GEOTECHNICAL AND ENGINEERING GEOLOGICAL INVESTIGATION OF SIBILU DAM SITE, RESERVOIR AND CATCHMENT AREA

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IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF MASTER OF SCIENCE IN GEOLOGY

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GEOTECHNICAL AND ENGINEERING GEOLOGICAL INVESTIGATION OF SIBILU DAM SITE, RESERVOIR AND CATCHMENT AREA

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ABSTRACT

In Sibilu dam catchment geomorphological, geological hydrological and engineering geological studies were conducted to characterize the limitation and importance of the area for the new dam construction.

Using mainly the aerial photos and topo-maps of the area relief and landform, slope and geomorphological maps of the catchment are produced at the scale of 1:50,000. Topographic features clearly show that all surface water converges to the reservoir. Hydrological evaluations also indicate that there is no out flow of groundwater from the catchment through other routes, which is in favor of the reservoir condition.

Geological maps of Sibilu catchment and reservoir area are produced at the scale of 1:50,000 and 1:12,500 respectively. Basalt, trachyte, pyroclastic deposits, rhyolite, ignimbrite and recent Quaternary deposits are exposed in the area. The structural features of the catchment are mapped from aerial photograph interpretations. The NW-SE and NE-SW lineaments are found to be the dominant lineaments in the catchment. But the measurements and interpretation of the joint sets orientations in the reservoir area, conformed that the N-S and E-W are the dominant joint sets over NW-SE and NE-SW. Beside their concentration these joint sets, especially the E-W, are open and continuous.

The rock and soils units of the reservoir were described using their lithology and genetic type as the main classes for engineering geological purpose. But detail engineering geological descriptions relay on the assemblage of basic engineering behaviors of these main groups. So eight engineering geological subgroups of the rock units are identified by their textural, joint and compaction natures: aphanatic, scoracious, vesicular and halocrystalline basalts; massive and columnar jointed trachyte; unwelded friable and welded pyroclastic deposits. Rock units in the area are fractured and jointed by different sets. The strength of basaltic rock ranges from strong to extremely strong with weathering grades of I to IV. Columnar trachyte show very strong nature and weathering grade II. Welded

pyroclastic deposits and massive trachyte show medium strong nature with weathering grades of II and IV respectively. Friable pyroclastic deposit is the only rock unit show weak mass strength. Soil units were described into five engineering geological subgroups using their grain size distributions and index limits: clay, silty clay, sandy clay, gravelly clay and clayey gravels. Clays have 1-3% gravels, 3-9% sands, 25-32% silts and 57-68% clay fractions; with 65-106% liquid limit, 30-85% plastic limits and shrinkage limit 8-15%. Silty clays have 4-5% gravels, 6-11% sands, 37-41% silts and 46-51% clay fractions; with 28-34% liquid limit, 5-6% plastic limit and 51-57% shrinkage limit. Sandy clays have 2-4% gravels, 38-39% sands, 22-25% silts and 34-36% clay fractions; with 43-48% liquid, limit 12-18% plastic limit and 20-25% shrinkage limit. Gravelly clays have 22-31% gravels, 13-17% sands, 23-24% silts and 31-39% clay fractions; with 31-38% liquid limit, 6-11% plastic limit and 15-19% shrinkage limit. Clayey gravels have 54-61% gravels, 8-18% sands, 16% silts and 12-15% clay fractions.

With these descriptions, it was possible to classify rock units as high, medium and low rock mass strength; and soils classified using the UCS as inorganic clays of high to extremely high plasticity (CV, CE, CH); organic clay of high plasticity (OH); inorganic silts and clays of low plasticity (CL, ML); inorganic silts of intermediate plasticity (MI) and clayey gravels, poorly graded gravel-sand-clay mixtures (GC). All these are presented on the engineering geological map of the reservoir area at the scale of 1:12,500.

Black clay soils are found in flat terrains with poor drainage conditions, while red clay soils were developed on sloppy and gentle areas with good drainage conditions. These soils have formed over the volcanic rocks in the area. Chemical analysis shows that the black clays have an average of 41% silica, 14.1% of total iron and 25.7% of alumina. Red clays have got an average of 34% silica, 24.5% of total iron and 24.9% of alumina. The average composition of basalts of the Ethiopia plateau (Barth, 1962) is 44% silica, 13% of total iron and 9% of alumina. Through this, it is clear that the loss of silica in black clays is slight, but more evident in red clays. Their physical geotechnical analysis exhibits that black clay soils show moisture content of 38.75-57.2%, liquid limit of 89-106% and 69-83 plasticity index and have 57-68% clay fractions. While the red clay soils with 28.6-47% moisture

content, 28-70% liquid limit and 5-32 plasticity index have 34-65% clay fractions. In the plasticity chart most of the black clay soils plot near U-line and the red clays at and below A-line. Comparison of the activity of these soils indicates that black clay soils are more active than the red clay soils. Most of the black clay soils are also potentially expansive while the red clays do not.

The black clay soils contain montimorillonite and red clay soils contain kaolinite as the principal and dominant clay minerals in the reservoir. The main concern of dealing the clay minerals in the dam engineering is to define their dispersivity and the black clay soils, contain high montimorillonite, are found to be potentially dispersive.

Sibilu reservoir intersects ridges and hills, which shows small-scaled mass movements. The tectonic and weathering features on these terrains seem not to create considerable problems for the reservoir and dam conditions. But the one on the Asere ridge liable to cause stability and storage problems during the establishment of the dam.

From the borehole data it was able to identify three geotechnical layers in the dam site: soil materials; highly weathered and fragmented basalts; and jointed sound basalt.

The rock and soil materials for the construction of the dam are almost available in the vicinity of the area. For the clay core the reservoir soils are examined and the red clay soils are preferred than the black clay soils by their geotechnical properties. The Buba hills basalts fulfill the requirements as the construction material for the dam. In the construction materials only sands for filter material are not available in the surrounding area.

CHAPTER-1 INTRODUCTION

1.1. Back Ground

The importance of geology in engineering practice is highly appreciated for large hydraulic structures, particularly during the investigation and construction of dams and tunnels where many relevant problems are closely associated with the geological conditions of the area. Investigation is not limited to the dam site only, but it must also involve the reservoir and catchment area in order to gather enough and reliable information for the success of the project. The studied area, the Sibilu catchment, is the catchment of the newly proposed rock-fill dam site to solve the Addis Ababa water supply problem. In this new dam site different consultants conducted investigations, however there is no final report. The present work is designed to support the final and detail geotechnical investigation.

Despite many works done on the dam site, there is no engineering geological map in the reservoir and the catchment. To achieve this basic requirement and characterizing the geologic materials of the area, it was desired to study the engineering geological properties of the rocks and soils of the area. Soils, which are the weathering products of volcanic rocks, are the most wide spread types of soils that cover the Sibilu catchment. Studying the environmental and geological influence of these soils, on the genesis and engineering geologic properties, is crucial in understanding their importance and limitation in the engineering practices. The influences of these factors on the physical properties of soils are the main concern in engineering geology. There is also a vital need in identifying the type of clay minerals and their effect on the dam engineering of the area.

In addition, there is an increasing practical interest in characterizing the geotechnical properties of the clay soils comparing with tropical soils. All these considered initiating this research on the Sibilu dam catchment.

1.2. Location and Accessibility

The Sibilu dam site is located west of Chancho, a small town situated along Addis Ababa-Debre Markose road at a distance of 45 km from Addis Ababa. Its catchment is found in the central part of the Ethiopian plateau bounded by the Entoto ridges to the south and basaltic ridge to the east. It is enclosed within the limits of $9^0$05"-$9^0$18" N latitude and $38^0$33"-$38^0$50"E longitude (Fig.1.1). The catchment covers 486 km^2, while the reservoir area, which lies within the Sululta plain, covers 33.6 km^2.

The Addis Ababa-Chancho road constitutes the major access to the study area. A dry weather road from Chancho to Derba that branch off the main road reaches the dam site. The reservoir area is also accessed by different subsidiary dry weather roads. As a whole, accessibility in the area is good.

1.3. Physiographic Setting

The Studied area lies in the central part of the Ethiopian plateau in the southeastern Abay basin. It extends westward into Eastern Wollega and forms a crescent shape that drains into the Abay River to the north. Except with fewer scattered hills and ridges, most of the catchment is nearly flat and surrounded by continuous Entoto rhyolitic and basaltic ridges to the south and east respectively i.e. it is dominated by flat plain with undulating topography. Elevation generally drops towards the north (Mohr, 1967). It is mainly bisected by the Sibilu River, which originates from the Entoto Range. In the reservoir area, the Sibilu River meanders in the flat-lying Sululta plain. Most of the streams that drain the studied catchment flow to the northeast or northwest and are dry except in the main rainy season.

Vegetation is sparse consisting mainly Eucalyptus and Acacia tree together with scattered bushes and minor other kind of plants which is mostly concentrated in the mountainsides of Entoto ridge. The flat plain part of the catchment is mainly a pastureland and crops with scattered trees. The Sibilu reservoir, at present, is being used mainly for grazing and small scale farming by local people i.e. the low lying areas are left for grazing while the relatively high areas on the gentle slopes are generally cultivated.

1.4. Previous Works

Relevant investigations were carried out since 1984 when the need of water supply for the Addis Ababa became an important issue. The previous studies made on the Sibilu Dam and reservoir include preliminary identification of regional water resource by Addis Ababa Water Supply and Sewerage Authority (AAWSA) project stage II, (1984); feasibility study by SEURECA (French consultant) associated with British consultant- Sir Alexander and Patress, (1991) and part of detail investigation by AE- HBT Joint Venture which was interrupted without finalized report.

Morin and Parry (1971) investigated the geotechnical properties of Ethiopian volcanic soils, to which the studied area is included. The regional geology of the area were described by many authors: Mohr (1967, 1971), Zanettin *et al.* (1973, 1974, 1977), Kazmin *et al.* (1975), Morton *et al.* (1979), and Haile Sellase Girmay and Getaneh Assefa (1989).

There is also unpublished recent geological work in the area done by Tefera Eshete (1995), which was sponsored by Ethiopian Geological survey (EIGS) and AAWSA.

1.5. Objective of the Work

The main objectives of the present study are:

- To map and analyze the engineering geological and geotechnical properties of geological materials and structural features in the catchment, reservoir and dam site of Sibilu Dam.
- To identify and examine the clay soils minerals and their effects in the reservoir and foundation conditions of the dam.
- To assess construction materials for the proposed dam structures.

Under these basic objectives more emphasis is given to:

- Describing and classifying the rocks and soils of the reservoir area according to their engineering geological properties to produce engineering geological map,
- Defining geotechnical properties of different clay soils in the reservoir area,
- Identifying clay minerals in the reservoir and dam site to discuss their effects on the construction of the dam and,

- Describing the limitations and importance of the available clay soils as the construction materials for the dam.

1.6. Materials and Methods

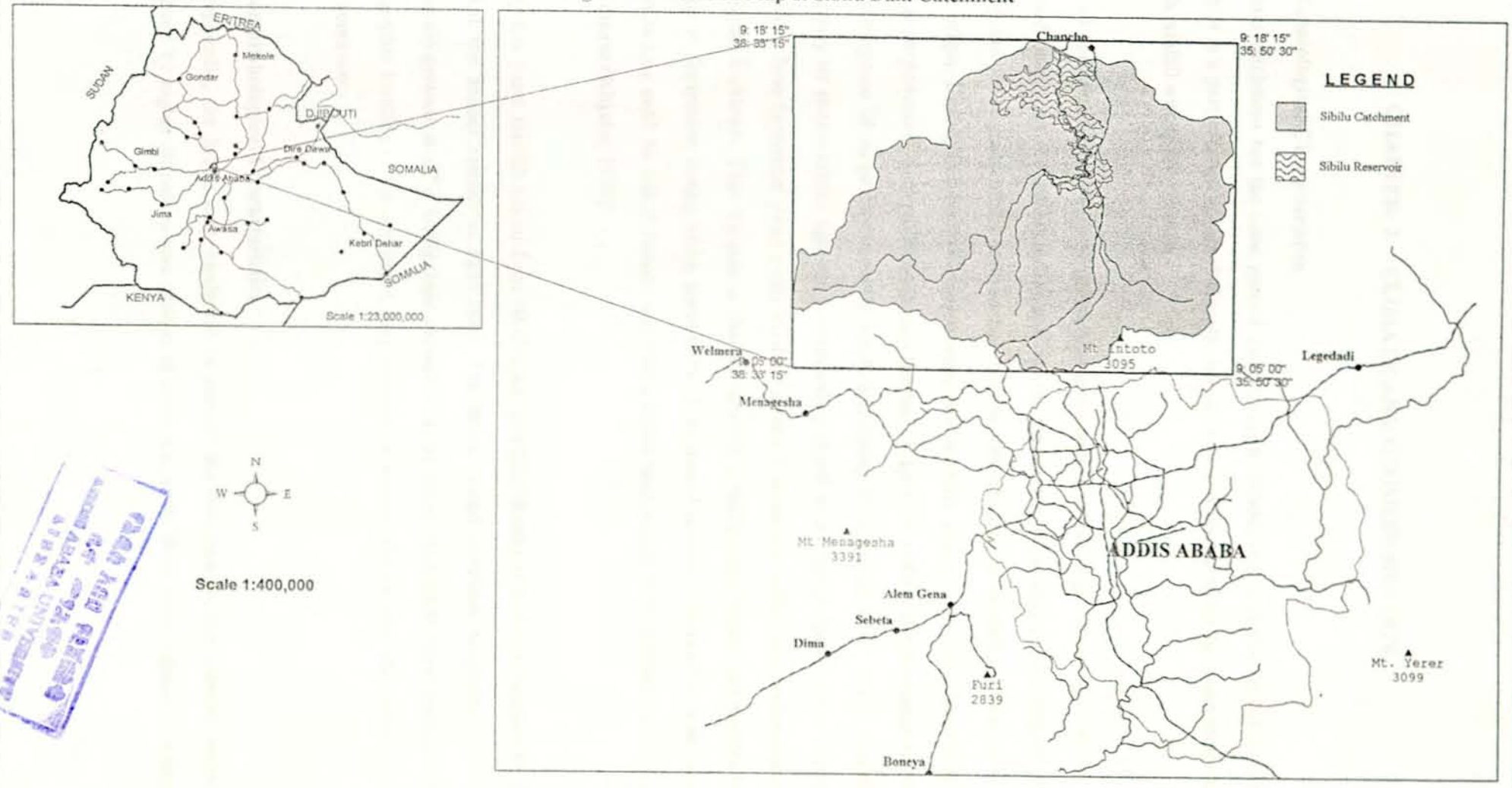
This work was carried out using different materials and equipments.

- Eighteen aerial photos of the catchment and Twenty-four of reservoir area produced by the Ethiopian Mapping Agency in 1974 and 1996 at the scale of 1:50,000 and 1:8,000 respectively.
- Topographic maps (North east A.A., North west A.A., Derba and Chancho sheets).
- Geological map of Addis Ababa at the scale of 1:50,00 by Morton *et al.*, 1979.
- GPS (garmin model) to locate the area during field works.
- Compass and meter scales to measure structural features.
- Geological picks and hammer in assessing the strength of rock mass.

Preliminary interpretation of aerial photographs and preparation of base maps were done in the office, followed by a fieldwork, which was conducted, from April 24 to May 03, 1999. During the fieldwork surface mapping, structural measurements, simple field manual insitu testing and sampling were conducted. Twenty soil samples for physical and geotechnical analysis, eight soil samples for chemical analysis and three water samples from surface/river, spring and dug well were taken and analyzed in Kajima site office laboratory, National Soil Laboratory and EIGS laboratory respectively. Other data like hydrometerological data of the three stations (Addis Ababa Observatory, Entoto and Chancho) and Sibilu river discharge data were collected from the Ethiopian Metrological Service Agency and Ethiopian Valleys Development Studies Authority respectively.

Data processing and presentation was done with the help of different computer softwares; word text documents using Microsoft Word; synthesis of hydrometerological data using EXCEL; digitizating and editing of maps using AtlasGIS; graphs, charts and section plotting using AutoCAD R.14; and plotting of rose diagrams using SsWin geo-soft.

Figure 1.1 Location Map of Sibilu Dam Catchment



CHAPTER- 2 CLIMATE AND GEOMORPHOLOGY

2.1. Climatological Characteristics

The Sibilu catchment has the same general climatological characteristics as that of Addis Ababa. Globally it is a part of tropical humid climatic region, which is characterized by warm temperature and high rainfall with higher altitude.

The broad climatic characteristics of the studied area, with its alternating wet and dry seasons, are determined largely by the annual movements across the country of equatorial low pressure zones caused by the convergence of dry north-easterly winds with moist winds of south-easterly or south-westerly origin. During October to February when northeasterly winds persist long periods of dry weather are experienced. Between February and the end of April the weather becomes more unsettled and a convergence of moist south-easterly winds originating from Indian ocean with a weakening north-easterly air stream causes light rains–commonly referred to the "Belge Rains". The main rains falls between June-September when moist winds from the Atlantic and Indian oceans converge over the Ethiopian highlands. Thus the year is characterized by a major rainy season four months long, from June to September, during which about 65% of the annual rainfalls, followed by a dry season four months long until the end of January and then a minor rainy season from February to the end of April (Admasu Gebyehu, 1996).

A twenty-five years rainfall record from NMSA for Sibilu catchment is analyzed (chapter 4). It is found that the annual rainfall is 1228.3mm. The mean annual minimum temperature 8°c and maximum temperature is 18° c. Using these average climatic values, its altitude above mean sea level and geographic location of the catchment, it is possible to suggest that the area has humid tropical climatic condition.

2.2. Geomorphological Characteristics

Physiographically, the Sibilu dam catchment is part of the Ethiopian central plateau, which is characterized by higher altitude (above 2000m of mean sea level). With fewer peaks at the Entoto

ridges, most of the catchment consists of plains covered by clays. It is dominated by flat to undulating topography with a general elevation drop towards the north. The reservoir and surrounding area characterized by scattered hills and ridges with flat flood plain (Mohr, 1967). On the far south and east the catchment is bounded by east-west trending Entoto range and a series of basaltic mountains respectively.

