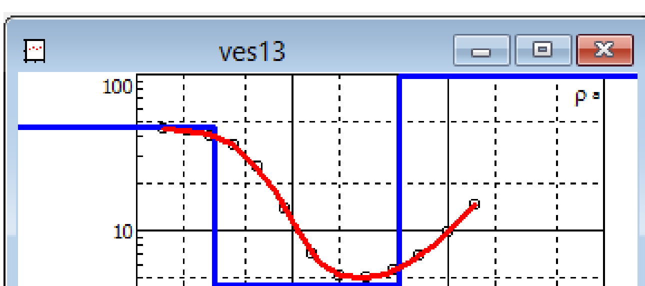
RMS=0.0172%

N	ρ	h	d	Alt
1	20.7	4.3	4.3	-4.296
2	34.3	16.4	20.7	-20.74
3	69.1			



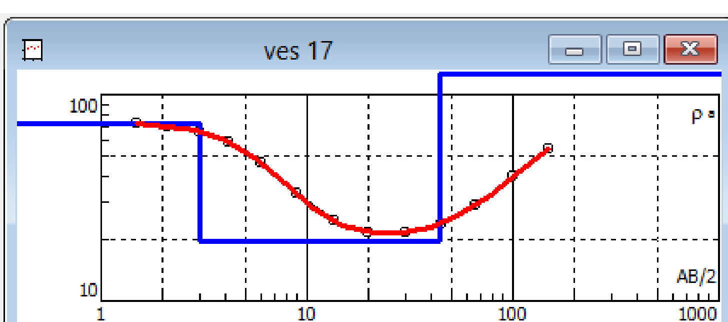
RMS=0.0773%

N	ρ	h	d	Alt
1	46.7	3.53	3.53	-3.529
2	10	50.2	53.8	-53.76
3	197			



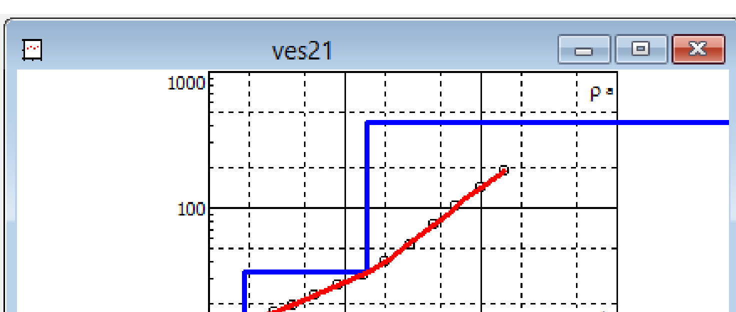
RMS=0.183%

N	ρ	h	d	Alt
1	46	3.16	3.16	-3.161
2	4.48	45.4	48.6	-48.6
3	1536			



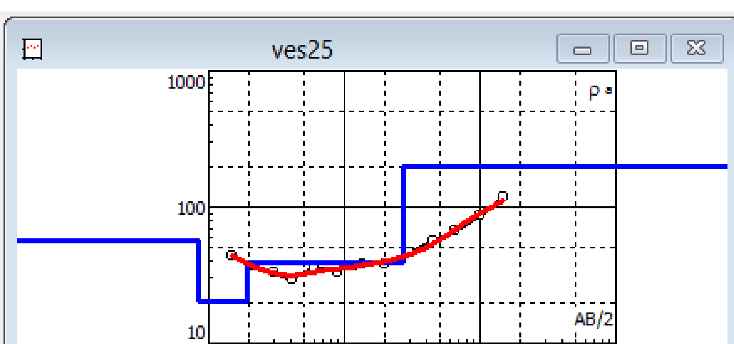
RMS=0.0728%

N	ρ	h	d	Alt
1	72.9	3	3	-3
2	19.4	41	44	-44.04
3	218			



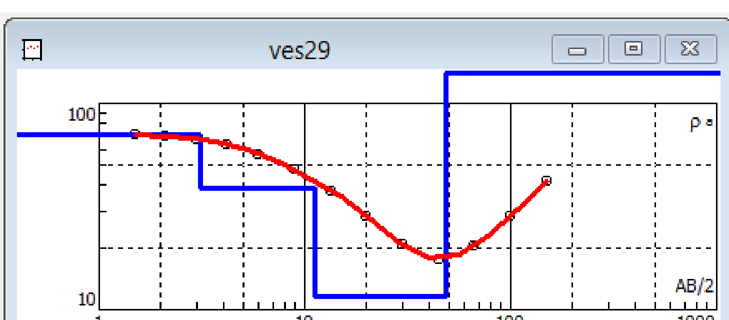
RMS=0.0219%

N	ρ	h	d	Alt
1	13.6	1.84	1.84	-1.838
2	34	12.6	14.5	-14.47
3	426			



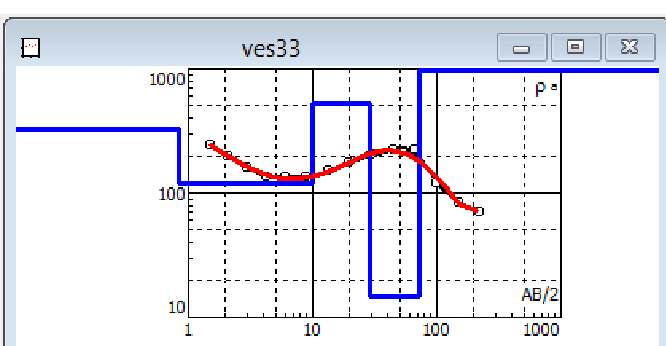
RMS=3.81%

N	ρ	h	d	Alt
1	56.3	0.852	0.852	-0.8522
2	20.4	1.09	1.94	-1.938
3	38.8	24.9	26.8	-26.79
4	200			



RMS=0.0777%

N	ρ	h	d	Alt
1	70.3	3.1	3.1	-3.104
2	38.8	8.07	11.2	-11.18
3	11.6	37.3	48.5	-48.47
4	1234			



RMS=4.16%

N	ρ	h	d	Alt
1	323	0.836	0.836	-0.8357
2	120	9.31	10.1	-10.15
3	530	18.5	28.6	-28.61
4	14.8	44.5	73.1	-73.07
5	1800			

Appendix D: Lithological log of boreholes used for interpretation of VES data

Appendix-D-1

Borehole number 1

Location: x = 530883, y = 949478, z = 1701m

Site name: Daka Adi

Static water level: 173 meter

Depth interval (m)	Total thickness (m)	Lithological description
0-1	1	Light brown soil
1-39	38	Lacustrine sediments
39-41	2	Highly weathered massive basalt
41-47	6	Slightly weathered dark brown vesicular basalt