The altitude of the catchment varies between 2530m above mean sea level (a.m.s.l.) at the riverbed at the dam site and 3180m a.m.s.l. at its highest point of the Entoto Mountain. Over 60% of the total catchment area is above 2600m a.m.s.l. while the reservoir is below towards which the surface water converges.

The Sibilu dam catchment has got different landforms, which is associated with volcanism i.e. the topographic features of the study area are the results of young volcanism (Kazmin, 1975). The basaltic rocks cover most of the area (except the rhyolitic Entoto ridges to the south) and govern the macro relief conditions. The Sululta plain covers 65% of the total area, which is generally flat with an undulating micro relief. The scattered hills are without craters and rise to the maximum average of 40m above the plain while the Entoto ridge is built by an accumulation of lavas and ash eruptions which show asymmetrical nature, with a steep front on the Sibilu side i.e. faulted and relatively gentle slope on the Addis Ababa side (Lulseged Ayalew, 1990).

The landscape of the study area is further obliterated by weathering and erosion giving rise to the different slope types and soil formations. At places, erosion produces many steep-sided gullies and ravines on the hill slopes. This is due to high concentration of the runoff in the southern part, which rapidly decreases toward the flat area. It also affects most of the rock bodies and still acts in the mountainous areas to accumulate thick layer of soils in the low-lying areas. The soil development in the reservoir flat area is alluvial while the rest is residual.

In the Entoto ridges, slope movements that are acted under the influence of gravity and water actions (include creep, slide, and fall) are also observed and able to modify the morphology even more. As a

whole, the southern and eastern part of the watershed is characterized by steep slope and rough top surfaces (at places the highland plateaus with flat surface are observed), while the hills in the Sululta plain show gentle slopes. Almost all the lower part of the slope areas are covered by a thin layer of colluvial deposits.

2.2.1. Relief and Landforms

Landforms usually described using slope degree, type and processes responsible for their shape modification. The dominant slope is the most important criterion, followed by relief intensity (Graef, 1996). Four main types of landforms characterize the Sibilu catchment: level land, gently sloping land, steep land and composite landforms (Fig. 2.1).

A. Level Land: it covers 116.3 Km^2, which is mainly exposed in the northern and central part of the catchment area. It is bounded by steep land to the west, gently sloping land to the east and composite landforms to the south. It is composed of flat low lying plain with small hills and foot slopes. Structurally it is horizontal or nearly and bisected by the main perennial Sibilu River in the north-south direction which is flowing to the north. In the northern and central part of this level landform, the Sibilu River has a broad and flat-floored valley. This valley floor is much wider than the river channel and characterized by extensive floodplain, across which the river meanders. The flood plain is a wide flat plain of alluvium deposits and identified by its marshy condition with several swamps and some oxbows and meander scars. Its tributaries that are small and seasonal streams flowing in the east-west direction and also poorly dissected it.

The elevation of this landform varies between 2530m a.m.s.l. and 2604m a.m.s.l. i.e. its relief intensity (difference between highest and lowest elevation points within the land form) is 74m. It has a general, gradually descending slope of about 2% in the north direction. The east and west sides of the river sloped to the river with about 1% average slope.

In this landform groups there are scattered small hills (max. of 15m high above the plain) with the slope of 2-5% and grouped under gently undulating slopes according to FAO-UNESCO slope gradient classification, (1997) (table 2.1). The slopes are almost uniform and have longer length (0.8-2 km). The foot slopes, which are mostly covered by transported materials from slope land, are low

topographic relief and found immediately next to slope land in the west portion. Its slope is very gentle with about 1-3% and grouped as flat to gently undulating.

B. Gently sloping Land: it covers 81.1 Km^2, which comprises the southwestern and western part of the watershed. It bounded by composite landforms from southeastern side and level land from northeastern side. It is composed of gentle slopes and hill slopes with a small portion of the flat plateau at the top part. It is highly dissected by large seasonal streams, which are flowing in the northeastern direction, with marshy lands at the plateau.

Slope class	Slope gradient classification
0-2%	Flat
2-5%	Gentle undulating
5-8%	Undulating
8-15%	Rolling
15-30%	Moderately steep
30-60%	Steep
>60%	Very steep

Table 2.1. Different slope gradient classification, after UNESCO-FAO (1997)

The elevation of this landform varies between 2600m a.m.s.l. and 2720m a.m.s.l. i.e. its relief intensity is about 120m. It has a general slope of 15% descending to the east. The southern part of this landform, which consists of the flat plateau, has lower slope gradient 5-7%, while the central portion has higher gradient up to 20% at places.

The hill slopes of this landform are moderately steep slopes of 15-20%. The slopes are convex in nature and has relatively medium slope length (0.5-0.9 km), sometimes covered with unevenly distributed boulders of micro relief. The flat plateau, 1-2 km^2, is flat to gently undulating surface (1-4%). It is poorly drained marshy area.

C. Steep Land: Most of the steep sloped lands of the catchment are grouped under this landform type. It covers 153.5 Km^2, which is mainly exposed on the southern and eastern boundary of the catchment. Usually it is followed by the level landform. It is composed of sharp steep Entoto escarpments and steep gullied slopes of basaltic mountains in the east of the catchment. These mountains have been deeply dissected by radial valleys and exhibits large seasonal streams. The flow direction of these streams is to the north and west, for those, which originate from Entoto and basaltic mountains respectively.

The elevation of this landform varies between 2620m a.m.s.l. and 3180m a.m.s.l. i.e. its relief intensity is about 562m. It has a sharp descending slope of 32-65% to the north and to the west. The slope of the basaltic mountains is relatively gentle (38-50%) than the Entoto ridge (32-65%). All slopes grouped under steep to very steep.

The slopes of the steep land are convex in nature and show uniform slope direction. The slope length, shorter than other landforms in the drainage catchment, is 0.1-0.3 km. It is well drained. Erosion develops first on the upper slopes and represents the early stage of dissection followed by deep gully formation.

D. Composite Landform: it covers 131.8 Km^2, which comprise the south central part of the catchment. The level land in the north, gently sloping land in the south and eastern side, bound it. It is composed of different landforms i.e. hill slope, valley floor, plain and sloped parts without definite slope direction. Hence, within the area there is no dominant morphological feature and slope direction. It is dissected by four more or less straight perennial streams, which are almost parallel flowing in the N-S direction. The streams in this landform have steep sided valleys with V-shaped cross-section. The valley is also highly gullied.

The elevation of this landform varies between 2547m a.m.s.l. and 2788m a.m.s.l. i.e. its relief intensity is 241m. It has high range of slope gradient 1-72%, with relatively variable slope lengths. There is no defined slope direction in this landform.

Plateau of this landform are flat with slope gradient of 1% but higher altitude than the plain. The hill slopes are gentler than the valley slopes, which are the steepest in the catchment (60-72%).

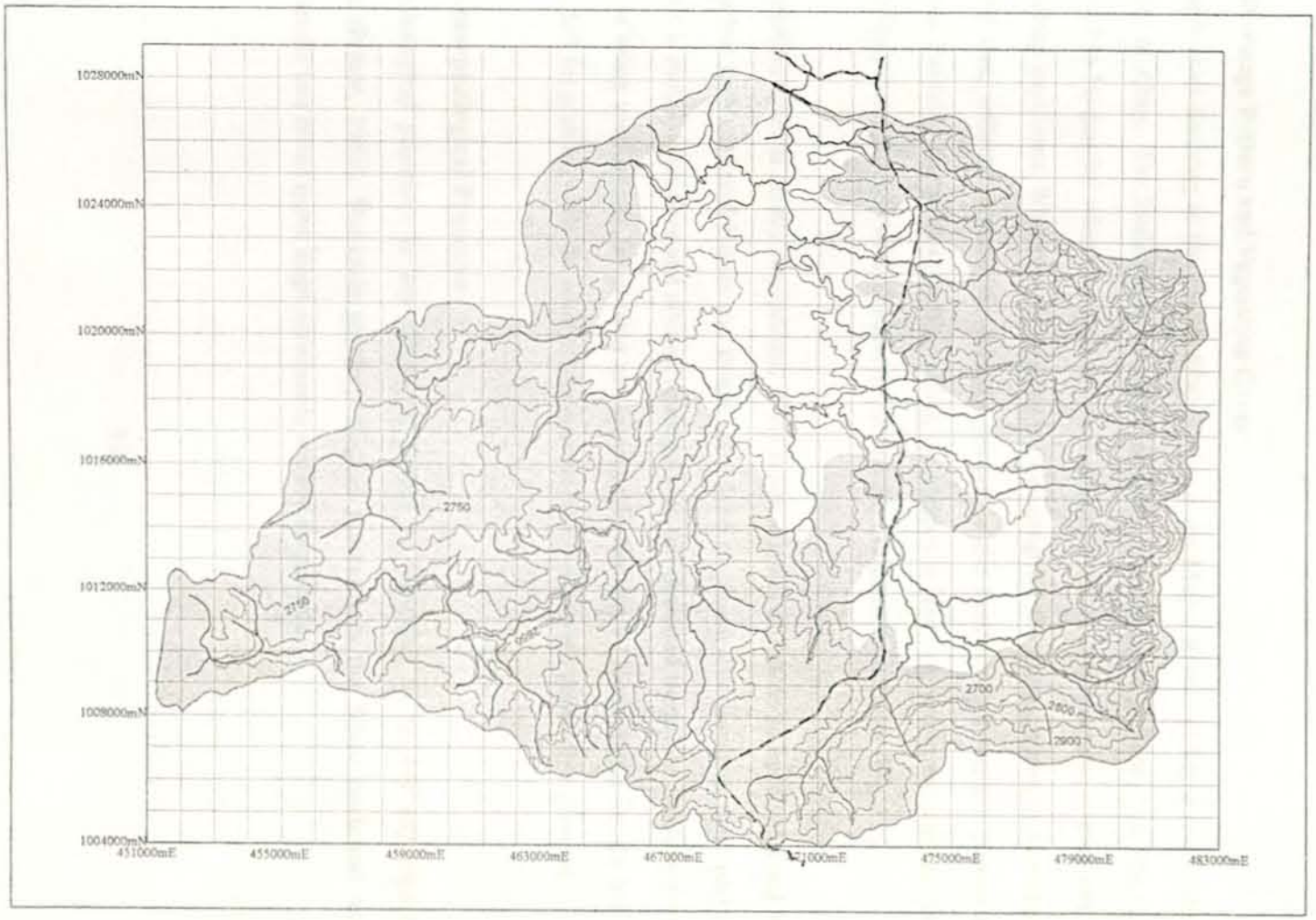


Figure 2.1 Landforms and Relief Map of Sibilu Catchment

(reduced from 1:50,000 scale)

N
W E
S

Scale: 1:200,000

LEGEND

- Level land
- Gently sloping land
- Steep land
- Composite landform
- Reservoir area
- Dam site
- Road
- Rivers / streams
- Contour lines

The slopes in this land show different nature, convex faced and has irregular trend. The valley floors represent the lowest relief in this landform. Generally this group shows irregular topographic relief.

Landform group	Area cover	Relief intensity	Slope class	Slope length
Level land	116.3 km^2	74m	1-5 %	0.8-2 km
Gently sloping land	81.1 km^2	120m	5-20 %	0.5-0.9 km
Steep land	153.5 km^2	562m	32-65%	0.1-0.3 km
Composite	131.8 km^2	241m	1-72 %	Variable

Table 2.2. Summary of the relief and landforms in Sibilu catchment

2.2.2. Drainage Pattern and Vegetation Cover

The major river draining in the area is Sibilu. It joins the Muger River, which is one of the main tributaries of Abay. The Sibilu River meanders in the flat topography of Sululta plain. The drainage lines trend to be parallel where the ground has a general slope in direction that is observed in the eastern steep landforms. Where the topography is more irregular, the drainage pattern develops like a branching tree, referred as dendritic drainage pattern in the southern and western portion of the catchment. Probably due to local tectonic effect, the composite landform shows more or less parallel, N-S running perennial rivers with all intermittent and short dendritic tributaries (Fig. 2.2).

The vegetation cover is mostly concentrated in the mountainsides of Entoto as Eucalyptus and Acacia tree together with scattered bushes and minor other kind of plants. The northern plain part of the catchment is mainly a pastures and alternating crops with few scattered trees. The Sibilu reservoir, at present, is being used mainly for grazing and small scale farming by local people i.e. the low lying areas are left for grazing while the relatively high areas on the slopes are generally cultivated.

2.3. Geomorphological Processes

Geomorphological processes in any catchment should be identified to employ any engineering practices (Prince, 1983). The main geomorphological processes in the Sibilu catchment may be grouped under two broad types: slope movements and soil formations.

2.3.1. Landmass Movements

Much of the steep land and composite landforms of the Sibilu catchment are characterized by highly sloped areas. These slopes play an important role in the processes of mass movements, associated with its climatic conditions (Fig. 2.3). Materials are moved down slopes by two main ways. These are mass wasting and down wash, which are important in denudation. By the action of mass wasting and down wash, material is removed, so facilitating the continuing work of weathering (Wight, 1987).

i) Mass Wasting- is the creeping, flowing, sliding or falling of rock and weathered material down hill under the influence of gravity. The main types of mass wasting favored in Sibilu catchment, due to its slope, climatic and geologic character, are soil and talus creep, rockslides and some rock falls.

- *Soil and Talus creep-* Most of the basaltic sloped mountains, which are deforested and the uncultivated hills, are characterized by this types of mass wasting.

- *Rockslide-* Most of the Entoto ridges, due to steep slopes, fractured nature of rock mass, deforestation and other human activities like road cuts, are affected by rockslide. This is identified from aerial photos and large accumulation of rock fragments and debris masses.

ii) Down Wash- is the movement of material down slopes by running water as a result of heavy rainfall. The impact of rain splashing on the ground may add to the effect of down wash by loosening individual particles. During torrential rainfall it become dominant transporting agent in the sloped areas. In this catchment there are two types of down wash processes, which are manifested by different features.

- *Sheet Wash-* is a removal of the top layer of the soil and other fine materials from sloped areas. So most of the slope areas in the catchment, which are not strongly vegetated, show this phenomenon. It is manifested by alluvial fan deposits of the sloped streams run to flat topography (to Sululta plain). It is observed at the foot of Entoto and eastern basaltic mountains.
- *Gullying-* is prominent on steep slopes of Entoto ridges and composite landform of the catchment.

2.3.2. Soil Formation

This is a natural process facilitated by the degradation of rock into somewhat disorganized sediments or fragmented materials, which then is finally transformed into an organized material and a series of different soil horizons comprising the soil profile. Geomorphology and climate, within a given parent material, drainage and vegetation types, are the major controlling factors in the soil formations (Graef, 1996).

In the studied catchment the volcanic terrains are subjected to high rainfall and temperature in described landforms, which explains the suitable conditions for distinct chemical weathering to produce characterizing clay soils. Many researches have been done in tropical soils to model the interrelation between the different controlling factors and the product soil material by different authors. Tricart, (1972) tried to relate the annual rainfall amount with clay type of the soil in sloped, well-drained basaltic terrains of humid tropics region. Jenny (1964) also described the annual temperature and clay contents of the soil in different drainage conditions of basic Tertiary basaltic rocks (cited in Tricart, 1972). In Ethiopian plateau especially in the northwest of Addis Ababa, there was a study conducted by Thompson, (1965) to define the relationship between volcanic clay soils with the existing climatic conditions. Also Morin and Parry (1971) studied geotechnical properties of Ethiopian volcanic soil related with their formation and controlling factors.

The clay formation of the studied catchment is controlled by climate, nature of the source material, topography, drainage, vegetation cover and time; like any other catchment. The catchment, as discussed before, is characterized by humid tropical climate and volcanic terrain. Its topography can broadly grouped under sloped area around the watershed boundary and the remaining plain. The drainage can also be related with its topography i.e. the sloped part with well-drained conditions, which favor extreme leaching while the plain is poorly drained which facilitates limited leaching. So all these conditions lead to tell the type of clay minerals formation, i.e. kaolinite in the well-drained area (Morin and Parry, 1971) but in poorly drained areas the formation of montimorillonite is favored. Better characterization about their genesis, geotechnical properties and their significance in dam engineering practice will be discussed in chapter 6.

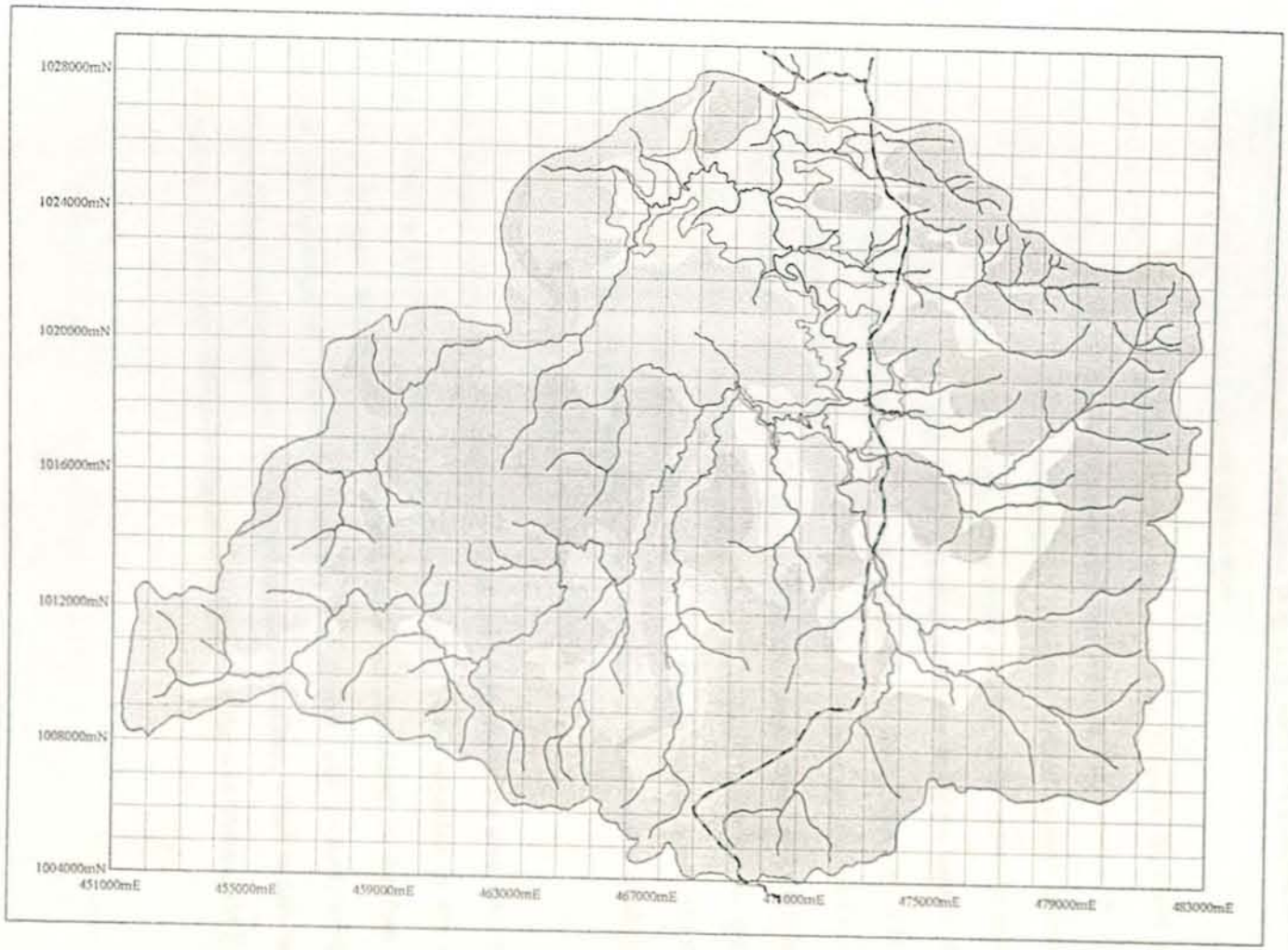


Figure 2.2 Slope and Drainage Map of Sibilu Catchment

(reduced from 1:50,000 scale)

N
W E
S

Scale: 1:200,000

LEGEND

- Flat and gentel (<12%)
- Moderate (12-35)%
- Steep (35-60)%
- Very steep (>60%)
- Dam site
- Reservoir area
- Roads
- Rivers / streams

2.4.Geodynamic Evaluation

The significance of discussing in detail the geomorphological aspects, in relation to climate in a given catchment, is to identify the geodynamic phenomena, which are active at the present time, and to understand their future effects in the engineering structures of the area (Soeters and Rangers, 1985). The geologic features include those due to erosion and deposition, slope movements and volcanic and tectonic activities are important in the area. All these features can be shown in the geomorphological maps, which is the way to represent the geodynamic evaluations (Fig. 2.3). Then it is possible to see the conditions favoring their development, intensity and occurrence.

In the Sibilu catchment erosion produces steep-sided gullies and ravines on hillsides. It creates an irregular surfaces (as composite landforms) and increase sediment load in the streams. It also facilitates the increasing of the possibility of slope movements. It is also favored by over grazing, deforestation and other human activities at Entoto ridges. Due to the position of the reservoir to the Entoto ridges, where erosion is predominant, may cause silitation problems in Sibilu dam in the future unless proper consideration is taken. So human activities in the sloped areas, which are able to facilitate erosion should be discouraged. Mass movements in the Sibilu catchment are observed in the Entoto ridges and composite landforms where there are slopes. Most are creep, sliding and some falls in the areas with upper most surfaces. These small-scaled mass movements seem not to create considerable problems in the near future. Some road cuts in the Entoto ridges needs stability considerations and the quarry near the reservoir should be seen its effect in the reservoir conditions. This feature in terms of the reservoir water tightness is discussed in chapter 7.

Volcanic and tectonic features in the area are expressed in the all the landforms of the area, which are then modified by weathering processes. There is no active volcanic event recorded in the area recently. Some tectonic features: lineaments, fractures and joints are considered in the dam and reservoir conditions and discussed in chapter 3. Generally the climate and geomorphological characteristics of the catchment has significance roll in geodynamic evaluations, which in turn be the main parameter in dealing with the engineering-geological investigation of the area (Prince, 1983).

Seismicity risk analysis is also incorporated with geodynamic evaluation of the area during site investigation. Earthquakes impose additional loads to dams and cause instability problems so seismic study should be considered (Price, 1983). Seismicity analysis is based on historical records and geology of the area. Statistical procedures can be applied to know the probable locations, magnitude, occurrence and frequency of the earthquakes.

From seismic risk map of Ethiopia the study area lies in the second risk zone, which is characterized by micro-earthquakes with magnitude less than 3. Hence, considering the seismicity and earthquake risk of the area, it is better to include appropriate hazard mitigation measures in the design of the proposed dam.

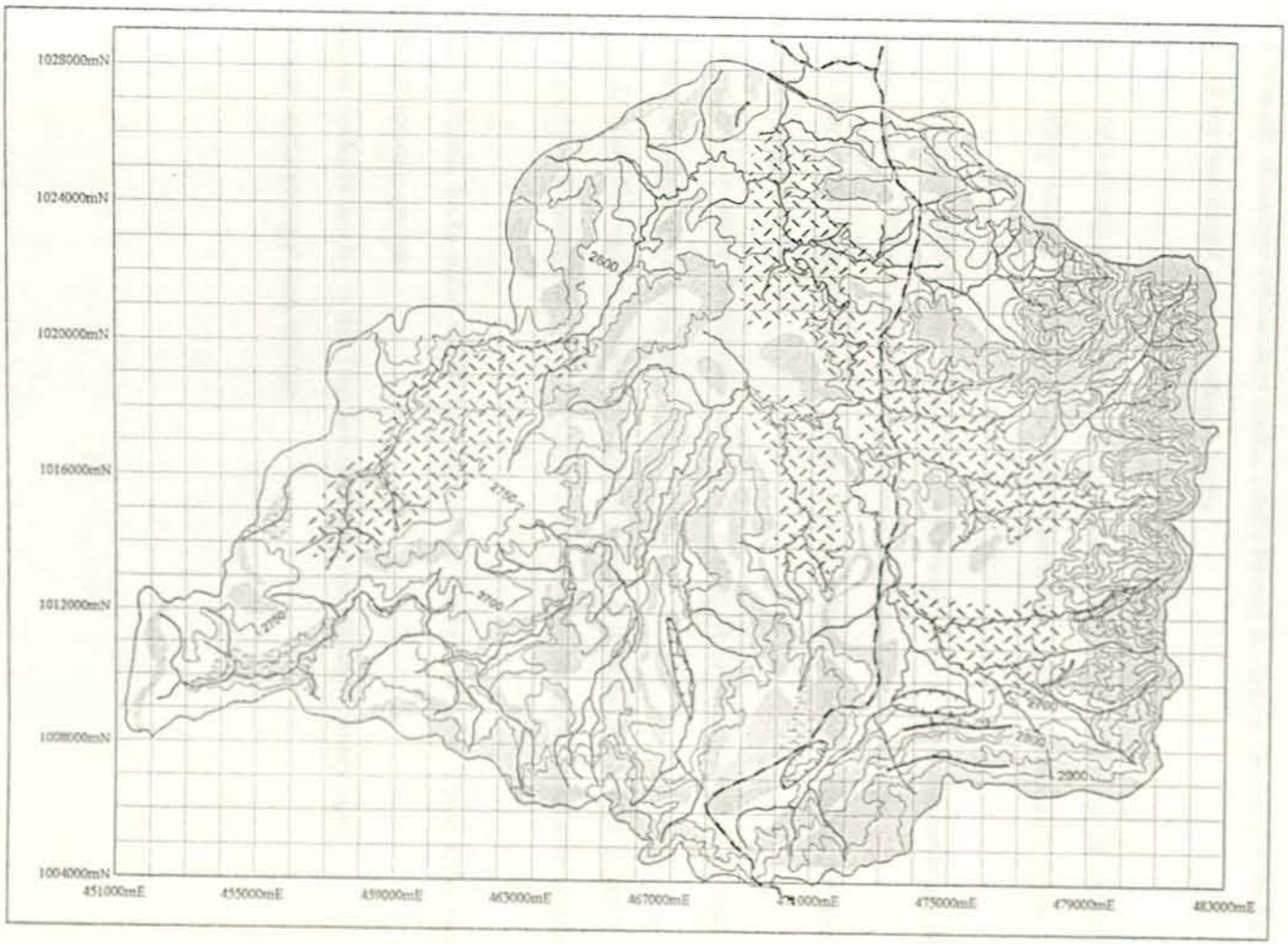


Figure 2.3 Geomorphological Map of Sibilu Catchment

(reduced from 1:50,000 scale)

Scale: 1:200,000

N
W E
S

LEGEND

- Soil units
- Rock units
- Swamp area
- Major flood plains
- Reservoir area
- Dam site
- Road
- Rivers / streams
- Land slide trace
- Escarpment
- Mass movement
- Contour lines

CHAPTER-3 GEOLOGY

3.1. Regional Geological Setting

The Sibilu dam catchment is located in the plateau region of central Ethiopia. The volcanic successions of the central plateau and adjacent escarpment have been described from the stratigraphy and tectonic viewpoints by different researchers. Mohr (1967, 1971), Zanettin *et al.* (1974, 1977), Kazmin *et al.* (1975), Morton *et al.* (1979), and Haile Sellase Girmay and Getaneh Assefa (1989) are few to mention. According to Kazmin *et al.* (1975) the plateau region of central Ethiopia is occupied with less dominant Mesozoic sedimentary rocks, which belong to Antalo Group and Amba Aradom Formation, and the dominant Cenozoic volcanic rocks.

The Mesozoic sedimentary rocks are exposed to extreme north and northwest of the study area (Figures. 3.1). They include Abay Beds, Antalo Limestone, Agula Shale and Amba Aradom Formation.

Abay Beds: are middle Jurassic in age. They are associations of gypsum, limestone, dolomitic limestone, sandstone and shale. Sometimes they are variegated shales with gypsum.

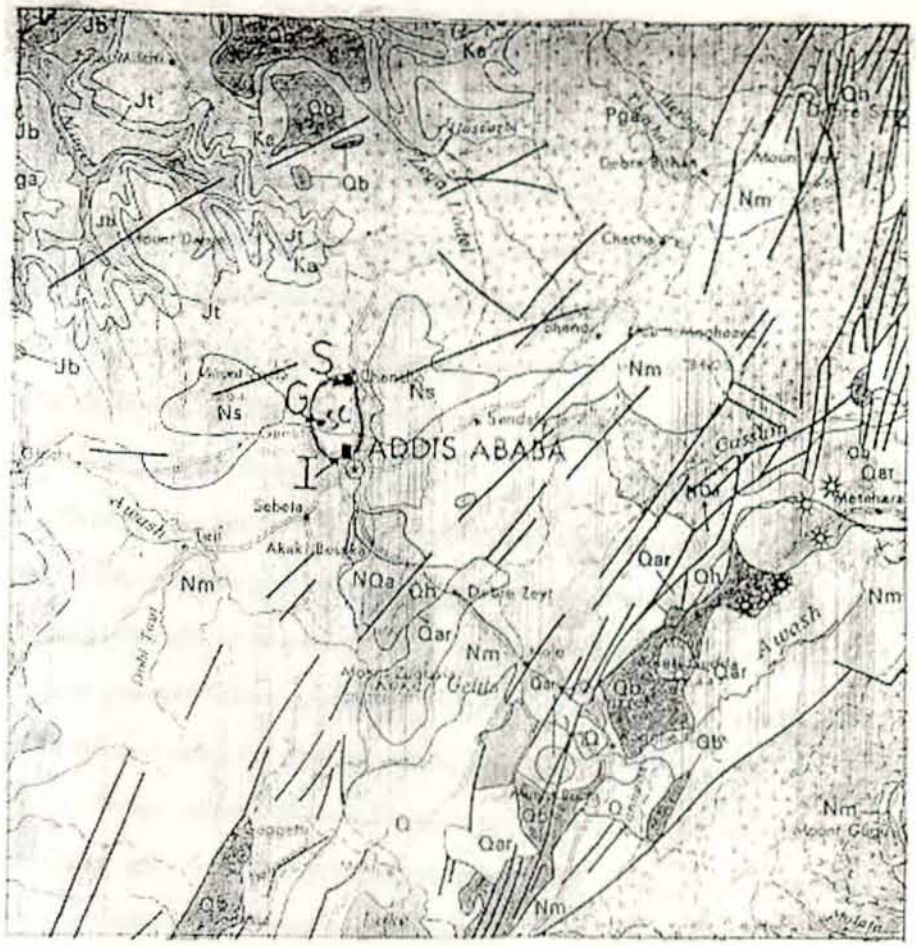
Antalo Limestone: is upper Jurassic in age. It is composed of oolitic, detrial fine and micro-grained limestone and marls.

Agula Shale: is upper Jurassic-Kimmeridgian in age. It is an association of shale, marl, claystone, limestone, dolomite and gypsum.

Amba Aradom Formation: is lower Cretaceous in age. It is an association of clayey shale and marl with conglomeratic sandstone. This formation also includes the upper sandstone of Harar and Arussi.

The Cenozoic volcanic rocks occur within and adjacent of the studied area. These rocks have been broadly divided into two groups:

- Volcanic rocks belonging to the Trap Series of early and middle Tertiary age.
- Volcanic rocks younger than this age.



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Qh- Holocene, Conglomerates, Sand silts, Clays, reef limestone **Q**- Undifferentiated

Qb- Basaltic flows and related spatter cones

a) Transitional type between alkaline and tholeiite basalt

b) Alkaline olivine basalt

Qar- Silicous domes and flows **NQa**- Afar group: Basalts, subordinate acid lavas, ignimbrites

Nm- Magdala group: Rhyolites, trachytes, ignimbrites and agglometrates basalts

Trap Series

Ns- Shield group: Alkali basalts, tuffs, agglomerates

Pg – Ashangi group:

a) Alkali olivine basalts, tuffs, rare rhyolites

b) Doleritic sills and gabbro-diabase intrusive

Antalo Group

Ka- Ambaradam formation **Jg**- Agula shale

Jt- Antalo limestone **Jb**- Abay beds

Ja- Adigart sandstone

SC= Sibilu catchment S= Sibilu dam site G= Gerbi dam site I= Proposed site of Entoto tunnel

Figure 3.1. The regional geological setting of the study area (after Kazmin, 1975)

The volcanic rocks belonging to the Trap Series include Ashangi group and Shield group. These rocks have been considered to be related with extensive fracturing that occurred synchronously and immediately following the uplift of the Arabo Ethiopian swell (Mohr, 1971; Kazmin, 1975).

Ashangi Group: Paleocene-Oligocene-Miocene in age. This broad group is classified into alkali olivine basalt and tuffs, rare rhyolites and dolerite sills and gabbro-diabase intrusive. As a formation it is explained as alkali olivine basalt, pyroclastics and rare rhyolite injected by dolorite sills, acidic dykes and gabbro-diabase intrusion.

Shield Group: Miocene in age. It is composed of alkali olivine basalt, tuff and agglomerates. The alkali olivine basalt in this group shows amygdaloidal textural features.

The volcanic rocks thought to be younger than the rocks of the Trap Series are Magdala group and Afar group. These younger volcanic rocks suggested to be associated with the rift system faulting and occur within the rift and along the adjacent plateau (Mohr, 1971; Kazmin, 1975).

Magdala Group: upper Miocene-Pleistocene (?) in age. It is an association of rhyolites, trachytes, rhyolitic and trachytic tuffs interbedded with lavas and agglomerates of basaltic composition i.e. ignimbrites, agglomerate and basalts.

Afar Group: Miocene-Pleistocene in age. This group consists of basalts, subordinate acid (silicic rocks) and ignimbrite.

The Sibilu reservoir and dam site comprises of volcanic rock belonging to the Ashangi group of the Trap Series. These rocks also occur in the central and southern part of the Sibilu catchment, whereas the rocks including in the Shield group of the Trap Series exposed to the west and east of the Sibilu catchment area. The southern boundary of the catchment constituted by rocks of Magdala group.

3.2. Geology of Sibilu Catchment

3.2.1. Lithological Units of Sibilu Catchment

The geology and volcanic sequences of most of the central and southern part was systematically explained with the analog of the geology of Addis Ababa by Morton *et al.* (1979) and Haile Sellase Girmay and Getaneh Assefa (1989).

Haile Sellase Girmay and Getaneh Assefa (1989) proposed the stratigraphy of the area starting from Sululta (central part of the catchment) to Nazareth. They redefined the litho-stratigraphic units and modified the existing stratigraphic sequence. The suggested Miocene-Pleistocene volcanic successions in the area from bottom to top are Alaji basalts, Entoto silicics, Addis Ababa basalts, and Nazareth group and Bofa basalts.

In the Sibilu catchment the type of rocks observed are basaltic lava flows, rhyolitic lava flows, trachytic lava flows and welded (ignimbrites) and unwelded pyroclastic deposits (Fig. 3.2). The Sibilu catchment partial geologic map at the scale of 1:50,000 was produced by Morton *et al* (1979). But this map covers the central and southern part of the catchment. To complete the geologic map to the north, aerial photo interpretation and field mapping was done. The southern and central part of the catchment is already in the defined zone of the above stratigraphy. To suit the rest of the rock units of the catchment in the proposed stratigraphy the rocks textural features and geographic locations are considered, and a plain correlation was drawn. Most part of basaltic unit is associated with Alaji basalt and some to Addis Ababa basalt; the rhyolites, trachytes and ignimbrites, to that of Entoto silicic rock unit, and some welded tuff (ignimbrite) to the Nazareth group (Haile Sellase Girmay and Getaneh Assefa 1989) and Quaternary deposits are also noted.

A. Alaji Basalts

These rocks unit is exposed at the crest of Entoto hills which bounds the southern limits of Sibilu catchment and across the Sululta plain (Zanettin *et al.*, 1974). The outcrop of Alaji basalt extends from the crest of Entoto (ridges bordering the southern part of the catchment) towards the north (Haile Sellase Girmay and Getaneh Assefa 1989).