47-58	11	Dark brown vesicular basalt
58-76	18	Ignimbrite
76-88	12	massive rhyolite
88-93	5	Volcanic sediments
93-114	21	Trachytic tuff
114-132	18	Weathered brown ignimbrite
132-138	6	Greenish ignimbrite
138-144	6	Fractured basalt
144-150	6	Fractured ignimbrite
150-162	12	Weathered scoracious basalt
162-174	12	Volcanic product
174-180	6	Slightly weathered dark brown scoracious basalt
180-186	6	Dark massive rhyolite
186-192	6	Slightly weathered rhyolite
192-207	5	Rounded unconsolidated granular sediments
207-224	17	Coarse-grained consolidated sediments
224-226	2	Fine sand
226-240	14	Fractured ignimbrite

Appendix-D-2

Borehole number 2

Location: x = 531205, y= 946090, z=1660m

Site name: In Adama Science and Technology University (ASTU) compound

Static water level: 174 meter

Depth interval (m)	Total thickness (m)	Lithological description
0-14	14	Silty sand
14-28	14	Medium sand
28-52	24	Medium to coarse sand
52-58	6	Highly weathered ignimbrite
58-74	16	Moderately weathered ignimbrite
74-88	14	Massive ignimbrite
88-110	22	Massive basalt
110-112	2	Pumice
112-120	8	Massive basalt
120-130	10	Ash
130-152	22	Massive ignimbrite
152-172	20	Fractured ignimbrite
172-184	12	Highly weathered ignimbrite
184-190	6	Fractured ignimbrite
190-202	12	Highly weathered basalt
202-248	46	No sample
248-294	46	Highly weathered ignimbrite filled with secondary materials
294-304	10	Massive and fractured basalt