This unit is composed of basalts, which show variation in texture from highly porphyritic to aphanatic. It is mainly composed of labradorite, andesite, pyroxene and magnetite. Within this unit there is an interaction of pyroclastic deposits and glassy welded tuff (Haile Sellase Girmay and Getaneh Assefa 1989). It may be possible to group the aphanitic basalts of the northern catchment in

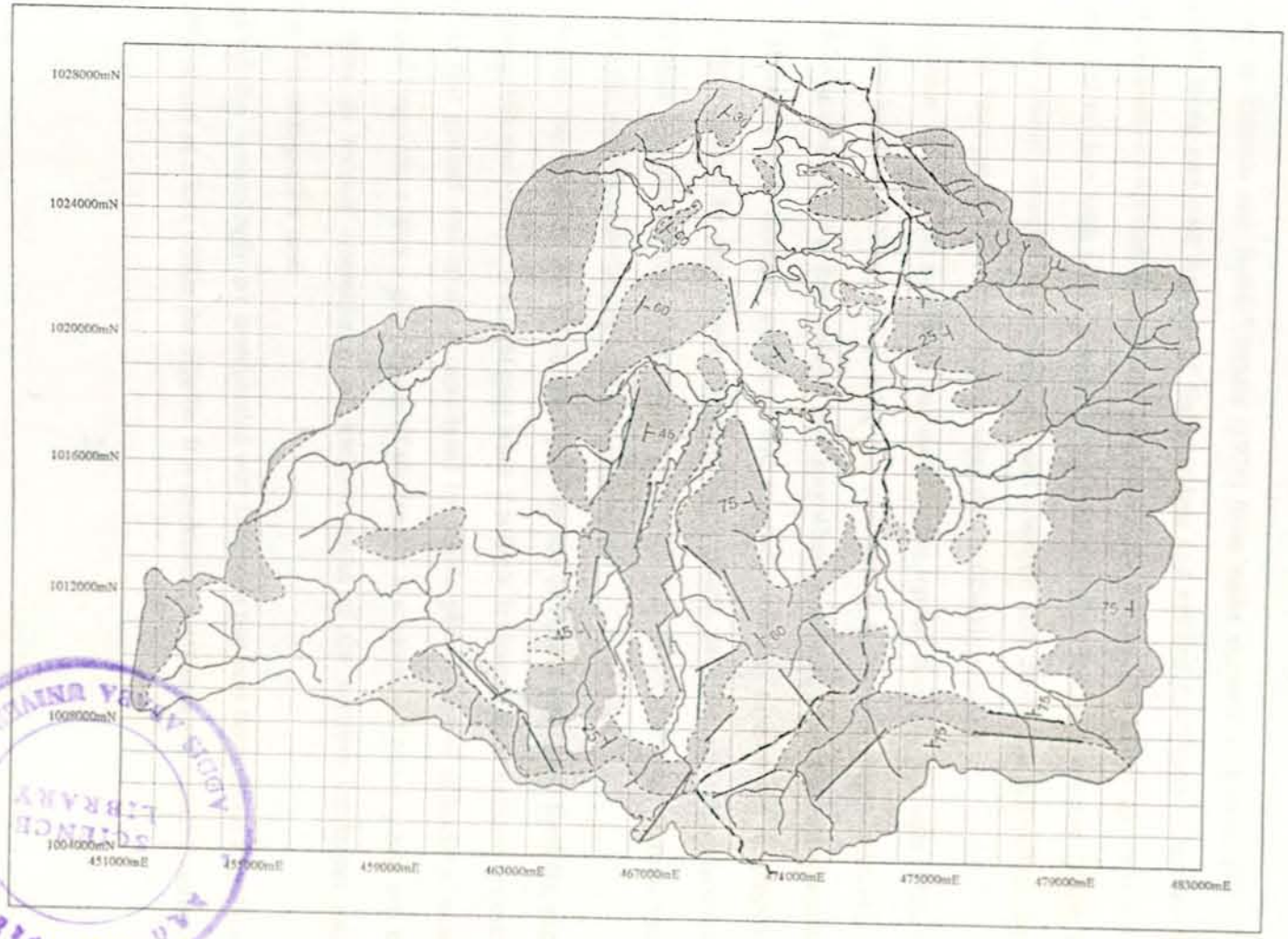

Figure 3.2 Geological Map of Sibilu Catchment

(reduced from 1:50,000 scale)

Scale: 1:200,000

N
W E
S

LEGEND

- Quaternary deposits
- Basaltic lava flow
- Rhyolitic lava flow
- Trachytic lava flow
- Welded tuff (Ingimbrite)
- Pyroclastic deposits (Unwelded tuff)
- 75 Strike / dip
- Dam site
- Lineament
- Inferred contact
- Reservoir area
- Road
- Rivers / streams

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this stratigraphic unit. This unit is underlain by tuffs and ignimbrites, on the other hand its stratigraphic relationship with the Entoto silicics is difficult to determine as it occurs in a fault contact. Mohr (1967) proved that Entoto trachyte overlies the Alaji basalt. The Alaji volcanism in this part was outpoured from the end of Oligocene until middle Miocene (Zanettin *et al.*, 1974) and also samples collected from that area yielded an apparent age of 22.8 m.y (Morton *et al.*, 1979), so that could be placed in Miocene time.

B. Entoto Silicics

According to Zanettin and Justin-Visentin (1974) these rocks exposed as a thick pile of flows accumulated along east-west fissures of Entoto ridges and uplifted northwards. There abundance becomes maximum on the Entoto ridges and less towards the plateau. The Entoto silicics is composed of rhyolite and trachyte with minor amount of ignimbrite (welded tuff) and obsidian (Haile Sellase Girmay and Getaneh Assefa 1989). Rhyolitic and trachytic lava flows are difficult to separate. However, they have got some peculiar features when they are freshly exposed.

Rhyolites: the rhyolitic lava flows outpoured on the top and foothills of Entoto ridge. In this rock unit flow banding, folding and jointing are common. It is forming ridges, relatively steep dissected hills and valleys. It is fine grained, light gray where it is fresh, reddish brown where its iron stained. Commonly it is strongly weathered and in places solution cavities are developed. The rhyolite is characterized by phenocrystes of plagioclase, quartz, sanidine, andesine-oligoclase and altered rebeekite in a groundmass of devitrified glass with iron oxide. The rhyolite rock unit was overlain trachyte, and it is underlain by tuffs and ignimbrites.

Trachyte: the trachytic lava flows outcrop on the top of Entoto ridges and foothills, exposed on the farming hills and valleys. It is light gray when it is fresh. It shows a quite uniform texture. It is very fine to fine grained and rarely is constituted by visible phenocrysts of orthoclase, sanidine, oligoclase and magnetite within a groundmass of plagioclase iron oxide and minor quartz and mafic minerals. With its textural resemblance the trachytic rocks of the northern catchment may be compiled in this stratigraphic unit.

Ignimbrites (welded tuff): are incorporated with the above two lava flows forms a gentle slope and probably occurs as a lens within the rhyolite. It is moderately weathered and crystal fragments are

scattered through a matrix of ash. Tuffs and ignimbrites show a sequence nature in the rhyolitic lava flow. They are welded and characterized by columnar jointing. They are usually composed of sanidine, rebeekite, anorthoclase, quartz and unidentified volcanic fragments (Haile Sellase Girmay and Getaneh Assefa 1989).

The Entoto silicics is unconformably overlain by Addis Ababa basalt on the foothills of Entoto ridges and underlain by Alaji basalt. The Entoto silicics are dated 22 m.y by Morton *et al.* (1979). Thus from the general stratigraphy established by Zanettin *et al.* (1974) both rhyolite and trachyte of the Entoto silicics belong to the 'Miocene Alaji rhyolite and basalt' sequences.

C. Addis Ababa Basalts

In the catchment, the oldest visible rock post-dating the Entoto silicics are the Addis Ababa basalts. The unit, which is mainly present in the central part of the Addis Ababa town, exposed in the Sululta plain is underlain by the Entoto silicics. It is amygdaloidal (vesicles filled with calcite) and of labradorite-bytownite, olivine and augite as phenocrystes. The ground mass is made up of andesine, labradorite, olivine, magnetite and pyroxene (Haile Sellase Girmay and Getaneh Assefa 1989). With its textural similarity, the northern catchment vesicular basaltic rock may be grouped in this stratigraphic unit.

D. Nazareth Group

The units identified in this group are denoted as ignimbrite (lower welded tuff), aphanitic basalt and upper welded tuff. Out of these only ignimbrite is exposed in the Sibilu catchment (Haile Sellase Girmay and Getaneh Assefa 1989).

Ignimbrite: it is also named as lower welded tuff. It outcrops as a small discontinuous body in Sululta plain. It is glassy with abundant fiamme and has columnar joints. The age of this rock as dated by Morton *et al.* (1979) at Sululta is 5.4 m.y. This age overlap with the period of Wechecha volcano, 4.6 m.y. Wechecha is located 15 km west of Addis Ababa and probably the sources of ignimbrite in the catchment (Morton *et al.*, 1979).

3.2.2. Geological Structures of Sibilu Catchment

In the Sibilu catchment and adjacent area different authors reported the occurrences of faults, joints and other structures within the different volcanic rocks (Zanettin *et al.*, 1977, Hailesallase Girmay, 1985).

A great fault is running east west via Kassam River, and it cuts across the western rift escarpment (northern Addis Ababa) and uplifted its northern block (Zanettin *et al.*, 1977) at about 8 m.y ago. This fault marks the outer boundary of the western Ethiopia rift margin immediate north of Addis Ababa-Ambo road (Zanettin *et al.*, 1977). The Entoto silicics confined along this fault and form a ridge. This ridge bounded the catchment in southern direction. This fault has a down throw to the south in the catchment area (Haile Sellase Girmay and Getaneh Assefa 1989).

In the present work the structural features, which are inferred in the catchment, are obtained from 1:50,000 aerial photographs of the area. From these large-scale photos lineaments are mapped (Fig.3.2). These lineaments include straight contacts between various rock units, sudden and straight lithologic contacts, straight river courses and aligned topographic features. Through these attempt around thirty-four lineaments are mapped and they are grouped in the four sets of orientation i.e. NW-SE, NE-SW, E-W and N-S.

NW-SE lineaments: are most dominant (fourteen) types of the structures in the catchment. Three 0f them follow straight topographic alignments and four of them follow straight river courses and the rest are manifested by lithological contacts.

NE-SW lineaments: are also abundant (thirteen) in the study area. Four of them traced from straight stream courses, five of them from lithological contacts and the rest are recognized from straight topographic alignments.

N-S lineaments: are four in the study area. Half of them are observed in the western side of the reservoir area, which are traced in the basalt. The rest are in the dam site as a straight river courses.

E-W lineaments: are almost observed in the Entoto ridges as a topography lineaments of possible fault scarps traces and straight lithologic contacts between basalts and rhyolite, rhyolite and ignimbrite. One is found in the dam site as straight river course.

3.3. Reservoir Geology

The reservoir area of 128.5 km^2 is mapped at the scale of 1:12,500. The mapping was conducted mainly by taking traverses along and across the trend of the topographic lineaments and occasionally traverses were taken parallel to topographic contours in the order to know the extent of sub-horizontal rocks.

Structural data like lineaments; landslide and contacts between various rock units were first inferred from the aerial photographs of 1:8,000 scale of the reservoir. Also aerial photos used to locate observation points were verified during field inspections. Fractures and joints were measured from every exposure observed.

Topographic map at the scale of 1:12,500, which is obtained by blowing up of the 50,000 topographic map of that particular area, was used as a base map to plot every observations, and during office work computer software was used to prepare the maps and rose diagrams.

3.3.1. Lithological Units of Sibilu Reservoir Area

The Sibilu reservoir comprises of various types of Quaternary deposits, basaltic lava flows, trachytic lava flows and pyroclastic deposits (Fig. 3.3) and their topographic appearance is shown on three selected geological cross-sections (Fig. 3.4).

A. Quaternary Sediments: of the area include residual soils, alluvial and colluvial deposits.

Residual (elluvial) deposits ranging in size from silts to clay are commonly observed on the top of the ridges especially in the western and southern part of the mapped area. They are formed from the weathering of the basalts and trachytes.

Alluvial deposits consisting of gravels and silt to clay soils occur at the flood plains and channels of the Sibilu River and its tributaries. At southern part of the reservoir some oxbow and meander scar deposits are formed.

Colluvial deposits dominantly occur on the sloped hills found in the reservoir forming gentle slope. Its thickness varies from approximately 1-3m and consists of predominantly of slope wash clayey brownish soil and gravels to blocks of volcanic rock fragments mixed with gravels and sandy materials.

B. Basaltic Lava Flows: is the most abundant rock type exposed at the Sibilu reservoir. It outcrops on most of the hills and the riverbeds and occurs as thick lava flow or as thin band intercalating with pyroclastic deposits. In the hand specimen the rock is dark-to-dark gray, very fine to medium grained. At places, plagioclase and/or olivine occur as phenocrystes in the black matrices. The rock in the reservoir shows different degree of weathering, from fresh to strongly weathered; locally it shows spheroidal weathering (Fig 3.5).

The rock also exhibits different types of textures i.e. aphanitic, scoracieous, vesicular and halocrystalline basalts. The rock is also affected by various sets of joint systems including columnar joints, minor fractures, and lineaments and occasionally shows flow banding.

Aphanitic basalt is the most dominant textural variety in this rock unit. It is exposed in the dam axis, especially in the west abutment and most of the reservoir flanks and upstream riverbeds. The color become darker and sometimes shows reddish brown to high degree of weathering. It is massive, very fine-to-fine grained. It is composed of dark mafic minerals.

It is highly weathered in most parts, around the dam site it shows spheroidal weathering and slightly weathered in the upstream. This basalt is strongly jointed including columnar joints. It shows flow banding at one place (at the junction point with Deneba River) upstream of the Sibilu River bed. It is also affected with minor faults trending E-W around the junction with Deneba River.

Scoracious basalt outcrops at the riverbed in the dam axis and east abutment close to Ochi hills. It is colored as light to dark gray. It is fine grained with some phenocrystes of plagioclase and/or olivine. It is fresh to slightly weathered. Joints of various orientations also affected it.

Vesicular basalt outcrops in the most top part of Asere ridge and becomes rich in plagioclase. It contains amygdules filled with calcite or weathered unconsolidated materials. It is slight to medium weathered; dark to dark gray, very fine to fine grained. Joints also affect it and the non-systematic joints become dominant over systematic ones.

Halocrystalline basalt outcrops only in the elliptical ridge found in the northwestern part of the reservoir, showing E-W trends. This textural unit consists of visible mineral crystals with the groundmass consisting of small granules of the dark minerals i.e. granulitic habit. According to Wahlstrom (1966) such texture is named, as halocrystalline basalt. It is dark green to black, medium grained. Megascopically, it contains feldspar and occasionally olivine. It is slightly weathered. It is jointed by various sets of joints and faulted by faults running N-S and N10^0 E.

C. Trachytic Lava Flows: is encountered at the east abutment of the dam site with limited width exposure of 20 to 40m and show a steep slope on the exposed section to be seen as a linear feature forming an escarpment in the plain. It also outcrops at a low topography in the eastern part of the dam site and well exposed to the east of the bridge on the road from Chancho to Muger. The trachyte is light gray in color; fine grained with some phenocyrsts composed of essentially feldspar and minor mafic minerals, and rarely contains amygdules filled with calcite. It is slightly to highly weathered. It is affected by systematic joint sets including columnar joints (Fig 3.6).

D. Pyroclastic Deposits: encountered in the Sibilu reservoir, in the dam site and Ochi ridge. It is also exposed at the western side of Sibilu River on foothills of Asere ridge. They are found intercalated with basaltic rock unit. This rock unit is highly friable at the dam site (Fig. 3.7), it is compact in the other exposures. It consists of intermingled tuff, agglomerate and locally scoria.

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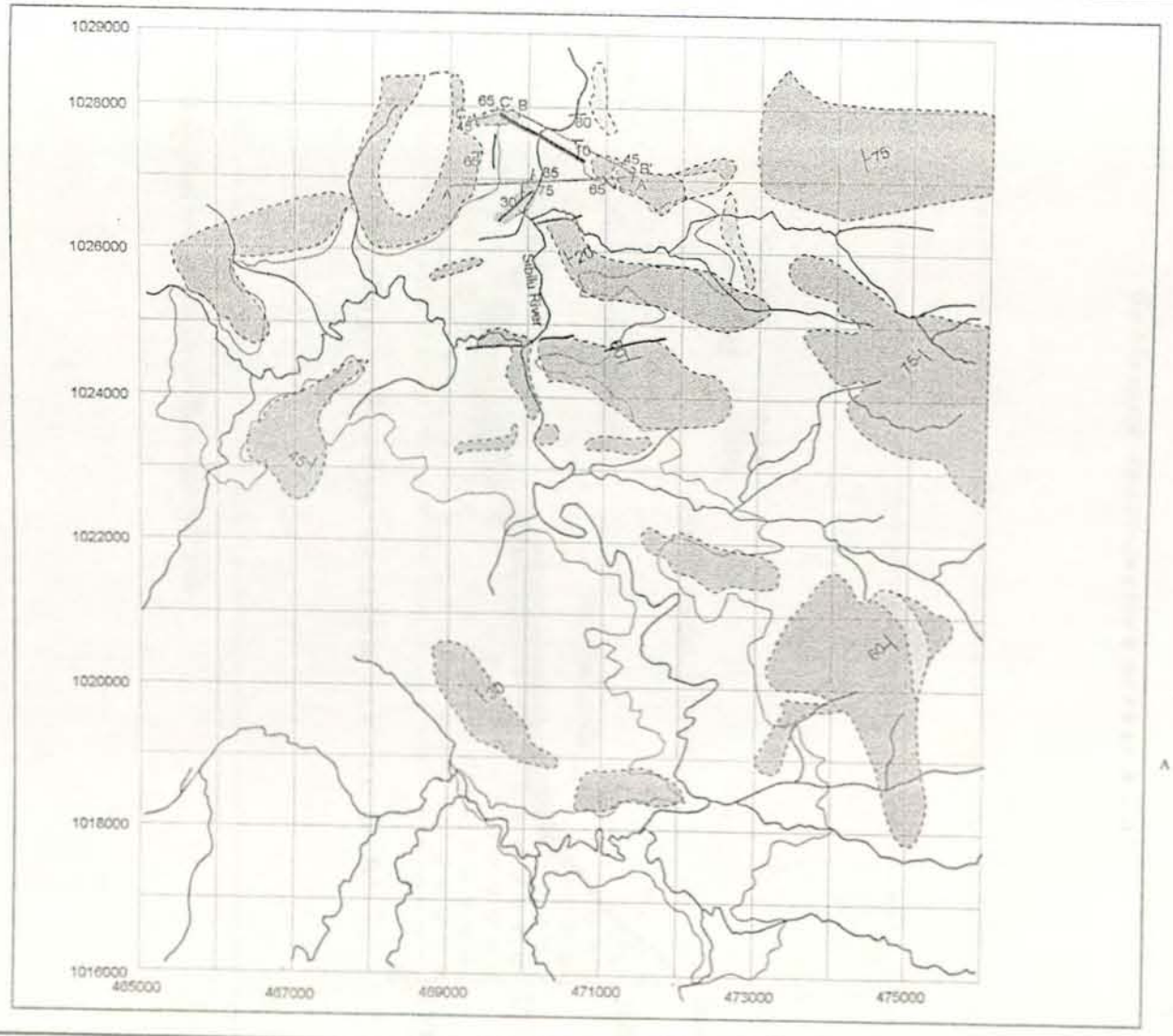


Figure 3.3 Geological Map of Sibilu Reservoir Area

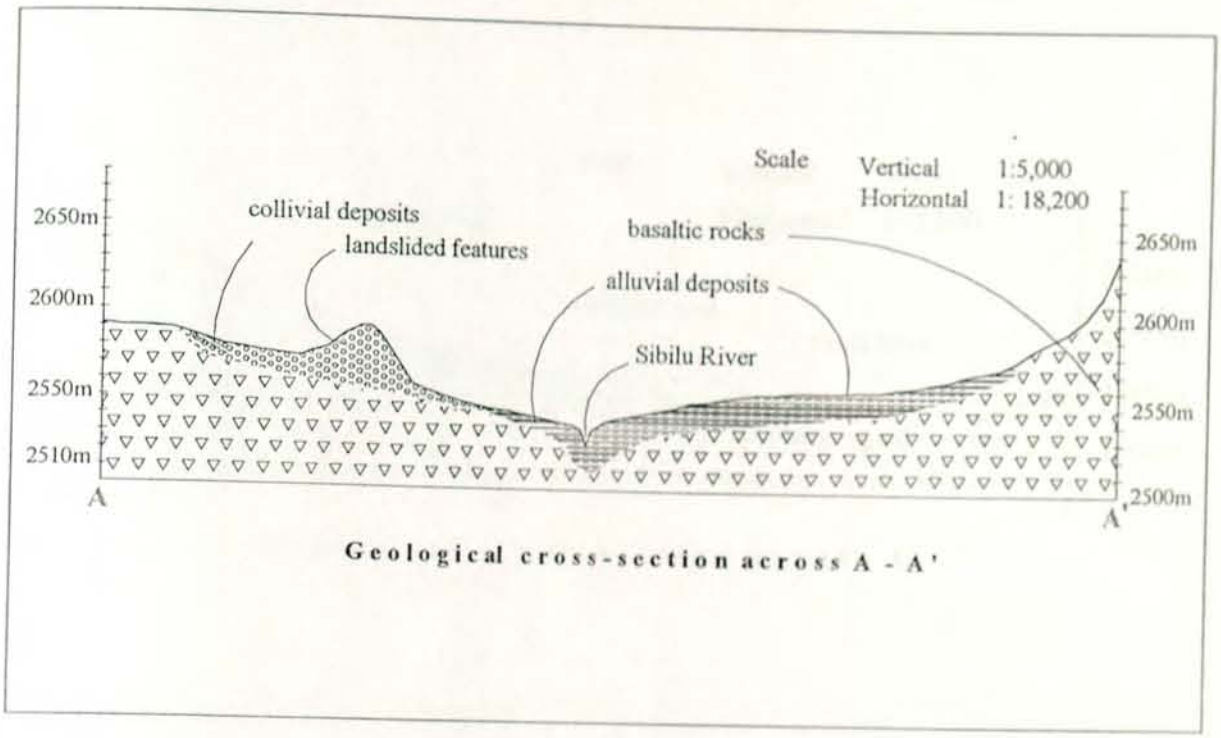
(reduced from 1:12,500 scale)

Scale 1:90,000

N
W E
S

LEGEND

- Quaternary deposits
- Basaltic lava flow
- Trachytic lava flow
- Pyroclastic deposits
- Reservoir area
- Dam site
- A — A' Cross-section direction
- River / stream
- Inferred contact
- Fault
- 75 Strike / Dip



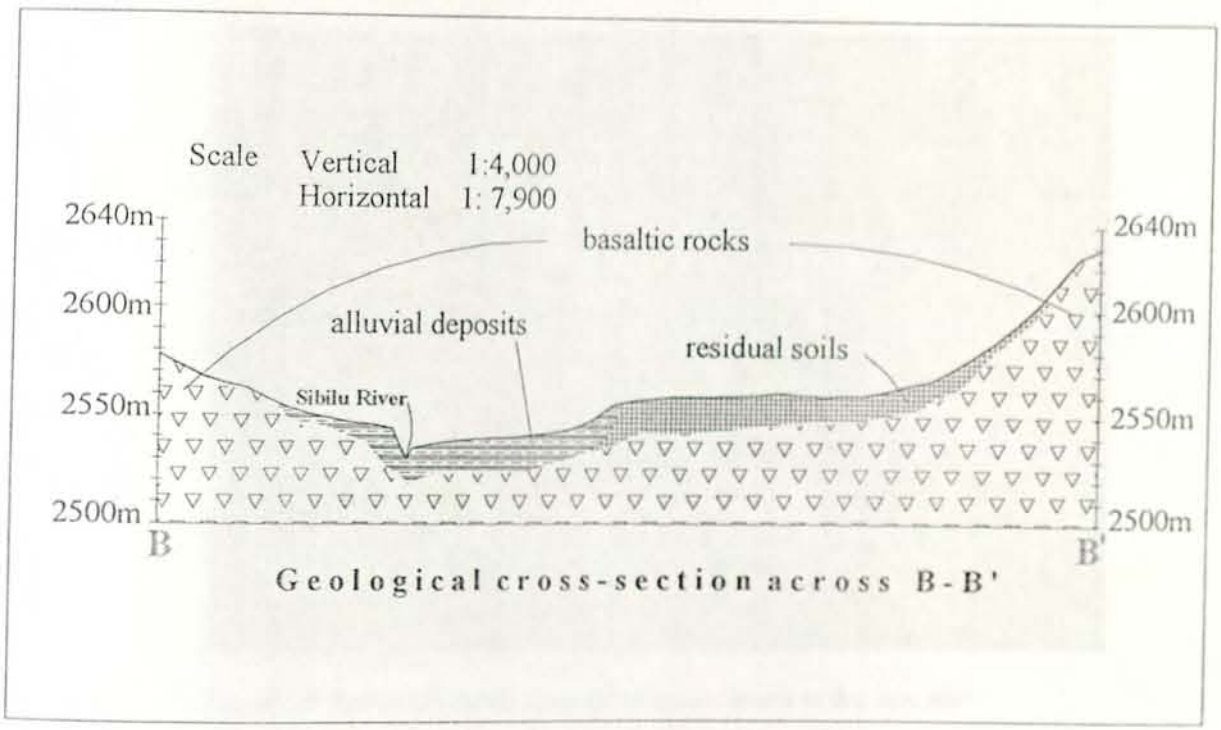


Figure 3.4. Geological cross-sections of Sibilu reservoir area

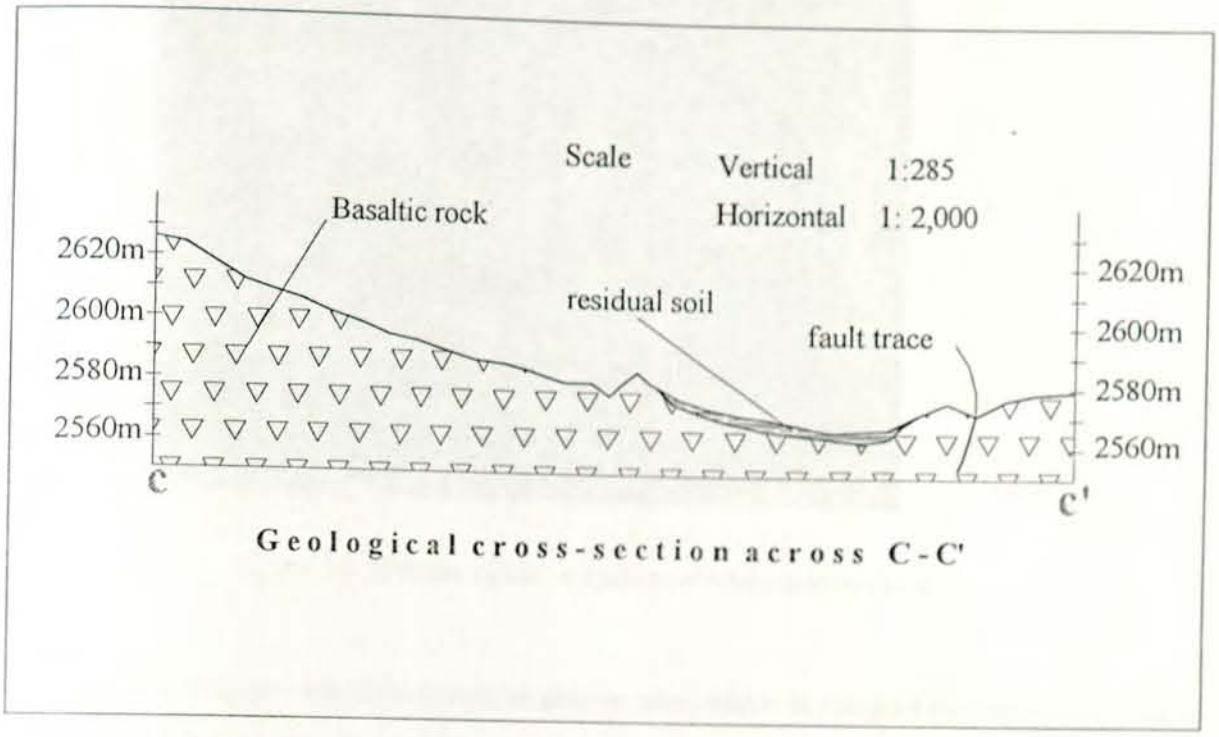


Figure 3.4. Geological cross-sections of Sibilu reservoir area

Figure 3.5. Spheroidal weathering of aphanatic basalt in the dam site

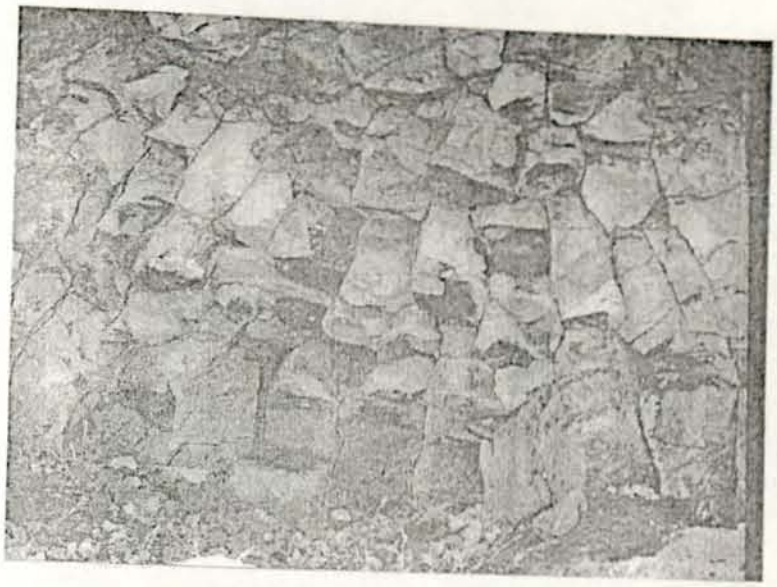


Figure 3.6. Columnar joints in trachyte of Sibilu reservoir area

The tuff is fine grained, light to pinkish gray in color, friable to compact rock composed of largely ash-sized particles including aggregates of quartz grains. At places, sub rounded to spherical basaltic early-formed rock fragments (varying in diameter from2-26cm) occur irregularly within the tuff. The scoria lenses that are highly vesicular and in places filled with calcite and quartz usually found in tuff, when the tuff grades up or down. It is light to dark gray, occasionally the vesicles and amygdules are flattened.

The agglomerates consist of welded aggregates of scoraceous (commonly basaltic) rock fragments. The aggregates are rounded to elliptical and range in diameter from 4cm up to 10cm. Though it is in small proportion ash also was noted.

Contacts between the pyroclastic components are commonly gradational and occasionally paleosoil varying in thickness from 10 to 20 cm occur separating the pyroclastic deposit from the underlying basalt. In addition, thin bands of fine-grained basalt alternate with these deposits.

Figure 3.7. Friable pyroclastic deposits at the dam site

3.3.2. Geological Structures of Sibilu Reservoir Area

The structural features (discontinuities) were first mapped from aerial photos of large-scale 1:8,000. These aerial photos lineaments are all straight features of topographic alignments, river courses, deeply eroded gullies, contacts of various rock units or soil/rock units and vegetation anomalies. Those, which are verified in the fieldwork as structural discontinuities, are mapped (Fig.3.3). As a whole, the recognized structural features are joints and faults.

A. Joints

The rocks of the Sibilu reservoir area are affected by different joint sets. A total of 524 joint measurements of strike and dip along with their apertures and spacing have been made from three reservoir parts i.e. northern, central and southern (annex-A). In the northern part which is considered as the dam site three sections are chosen in terms of their morphological setting i.e. the right and left high lands and the central flat-laying part (Fig .3.8): section 01, section 02 and section 03. This grouping used to characterize the joint orientations in a detail fashion and most of the measurements (415) were done in this part. While the rest readings were taken from the central (61) and southern (48) part of the reservoir. They are analyzed using Sswin computer software and explained in rose diagrams.

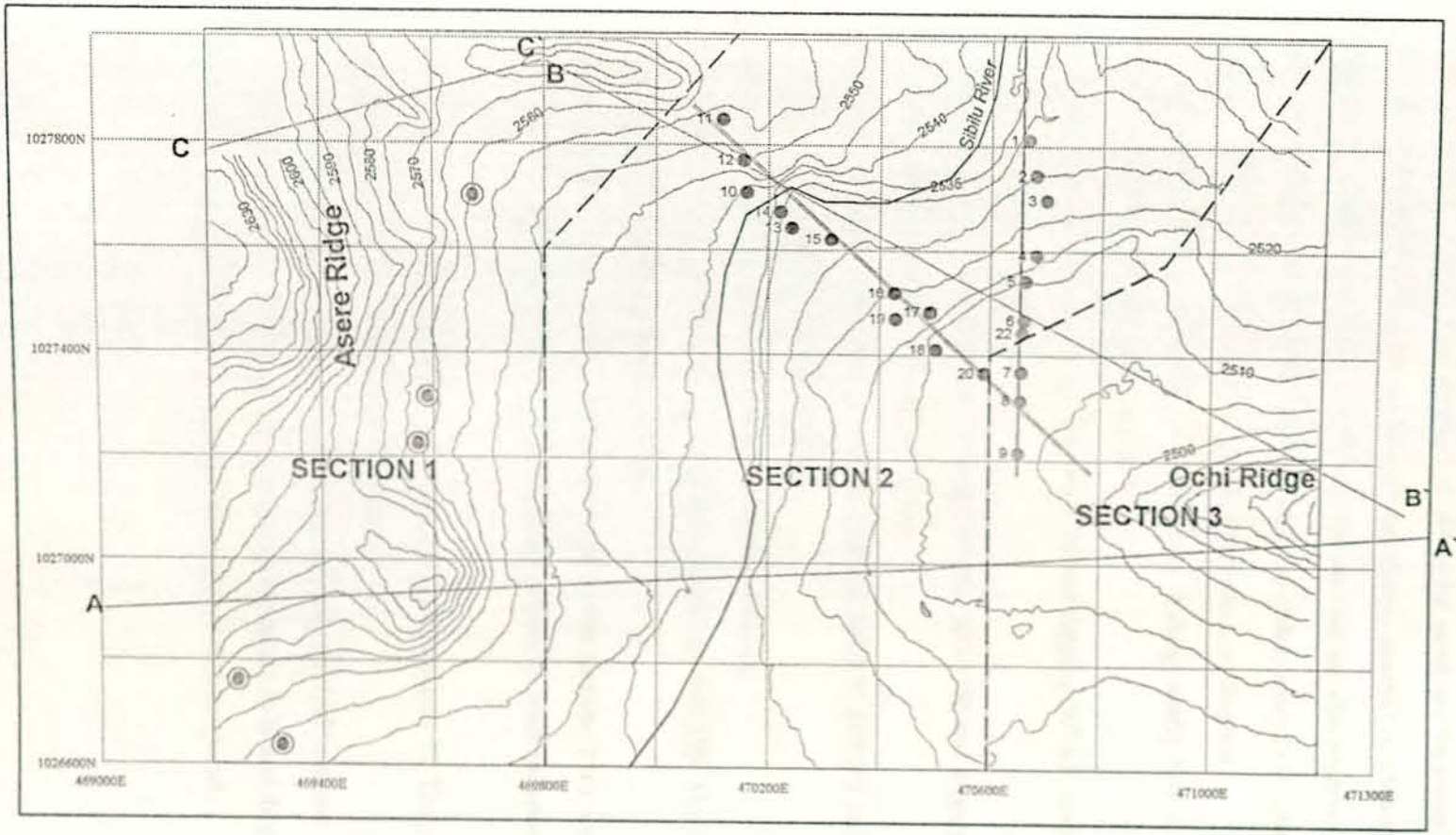


Figure 3.8 Sibilu Dam Site Area

(reduced from 1:2,000 scale)

N
W E
S

Scale 1:12,500

LEGEND

- Dam Axis
- Spillway Axis
- Dam Axis Boreholes
- Spillway Axis Boreholes
- Cross-section profile
- Spring
- Section boundary
- Contour line
- Sibilu River

Northern part: In this part the measurements of the three sections are differently processed (Fig.3.9). Major concentrations of joints in section 01 are NW-SE, E-W and N-S trending.

i) Joints strike about 280^0-350^0 and dip 60^0-85^0 towards SW are the main joint set in this section. They are tight or open (0.5 2.1cm) and closely to medium spaced (0.75-7cm).

ii) Joints strike approximately E-W and dips steeply to the south are the second major set of joints in this section. They are almost tight and closely spaced (10-15cm).

iii) Joints strike nearly N-S and dips 50^0-75^0 towards the east are also observed. They are moderately narrow to moderately wide (0.8-5cm) and widely spaced (61-240cm).

In section 02 four major groups of joint concentrations are shown on the rose diagram.

i) A major tight to narrow (<0.8cm) joint set occurs striking nearly N-S and dipping steeply towards E. They are closely spaced.

ii) An open (6.3 14cm) joint set occurs striking E-W and dipping 50^0-65^0 towards north and are very widely spaced (1-2.4m).

iii) A wide (0.7- 1.8cm) joint set occurs striking NW-SE (320-350) and dipping 60^0-85^0 towards NE. They are medium spaced (25-42cm).

iv) A tight to moderately wide joint set occurs striking NE-SW (10-30) and dipping vertically. They are closely spaced (8-12cm).

In section 03 three major groups of joint sets are observed on the rose diagram.

i) Set 1 joints striking 10^0-80^0 dipping commonly steeply to 280-350. The joints are usually tight and closely spaced (0.8-5.2cm).

ii) Set 2 joints striking nearly N-S are also abundant in this section. They are dipping 60^0-85^0 towards E, tight to narrow (0-0.2cm) and closely to medium spaced (4-37 cm).

iii) Set 3 joints striking approximately E-W dipping 20^0-45^0 towards N. The joints are wide open (8-11cm) and widely spaced (35-72cm).

Central part: In this part the major concentrations of joints occur in three principal joint sets.

i) A major open (7- 30cm) joint set occurs striking nearly E-W and dipping 30^0-65^0 towards N. They are 8-17cm wide and at places widely spaced.

ii) A tight joint set occurs striking nearly N-S and dipping steeply towards E. They are narrow (0.2-0.6cm) and closely spaced (1-4.2cm).

iii) A commonly tight or rarely open joint set occurs striking 40^0-50^0 and dipping steeply towards SE. They are medium spaced (8-19cm).

Southern part: In this part very limited measurements are made due to less number of exposures. However three joints set are identified.

i) Set 1 joints striking E-W dipping 30^0-45^0 towards N. The joints are wide (9-14cm) and moderately to widely spaced (33-70cm).

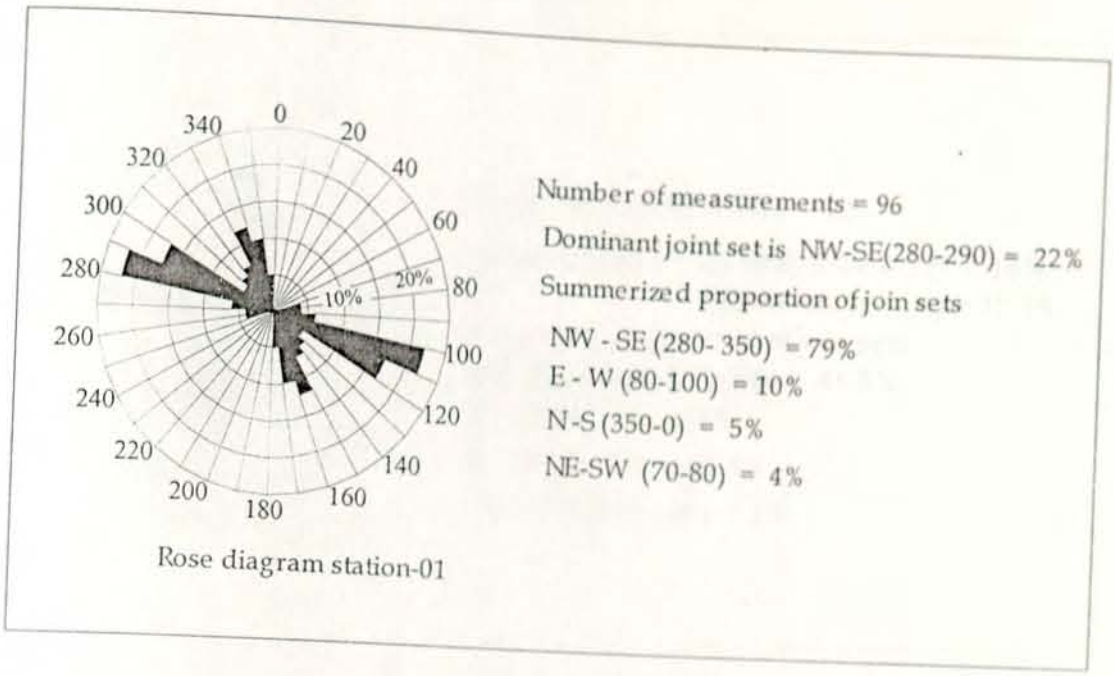
ii) Set 2 joints striking nearly N-S are also noted in this section. They are dipping 60^0-85^0 towards W, tight and closely to medium spaced (5-30 cm).

iii) Set 3 joints striking 330^0-350^0 dipping 50^0-65^0 towards 30^0-80^0. The joints are tight and widely spaced (70-122cm).

All in all, to characterize the reservoir area all the joint measurements are analyzed together and showed that the N-S and E-W are the dominant joint sets. This result is found different from the catchment structural lineament interpretation observed from the aerial photos i.e. NW-SE, NE-SW, E-W and N-S is dominant lineament order.

Section	Joint set	Orientation	Dip	Tightness	Spacing
01	NW-SE E-W N-S	280^0-350^0 80^0-100^0 350^0-10^0	60^0-80^0 75^0-90^0 50^0-85^0	0-2.1cm Tight 0.8-5cm	0.7-7cm 10-15cm 61-120cm
02	N-S E-W NW-SE NE-SW	350^0-10^0 80^0-100^0 320^0-350^0 10^0-30^0	80^0-90^0 50^0-65^0 60^0-90^0 Vertical	0-0.2cm 6.3-14cm 0.7-1.8cm 10-12cm	5-15cm 1-2.4m 25-42cm 8-12cm
03	NE-SW N-S E-W	10^0-80^0 350^0-10^0 80^0-100^0	Vertical 60^0-85^0 20^0-45^0	Tight 0-0.2cm 8-11cm	0.8-5.2cm 4-37cm 35-72cm
Central	E-W N-S NE-SW	80^0-100^0 350^0-10^0 40^0-50^0	20^0-45^0 Vertical 80^0-90^0	7-30cm 0.2-0.6cm Tight	8cm-5m 1-4.2cm 8-19cm
Southern	E-W N-S NW-SE	80^0-100^0 350^0-10^0 330^0-350^0	30^0-45^0 60^0-85^0 50^0-65^0	9-14cm Tight Tight	33-70cm 5-30cm 70-122cm

Table 3.1. Characteristics of sets of major joint concentrations at Sibilu reservoir



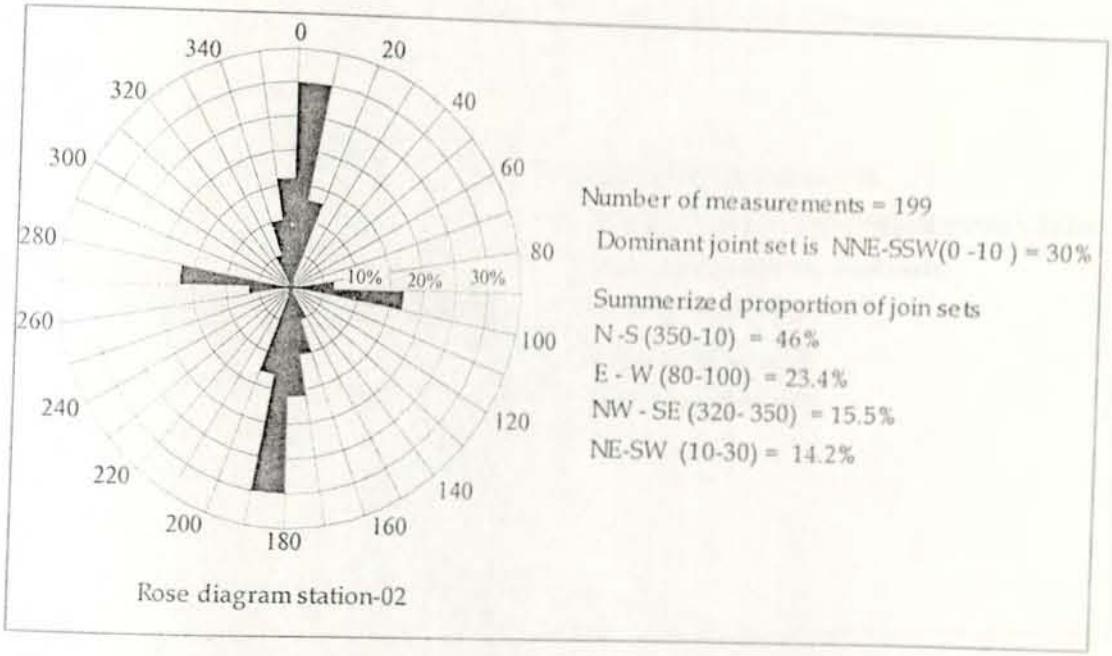
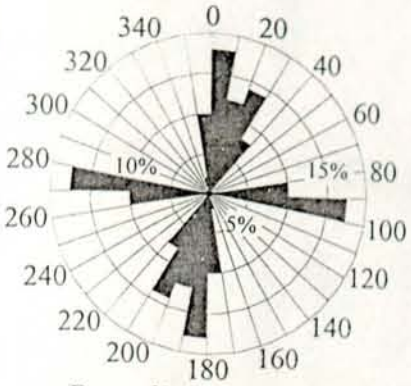


Figure 3.9. Rose diagrams of Sibilu reservoir joint sets



Rose diagram station-03

Number of measurements = 120

Dominant joint set are NNE-SSW(0-10) = 18% & EES-WWS(90-100) = 17.5%

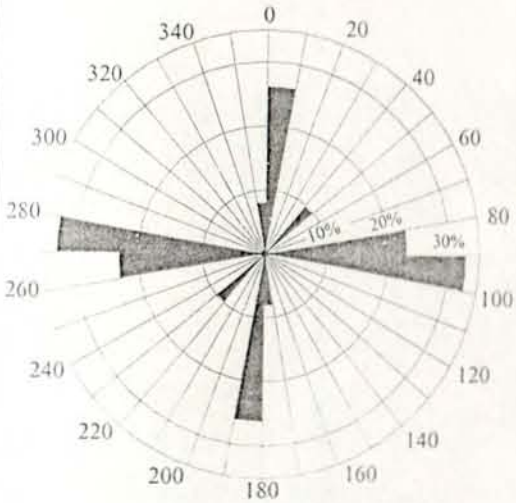
Summerized proportion of join sets

NE-SW (10-50 & 70-80) = 41.5%

N-S (350-10) = 28%

E - W (80-100) = 27.5%

NW - SE (340- 350) = 2%



Rose diagram for central reservoir

Number of measurements = 61

Dominant joint set is EES-WWN(90-1000) = 32.8%

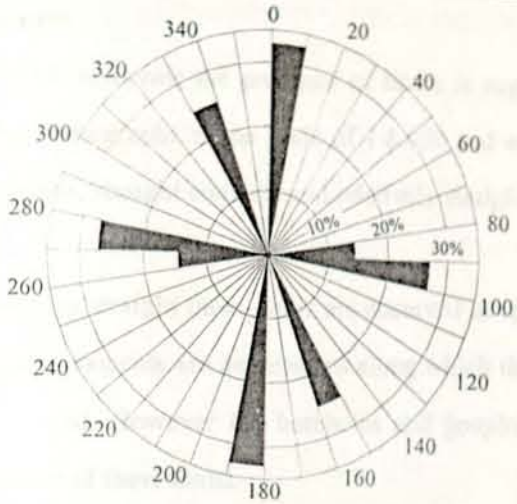
Summerized proportion of join sets

E - W (80-100) = 55.8%

N-S (350-10) = 34.3%

NE-SW (40-50) = 9.8%

Figure 3.9. Rose diagrams of Sibilu reservoir joint sets



Number of measurements = 48

Dominant joint set is NNE-SSW (0-10) = 33%

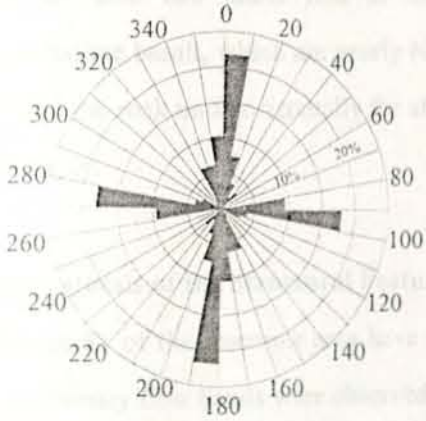
Summerized proportion of join sets

E - W (80-100) = 41.5%

N-S (0-10) = 33%

NW-SE (330-340) = 25%

Rose diagram for southern reservoir



Number of measurements = 524

Dominant joint set are NNE-SSW (0-10) = 21.8% &
EES-WWN (90-100) = 18%

Summerized proportion of join sets

N-S (350-10) = 31.5%

E - W (80-100) = 27.5%

NW-SE (280-350) = 23.2%

NE-SW (10-70) = 17.2%

Rose diagram for Sibilu reservoir

Figure 3.9. Rose diagrams of Sibilu reservoir joint sets

B. Faults

In Sibilu reservoir the presence of faults is suggested based on the features indicated on reservoir aerial photographs at the scale of 1:8,000 and using some surface features i.e. straight sheared rock fragments, straight contacts and relatively straight topographic alignments (Fig3.3).

Relatively straight three faults are observed in the field and aerial photographs at the Sibilu dam site. These lineaments are depressions along which the Sibilu River flows and they have a NNE-SSW and E-W trend. However the boreholes and geophysical surveys at the dam axis did not conform the presence of these faults.

In the central part of the reservoir the presence of faults is highly probable due to their surface features; and other faults in the reservoir is manifested by straight contacts and fragmented aligned rock bodies and high concentration of joints.

There are also two faults find in the northwestern part of the area affecting the elliptical halocrystalline basalt, which are nearly N-S and N10^{0}E, striking sinistral (left hand) fault that cut and displaced the rock unit horizontally for about 80m and straight fault zone with shattered rocks of 20m respectively.

3.2.3. Synthesis of the Structural Features in the Dam and Reservoir Conditions

All the rocks of the reservoir area have been affected by discontinuities including joints and faults. Rarely primary flow bands were observed in basalts of the reservoir.

The variously oriented joints, both systematic and non-systematic joints, cutting the rocks resulted in the decrease of the resistance to erosion and weathering which in turn gave rise to the easiest way to gravity movement and deposition of weathered materials. These deposits can affect different conditions in the reservoir due to its accumulation of unstable landmasses. Unstable landmasses can cause storage and stability problems in the reservoir conditions. Also during the impounding of the

dam the presence of unstable landmasses may initiate serious land sliding and then show the way to the failure of the dam.

As it is noticed from the joint sets orientation interpretation the N-S and E-W joint sets are the main concentrated joint sets in the dam site. Most of the E-W joints are open and continuous over the others in the dam site. These joints are highly liable to be leakage zones in the reservoir and under the dam. During impoundment of water they initiate further stability problems. Some set of joints in the dam site let water to seep under the foundation and decrease the foundation strength, which in turn lead to the collapse of the structure. But much emphasis should be given to the more concentrated joints during construction. Even after construction the dominant joint sets are able to cause differential settlement since they affect the foundation rock strength unevenly.

All in all the discontinuities in the reservoir and dam site should be investigated in detail to fully characterize the stability and leakage problem in the foundation and reservoir area.

CHAPTER-4 HYDROMETROLOGY AND GROUNDWATER

4.1. General

Hydrology of a given region depends primarily on climate, topography and geology. Climatic factors of importance are precipitation and its mode of occurrence, humidity, temperature, wind speed and radiation (Wilson, 1990). Hydrological studies are employed in different engineering practices like land use planning, site selection for engineering purposes in assessing and even the safety of engineering structures. Hydrometerological parameters should be fully considered as important parameters in dam engineering and in defining hydrological elements like precipitation, evaporation, runoff and infiltration (Wilson, 1990).

Surface water and groundwater also play important role on geomorphological processes, weathering and slope movements. Groundwater is normally under pressure, which increases with depth below the water table to very high values. Such water pressures have a significant influence on the engineering behavior of rock and soil masses. Their variations are responsible for changes in stress in these masses, which affect their deformation characteristics and failure (Bell, 1993).

In this section it is tried to assess the hydrometerological, hydrological and partly hydrogeological conditions in the study catchment from dam engineering perspective.

The occurrence of surface and groundwater is controlled by different factors mainly by geology and climate. The precipitation that falls on the basin enters into a number of pathways. Some of the water will drain the basin and then leave it to enter the stream channel as a runoff. If the surface material is porous, some water will seep into the ground. The remaining water will return to the atmosphere by evaporation from the water body, and transpiration from the vegetation. The infiltrated water joins the groundwater system and it can accumulate to give a promising groundwater potential (Fetter, 1994).

The study of hydrology requires the collection of data on precipitation, temperature, radiation, humidity, wind speed, pan evaporation and runoff. All of these main factors are considered.

4.2. Hydrometeorology

4.2.1. Precipitation

In the Sibilu catchment, 25 years (1975-1999) rainfall records of the three stations of relevance for the study area have been collected from the NMSA. The Sululta station, which is located at an elevation of 2604m a.m.s.l., is the only station found in the catchment. The other two, the Addis Ababa Observatory and Chancho, are the nearby available stations, which are located $9^0$02"N and $38^0$45"E, at an altitude of 2480m a.m.s.l. and $9^0$20"N and $38^0$46"E, at an altitude of 2620m a.m.s.l. respectively (annex-B).

The Sululta station has 25 years of complete data from which reliable annual average rainfall depth of 1228.3 mm is calculated. The Addis Ababa observatory and Chancho stations recorded annual average rainfall of 1223mm and 1225mm respectively. These rainfall records represent point data. In order to make proper hydrological evaluation these point data have to be changed into areal depth of precipitation. But they have almost the same annual average records. However in the present work they are considered as stated, and concluded that there is no significant variation in the rainfall distribution in the whole catchment and the surrounding areas. So it is possible to take the Sululta station's record only for the catchment. Hence, the annual average rainfall depth in the catchment is considered as 1228.3mm.

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Suluta	6.7	57	76.5	90.6	58.8	167	273.6	295.8	175.8	15.9	5.8	5.02	1228.3
A.A Obs.	17	44	66.3	98.9	87.2	136	263.5	282.3	182.7	27.1	9.4	8.34	1222.8
Chancho	15.8	42.7	63.9	93.9	63	156	291.5	305.3	123.3	15.1	2.8	2.2	1225.4

Table 4.1. Monthly average and annual rainfall values of the three stations

The mean monthly precipitation ranges from 5mm to 295.8mm, while total annual precipitation ranges from 1006mm to 1689mm. The twelve months have been classified into two rainfall groups based on their rainfall coefficient-C_{RF} (table4.1). The result shows that rainy months are from February to September when small rains in months February to May and big rains from June to

September occur, the dry months are from October to January. The rainfall coefficient is given by the formula:

$C_{RF} = p(m)/ 0.083 \times p(y)$:- where p(m) is mean monthly precipitation and p(y) is mean annual precipitation.

Where $C_{RF} < 0.6$ represent dry months

> 0.6 represent rainy months

0.6-0.9 small rains

> 1.0 big rains

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Sululta	0.07	0.6	0.75	0.9	0.6	1.6	2.7	2.9	1.7	0.16	0.06	0.05

Table 4.2. Rainfall coefficient of Sululta station

4.2.2. Evaporation and Transpiration

The total amount of water which returns back to the atmosphere within a given time by means of evaporation from land or free water bodies and transpiration from vegetation cover, is called evapotranspiration. Among the climatic factors that influence evapotranspiration rate are temperature, humidity, wind and solar radiation.

Temperature

Temperature plays important role in the evaporation process. Twenty-five years (1975-1999) temperature data recorded at Sululta station (annex-B) shows that the minimum temperature varies slightly from the lowest values in November to January (6.78^0c -7.3^0c) to the highest value of 9.4^0c in May and decrease in the following months. The highest maximum temperature in the area are recorded in March, April and May (19.4^0c –20.1^0c) and the lowest value in June, July and August (15.2^0c –16.4^0c). The mean yearly maximum temperature of the catchment is 18^0c, while the minimum temperature is 8^0c.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
t^0c max.	18	19	19.6	19.4	20.1	17.4	15.4	15.2	16.4	18	19	18.9
t^0c min	7.9	8.1	8.7	9.2	10.3	8.7	7.5	7.4	7.5	6.9	6.8	7.1

Table 4.3. Summarized monthly values for temperature data for Sululta station

A. Potential Evapotranspiration

Evapotranspiration is one of the most difficult components of the hydrological cycle to estimate. Its estimation involves climatic, soil and vegetation factors. It is usually calculated using different empirical formulas, which consider different parameters. Due to the only availability of temperature data in the catchment Thornthwaite (1948) heat index method is used in the present work to estimate the potential evapotranspiration of the area.

Thornthwaite method uses air temperature as an index of the energy available for evapotranspiration, assuming that air temperature is correlated with the integrated effects of the net radiation and other controls of evapotranspiration, and that the available energy is shared in fixed proportion between heating the atmosphere and evapotranspiration. The formula is expressed as:

$$E=16\,(10t/I)^{\alpha}$$

Where: E- monthly gross potential evapotranspiration in mm

t- mean monthly air temperature in ^{0}c

I- average annual heat index

α- $(6.75 \times 10^{-7} I^3)$- $(7.71 \times 10^{-4} I^2)$+$(1,729 \times 10^{-2} I)$+0.492

I- is obtained by summing the 12 values of monthly heat index (i), where i is given by:

$$i- \quad (t/5)^{1.514}$$

The monthly calculated potential evapotranspiration of the catchment (table 4.4) using the above method. It is adjusted by the correction factor of monthly sunshine duration of standard potential evapotranspiration (Leopold and Dunne, 1978), which is a function of latitude (10^0N). It is found to be 588.9 mm.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
PET*	48.1	51.3	53.2	55.8	55.8	46.9	42.6	41.6	44.6	46.7	47.7	48.8
10^0N	0.97	0.98	1.0	1.03	1.05	1.06	1.05	1.04	1.02	0.99	0.97	0.96
PET	46.7	50.3	53.2	57.5	58.6	49.7	44.7	43.3	45.5	46.2	46.3	46.9
PET- potential evapotranspiration, * uncorrected,								Annual PET= 588.9 mm				

Table 4.4. Potential evapotranspiration of Sibilu catchment

However, this result is extremely low estimate compared to other forwarded estimates in the surrounding areas under more or less same climatic conditions. Therefore, it is not used for further actual evapotranspiration calculations. Instead the values promoted for Addis Ababa and surrounding areas by Food and Agricultural Organization of the United Nations (FAO) is used. FAO has developed a comprehensive agricultural and environmental information database for the member states of the Intergovernmental Authority on Drought and Development (IGADD), including Ethiopia, Sudan, Uganda, Kenya, Somalia, Djibouti and Eritrea (FAO, 1995) cited in (Tenalem, 1998). The database contains detailed maps of crop production system zones, with physical and biological environmental data comparing rainfall, temperature, reference potential evapotranspiration, Normalized Difference Vegetation Index (NDVI), agronomy, livestock, biotic and abiotic conditions (table 4.5).

mm	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
A.A. area	90	96	114	108	108	88	76	78	82	102	90	88	1120

Table 4.5. Monthly average and annual rainfall values of the three stations

B. Actual Evapotranspiration

AET is computed from PET values by considering the available moisture in the root depth. In order to compute AET in the Sibilu catchment, the monthly water balance model developed by Thornthwaite and Mather (1957) as applied by Dingman (1994) is used. This method follows a simple bookkeeping procedure that needs the monthly values of effective precipitation and PET. To apply this method the soil and vegetation types in different parts of the catchment should be known and estimated as follows.

- On the steep land: the soil and vegetation types are clay loam with matured forest and covers 153.5 km^2 (Fig. 2.1).
- On the composite landform: the soil and vegetation types are silty loam with deep rotted shrubs and covers 131.8 km^2
- On the gently sloping and level lands: the soil and vegetation types are clay loam with shallow rooted crops and covers 194.7 km^2.

Thornthwaite and Mather (1957) suggested the available water capacities for combinations of soil texture and vegetation types. It is then found clay loams with matured forest has 350mm, silty loam with deep rotted shrubs 250mm and clay loam with shallow rotted crops has 100mm. Hence, AET value, for the Sibilu catchment, is computed using the procedure of Alley (1982) cited in Dingman (1994), (Table 4.6).

The weighted average annual AET of the Sibilu catchment is calculated to be and the different soil and vegetation types in the area with their AET and surplus values are summarized in table 4.7

Vegetation-soil complexes	Aerial proportion	AET	Surplus
Clay loam with matured forest	0.32	863	151.4
Silty loam with deep rotted shrubs	0.27	821	193.4
Clay loam with shallow rotted crops	0.41	716	298.4
Weighted Average	1.0	791.5 mm	222.9 mm

Table 4.7. Relation between soil types, vegetation root depths, AET and moisture surplus in Sibilu Catchment

4.3. Runoff

Water that drains across a basin into a stream channel as over land flow and groundwater contribution to a stream as base flow collectively known as runoff. In this work the term is used as its collective meaning.

Sibilu perennial stream, other perennial and several intermittent streams drain the studied catchment. This river is gauged upstream of the dam site near the Deneba River, which is located at 9^0 15" N and 38^0 43.6" E and covers 376.6 km^2. The flow data record is obtained from (EVDSA) Ethiopian

Computing of AET using Thornthwaite and Mather (1957) soil-water balance method for Sibilu catchment.

- Clay loam with matured forest; the maximum available soil moisture capacity is 350mm (1).
- Silty loam with deep rotted shrubs; the maximum available soil moisture capacity is 250mm (2).
- Clay loam with shallow rotted crops; the maximum available soil moisture capacity is 100mm (3).

mm.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	Remark
Pm	5.14	55.6	75.1	89. 1	57.1	159.5	223.2	215.7	123	4.7	3.0	3.3	1014.4	
PET	90	96	114	108	108	88	76	78	82	102	90	88	1120	
P-PET	-83.9	-40.4	-38.9	-18.9	-50.9	71.5	147.2	137.7	41	-97.3	-86.9	-84.8		
Sm	183	162	144	129	104	175.5	322.7	350	350	296	255	216		(1)
ΔSm	-33	-21	-18	-15	-25	+71.5	+147.2	+27.3	0	-54	-41	-39		(1)
AET	38.14	76.6	93.1	104.1	82.1	88	76	78	82	58.7	44	42.3	863	(1)
D	51.86	19.4	20.9	3.9	25.9	0	0	0	0	43.3	46	45.7	257	(1)
Sur	0	0	0	0	0	0	0	110.4	41	0	0	0	151.4	(1)
Sm	110	91	77	68	46	117.5	250	250	250	203	167	136		(2)
ΔSm	-26	-19	-14	-9	-22	+71.5	+132.5	0	0	-47	-36	-31		(2)
AET	31.14	74.6	89.1	98.1	79.1	88	76	78	82	51.7	39	34.3	821	(2)
D	58.86	21.4	24.9	9.9	28.9	0	0	0	0	50.3	51	53.7	299	(2)
Sur	0	0	0	0	0	0	14.7	137.7	41	0	0	0	193.4	(2)
Sm	29	18	9	2	1	72.5	100	100	100	79	60	44		(3)
ΔSm	-15	-11	-9	-7	-1	+71.5	+27.5	0	0	-21	-19	-16		(3)
AET	20.14	66.6	84.1	96.1	58.1	88	76	78	82	25.7	22	19.3	716	(3)
D	69.86	29.4	29.9	11.9	49.9	0	0	0	0	76.3	68	68.7	404	(3)
Sur	0	0	0	0	0	0	119.7	137.7	41	0	0	0	298.4	(3)

Legend: Pm- effective precipitation (total monthly precipitation- runoff), PET-potential evapotranspiration, Sm-soil moisture storage, ΔSm-change in soil moisture storage and AET- actual evapotranspiration, D- deficit and Sur- surplus moisture

Table 4.6. Calculation of actual evapotranspiration for Sibilu catchment

* *Note: - the model has the limitations in showing the actual temporal variations of surplus.*

Valleys Development Studies Authority for 1981-1999 though 1985,1986 and 1988 are not fully recorded (annex-B).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
Flow (m^3/s)	0.52	0.49	0.47	0.51	0.57	2.42	16.8	26.7	17.6	3.72	0.93	0.59	**5.95**

Table 4.8. Mean monthly flow data of Sibilu-Deneba station (1981-1999)

The data indicate that high mean discharge occurs in the months of June, July, August and September. It corresponds with the high concentration of rainfall occurring in that period as it is confirmed by the immediate correlation of rainfall and discharge.

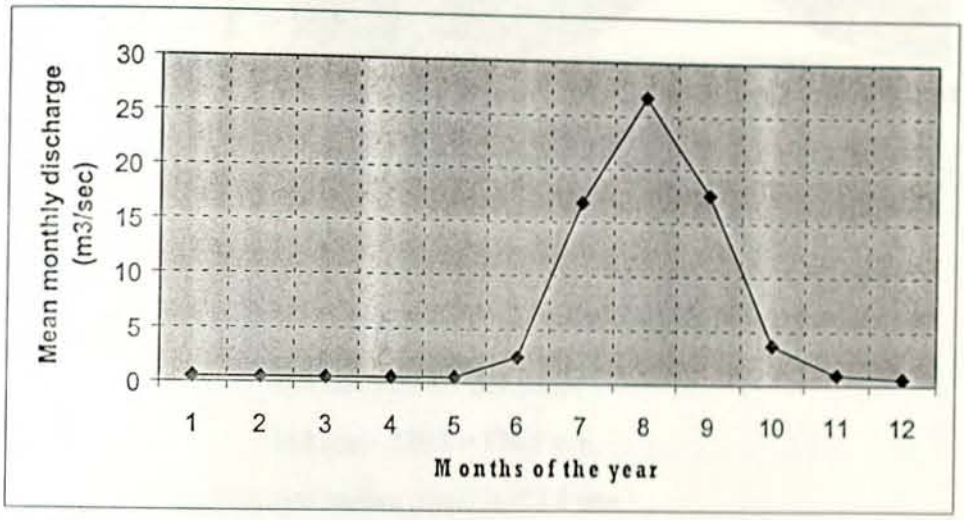


Figure 4.1.Hydrograph of the Sibilu River at the gauged station

The mean annual runoff depth throughout the Sibilu catchment has been calculated by taking into account the mean annual discharge of the river and surface are of the catchment.

Runoff depth= Q x t/A where: Q- mean annual runoff, in m^3/s

t- time in second

A- area of the catchment in m^2

Runoff depth= 5.98 m^3/s x 86400 x 365 s / 486 x $10^6 m^2$

= 0.388m = 388mm

The mean annual runoff depth of the Sibilu catchment is found to be 388 mm. This figure is the mean annual runoff depth that includes surface runoff and groundwater base flow.

A variety of techniques have been suggested for the separating base flow and surface runoff. For the problem at hand the surface runoff and base flow components were separated using the fixed base flow method, which uses a simple empirical relation to define the end of surface runoff from the recession limb of the hydrograph as described by Linsley et al (1982). It is a characteristic graph of flow recession complied by superimposing the recession curve on the stream. (Fig 4.2)

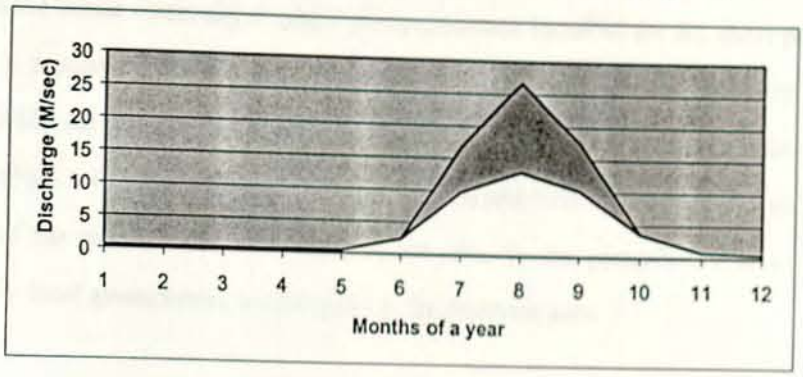


Figure 4.2. Base flow recession curve of the Sibilu River.

It is found that 54 % of the total flow is contributed by base flow.

388 mm x 0.54 = 209.5 mm

388 mm – 170.7 = 178.5 mm

Therefore, the mean annual surface runoff is 178.5 mm.

Comparison between the calculated surplus value and base flow shows that the surplus value (222.9mm) is greater than the base flow (209.5). This condition indicates that there is no out flow of groundwater from the catchment through other routes, which is in favor of the reservoir condition.

Generally, the above hydrological values should be checked by other methods to deal further in water management evaluation of the area.

4.4. Groundwater

Groundwater is often critical in various engineering works. Due to this, problems related to the subsurface water are of prime importance in engineering geology. Groundwater has impaired functions

in dams and also contributes a lot in stability of the reservoir slopes. These effects make the understanding, occurrence, and distribution of groundwater vital in dam engineering (Bell, 1993).

4.4.1. Depth to Groundwater Level

In the studied catchment, there are 30 boreholes (19-at the Sibilu dam and spillway site, 9-at Gerbi dam site and two in the Sibilu reservoir) at which piezometer was installed for the short period of time. The objective was to measure the water level condition in dry and wet seasons, but only static water level data was available for the present work. Beside the boreholes distribution within the catchment is totally uneven (Fig. 5.4) and measurements taken in different time. These conditions restrict the exact determination of the groundwater level depth in the area. So the groundwater level described in this work shows only local groundwater level depth i.e. the reservoir area.

From the data (annex-C) in the catchment the deepest water level is 27.52m and shallowest is 1.11m recorded. Considering only the reservoir area the depth of water level recorded ranges from 1.81m-20.1m (table 4.9). These data obtained from the measured boreholes found in the reservoir (6 upstream, 19 at the dam site and spillway) From the six upstream boreholes four are dry till the depth of 25m, while the rest show static water level at the depth of around 20m. Generally the depth of groundwater is in fractured and weathered top part of the bedrock (fig.7.11). But the lack of continuous recording system of the groundwater levels in the area make it difficult to understand the exact groundwater effects in foundation of the dam and slopes of the reservoir. This condition also affects the groundwater fluctuation assessment, i.e. to predict the time and magnitude of high and low water levels, which are more important in the engineering design of the area.

4.4.2. Groundwater Flow

Ground flow directions can be determined using water level measured in the catchment in the well-distributed points, and all the readings should refer one aquifer and made within a short period of time (Fetter, 1994).

Jointed and fractured basaltic rock constitutes most part of the bedrock in the study area. The variable degree of jointing and fracturing intensity in this rock makes its hydraulic characteristics heterogeneous. Beside, there is no enough evenly distributed static water level data. Even where the reading is available, there is no clear aquifer identification and the measurements taken in different times. All these make the groundwater flow direction interpretation in the study area difficult. Beside due their distribution the water table data used in this work, give only idea about local groundwater flow directions (Fig 5.5). The springs and seepage surfaces in the reservoir area are also flow to the reservoir following local slope directions.

Bore hole name	Borehole location		Ground elevation	Static water level
Sibilu resevoir-01	470087	1026992	2537	19.8
Sibilu resevoir-04	470150	1026988	2538	20.1
Sibilu dam-o1	470666	1027813	2536	3.6
Sibilu dam-11	470118	1027850	2553	1.81
Sibilu dam-13	470240	1027645	2537	12.77
Sibilu dam-14	470380	1027705	2536	11.7
Sibilu dam-15	470370	1027568	2541	14.69
Sibilu dam-10	470160	1027712	2539	2.25
Sibilu dam-02	470680	1027745	2540	3.2
Sibilu dam-03	470699	1027699	2543	5.1
Sibilu dam-16	470520	1027425	2558	14.34
Sibilu dam-12	470195	1027645	2549	2.63
Sibilu dam-04	470682	1027594	2549	4.0
Sibilu dam-19	470675	1027220	2559	12.8
Sibilu dam-17	470658	1027445	2558	14.8
Sibilu dam-06	470661	1027469	2558	10.2
Sibilu dam-07	470657	1027370	2559	9.6
Sibilu dam-20	470772	1027155	2562	11.45
Sibilu dam-18	470625	1027213	2561	16.78
Sibilu dam-o8	470655	1027315	2558	3.6
Sibilu dam-o9	470652	1027215	2559	2.2

Table 4.9. Static water level measurements in Sibilu reservoir area

Basically from the catchment geomorphological setting and the available static water level data, the general flow direction is estimated to be from south to north as that of surface water flow direction. Hence most of the surface water and groundwater emerges to the reservoir, which is in favor of the reservoir condition.

4.4.3. Water Chemistry

The chemistry of water has a significant effect on the development of an area. The presence of sulphate and chloride ions in the soils and groundwater causes deterioration of reinforced concrete structure.

Rethati (1983) categorized materials that are corresive to concrete, mortar, certain stones and bricks according to their effects as follows, considering only the components of groundwater:

- Dissolved materials: those soft waters with a salt content of less than 200mg/l, or of alkalinity less than 2.5.
- Materials causing double decomposition: those acidic water, water containing alkaline bases (pH>9) and salts that leach out.
- Materials causing swelling: those solutions containing sulphate ions concentration of 400mg/l and salts like sodium carbonate, which form crystal in concrete.

To test the suitability of the waters in the study area using the above conditions, the chemistry of the Sibilu river water, springs and dug water were considered. The water samples from the above three water bodies were sampled and analyzed in the EIGS laboratory (table 4.10).

The waters in the area are a little alkaline, hard water and less content of sulphate indicating they are not causing significant negative effect in the concrete structure of the dam. The river water has high Na cation while the ground water has high content of Ca, which may be associated with the mineralogy of the clay minerals in the soil formation and in turn affect the geotechnical properties of the soils (discussed in section 6.4).

Samples	CO_3^{-2}	HCO_3	Cl^-	SO_4^{-2}	F^-	NO_3^-	Na	K	Ca	Mg	HBO_2	SiO_2
River w.	-	151	5	2	0.35	1.33	16	2	20	7	<0.15	18
Springs w.	-	135	10	22	0.17	7.53	6.2	2.3	31	11	<0.15	32
Dug w.	6	168	9	7	0.20	14.18	9	4.1	37	10	<0.15	37

	PH value	Sulphate (SO3)
River w.	8.28	210
Springs w.	7.11	331
Dug w.	8.49	383

Table 4.10. Chemical composition of the waters in Sibilu reservoir area

CHAPTER-5 ROCK AND SOIL DESCRIPTION AND CLASSIFICATION FOR ENGINEERING GEOLOGICAL MAPPING OF SIBILU RESERVOIR AREA

5.1. Introduction

Classification of rocks and soils on engineering geological maps should be based on their physical and engineering properties of rocks and soils in their present state. Engineering properties are dependent on the combined effects of mode of origin, subsequent digenetic, metamorphic and tectonic history, and weathering processes. This principle of classification makes it possible not only to determine the reasons for the lithological and physical characteristics of soils and rocks, but also for their spatial distribution. This is a basic principle of engineering geological mapping; it implies not only the classification of individual rock/soil samples but also the use of many rock/soil samples, field observations and measurements to delineate uniform and continuous rock/soil units (UNESCO-IAEG, 1976).

A full description of a rock or soil for engineering purposes involves the designation of appropriate geological name together with as much detailed information as can be gained from the examination of an exposure. The description may be systematic if a limited range of the standard descriptive terms is used and for ease of application each descriptor may be classified. On the other hand, a classification should place the rock and soil in a limited numbers of groups each with definable properties, which can give a good guide to engineering performance. There is a three-part approach to engineering geological description and classification, which is practiced these days (UNESCO-IAEG, 1976) and is involved:

i) A taxonomic classification of rock and soil units delineated on engineering geological maps at various scales.

ii) A lithological classification, and the identification of fundamental lithological names to rock and soil units.

iii) A description of rocks and soil material and mass and the assignment of descriptive names for rock and soil types.

In the study area most of the flat area is covered by thick (2-6m) soils. The distinction of such soils relative to rocks outcropping in the area is based on the work of Anon (1972). According to the author,

"Soil is an aggregate of mineral grains that can be excavated without explosive or equipment for loosing. Rock, on the other hand is a natural aggregate of minerals connected by strong and permanent cohesive forces".

In the present work to determine engineering geological characteristics of the rocks and soils basic site investigation and field analyses was carried out.

5.2. Description of Rocks and Soils in Sibilu Reservoir Area for Engineering Purposes

5.2.1. Rock Descriptions

Rock mechanics is defined as the science dealing with the application of the principles of mechanics to the understanding of the behavior of the rock masses. A rock mass is rarely continuous, homogeneous or isotropic. It is usually intersected by a variety of structures and discontinuous such as faults, fractures, joints, bedding planes etc. In addition, there can be a number of different rock types, which may have been subjected to varying degrees of alteration or weathering. It is clear that the behavior of the rock mass depends on the characteristics of both the rock material and the discontinuities.

A complete engineering geological rock mass description contains details of the rock material and the natural discontinuities. For the present work the descriptive scheme, which has been proposed by ISRM (1981), is followed to fully characterize the rock masses (annex-D). In this rock description the main characteristics is given in the following order:

i) Rock name: supplementary petrographic properties.

ii) Rock material properties: color, texture (grain size, other textural features and fabric), state of weathering and strength.

iii) Rock mass properties: structure, discontinuities and weathering profile.

Following this description scheme, the rocks outcropping in the Sibilu reservoir area are characterized as follows. In the study area there are three lithological rock units: basalts, trachyte and pyroclastic deposits.

A. Basalt

This rock unit shows different local variations, which would influence its engineering significance. To describe it in detail, an attempt is made to identify a parameter that assembles most of its engineering properties. It is found that most engineering properties lies within the same textural variety. So here, texture is taken as a basic factor to group this basaltic rock unit into its different engineering subgroups. These are aphanatic basalt, scoracious basalt, vesicular basalt and halocrystalline basalt.

Aphanatic basalt: this textural variety of the basaltic rock is the dominant and widely distributed. The degree of weathering exhibits a good correlation with types of joints i.e. a massive rock which is jointed by various set of joints show high degree of weathering while columnar jointed basalt is slightly weathered, and rarely flow banded basalt.

i) Massive aphanatic basalt: it is fractured by minor faults mostly run E-W and NE-SW, and rarely NW-SE dips and steeply to N, NW and SW respectively. There are fractures on this rock, which are usually marked by straight sheared rock fragments, clear straight weak zone covered by brecciated sediments and strong concentration of non-systematic joint systems in aligned zone. These fractures have got a strike length 1.5m to 5m. It is also jointed mainly by three sets of joint systems; at places non-systematic joint systems and N20^{0}W joint set are observed.

The common joint sets are NE-SW, E-W and N-S. Around the dam site the NE-SW is continuous over E-W while in the upstream and eastern bank of Sibilu river E-W joints are continuous over NE-SW, which might indicate the area affected by different phase of deformations. Near the junction of Deneba and Sibilu rivers, the riverbank is jointed by horizontal joints.

NE-SW joint set is tight to moderately narrow (0-10cm), medium spaced (21-32cm) with an average trace length of 13m where it is continuous. Their strikes vary from N10^0-N40^{0}E and steeply dip to SE. Mostly they are dry, rough, and planar (category VII) and filled with soil.

E-W joints are wide (63-140 mm), closely spaced (5-17cm), dry, smooth, undulating (category V) around the dam site; very wide (10-15cm), widely spaced (70-200cm), with an average trace length of

5m.They are continuous in the central reservoir (Fig 5.1). Their strike varies 80^0-100^0 and steeply dip N. Mostly they are wet, smooth, planar (category VIII) filled with soil and transported sediments. *N-S joint set* are moderately wide to wide (20-170mm), closely spaced (40-270mm). Their strikes vary from 355^0 to 05^0 and steeply dip to E. They are dry, rough, stepped (category I) and filled with soil and rarely with calcite. The horizontal sets of joints at the riverbanks are tight to narrow (0-5mm), closely spaced (4-16cm), dry, smooth, undulating (category V) and bisected by vertical joint systems running E-W with an aperture of 1.3cm to 5cm and 60cm to 1m spacing. The vertical joints are dry, rough and planar (category VII) and filled with soil (Fig 5.2). There are also two horizontal joints, which slightly dip 5^0-15^0 to the east, very wide (25 and 32cm), spaced 30 to 35cm, persistence with strike length of 80m, exposed at the eastern flanks of the river in central reservoir. These joints are filled with soil and show growth of plants with smooth and planar surface (Fig. 7.7).

Usually the massive aphanatic basalts exhibit large equidimensional blocks (Eq-type) around the dam site. It shows medium sized polyhedral blocks (Po-type) in the other parts and at the center of the reservoir due to those two long horizontal joints the blockiness nature is tabular (Ta-type), which are very large. This rock variety is strong and weathering grade IV around the dam site while very strong and weathering grade II in most of the reservoir parts and riverbanks, while grade III in the reservoir flanks.

Figure 5.1. E-W wide and continues joints in central reservoir

ii) Columnar aphanatic basalt: it is exposed in the riverbed and in northeastern flanks of the reservoir. Due to its columnar nature it exhibits hexagonal sheet surfaces at the riverbeds. Columnar joints dip vertically and show narrow aperture (0.22-0.6 cm). They are wet at the riverbeds and dry at the other places, smooth and planar (category VIII).

The columnar aphanatic basalt exhibits very large columnar blocks (Co-type), very strong and weathering grade II.

Figure 5.2. Orthogonal joint sets at the riverbank

Scoracious basalt: this textural variety is jointed with two dominant systematic joint sets and at places the non-systematic ones are present. The systematic joint sets are E-W and NE-SW. The E-W joint system is continuous. This set of joints is continuous with on the average 1-1.5m trace length; medium spaced (27-43cm), tight to narrow (<10mm). Their strike varies 85^0-95^0 and steeply dips to the north. The discontinuity surfaces are rough and undulating (category IV) while a NE-SW joint set is moderately narrow to wide (0.5-2cm), widely spaced (0.5-1.1m). Their strike varies 40^0-55^0 dip steeply SE, mostly they are dry, rough, undulating (category IV). Scoracious basalts mostly exhibit polyhedral blocks (Po-type) and large in size; very strong and weathering grade II.

Vesicular basalt: this textural variety is jointed with both systematic and non-systematic joint sets of which the non-systematic ones are dominant. There are two systematic joint sets, E-W and $N20^0W$.

The discontinuity surfaces are rough and undulating (category IV) while an NW-SE joint set is moderately narrow to wide (0.6-2.1cm), widely spaced (0.5-1.1m). Their strike varies 295^0-340^0 and dip steeply SW. mostly they are dry, rough, undulating (category IV). Vesicular basalts mostly exhibit polyhedral blocks (Po-type) and large in size; very strong and weathering grade III.

Halocrystalline basalt: this textural variety is jointed by non-systematic joints, E-W and 280^0-285^0 running joint sets.

The E-W joints are moderately narrow (10-15mm), moderately spaced (2-6.8cm), with average trace length of 20m. It is continuous over the other joint sets but abruptly cut by N-S fault. Their strike varies 260^0-280^0, and are vertical. They are dry, steep (category I) joints.

The 280^0-285^0 joints are moderately open (2-20cm), very widely spaced (6-7.2m) with an average trace length of 7m. They dip 20^0-35^0 to NNE. They are dry rough and undulating (category IV) joints.

The halocrystalline basalt exhibits very large polyhedral blocks (Po-type), very strong and weathering grade II.

B. Trachyte

This unit also shows local variations, which influence its engineering properties. Here it is divided into massive trachyte and columnar jointed trachyte.

Massive trachyte: due to its high degree of weathering it was difficult to observe the joint sets very clearly, but it is possible to identify three sets of joints; namely E-W, N-S, and NE-SW running joints.

E-W joints are moderately wide (2-5cm), closely spaced (3-16cm), dry, rough and undulating (category IV). Their strike varies from 85^0-90^0 and dip steeply to the north.

N-S joints are tight to very narrow (0-4mm), widely spaced (77-135cm), dry rough and undulating (category V). Their strike varies 25^0-45^0.

Usually the massive trachyte exhibits small polyhedral blocks (Po-type). It is medium strong and weathering grade IV.

Columnar jointed trachyte: the columnar joints dip steeply to south and become vertical to the north. It exhibits narrow aperture (2-4mm), dry, smooth and planar (category VIII).

The columnar jointed trachyte displays very large columnar blocks (Co-type), very strong and weathering grade II.

C. Pyroclastic Deposit

This pyroclastic deposit is found in the study area in two forms: friable pyroclastic deposit and compact pyroclastic deposit. The engineering properties of this unit are also described in these two forms:

Friable pyroclastic deposit: is well exposed at the western riverbank of the Sibilu dam site and intercalated with the basaltic unit, which has 6-8m thickness. This deposit is banded (thin agglomerate bands with tuffaceous pyroclastic deposit), fissured and mostly contacts with the overlying and underlying basaltic units, which show shear planes. The fissures occasionally filled with paleosoil (Fig 5.3). One set of fissures run 80^0, which intersect with agglomerate bands, show the sign of seeping water and they are wet. This condition may explain the discontinuity fissures and the agglomerate bands, which promote the permeability of this deposit.

Usually this deposit exhibits friable sediments in weathering, weak and displays weathering grade V.

Welded pyroclastic deposit: is exposed in the Ochi ridge. This welded pyroclastic deposit is jointed by three sets of joints: namely N-S, E-W and $N20^0$-$N40^0E$.

N-S joints are tight to moderately narrow (<1.5cm), medium spaced (20-30cm), continues and persistence with an average trace length of 8m, dry, smooth and planar (category VIII).

E-W joints are narrow to moderately narrow (0.2-1.15cm), closely spaced (2-10cm), cut by the N-S running joints, dry rough and undulating (category IV). $N20^0$-$N40^0E$ joints are moderately wide to wide (3-10cm), closely spaced (10-14cm), non-persistence, dry, rough and undulating (category IV). The opening of these joints filled with soil.

This welded pyroclastic deposit exhibits medium to large polyhedral blocks (Po-type), moderately strong and weathering grade II.

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Figure 5.3. Fissured pyroclastic deposit

5.2.2. Soil Descriptions

Soil mechanics is the science dealing with the basic scientific principles to understand soil behaviors in engineering practices. In nature, soils occur in a large variety. However, soils exhibit similar behavior can be grouped together to form a particular class in engineering uses; tests used to characterize the particular properties. The numerical results obtained on the basis of such tests are termed index properties of soils. The index properties of soils are soil grain properties and soil aggregate properties. Soil grain properties are those properties, which are dependent on the individual grains and manner of soil formation. The properties in this group are mineral composition, specific gravity, size and shape of grains.

Soil aggregates properties are those properties, which are dependent on the soil mass as a whole. These properties are of greater significance in engineering construction, since engineering structures are founded on undisturbed, natural soil deposits. The index properties are grain size distribution, Attergerg limits and indices of consistency. Characteristics of soils such as the size of the particles, shape and the degree of roundness are influenced by the basis of its geological origin.

followed to fully characterize the soil masses (annex-D). In this description the main characteristics are explained in the following order.

i) Soil name: genetic type and including minor constituents with their plasticity limits.

ii) Soil material properties: color, texture (particle shape, and composition) state of weathering, strength (consistency, shear strength, moisture content and compactness.)

iii) Soil mass properties: structure, discontinuities, weathering profiles.

The engineering geological soil units in the Sibilu reservoir are grouped under their genetic types: residual soil, alluvial soil and colluvial soil. These groups identified from their geomorphologic setting.

A. Residual Soils

These soils are formed by insitu weathering of rocks. They are observed in most of the high altitude areas and gently sloped part of the study area. The most abundant soils within this genetic group are clays, sandy clay and gravelly clay (Table 5.1).

Clay Soil: Most of the residual soils are clay in the study area. The grading characteristics of the particles size show that: clay fractions (<0.002mm) ranges 63-65%, silt sized (0.002-0.74mm) particles range 25-32%, sand sized (0.74-2mm) particles are 5% in all samples while the gravel sized (>2mm) particles range 1-5%. The range of their liquid limit is 65-94%, which is of high to very high plasticity group. Even their plastic indexes (30-77 %) conform that they are grouped in high plastic nature. The residual clay soil is reddish gray and/or dark gray in color and slightly weathered. Its strength is found to be firm to stiff from field test and also conformed by the laboratory results i.e. its consistency indexes ranges from 0.5 to 0.9. This soil mass show fissures at places, which is usually filled by coarse rock fragments and display weathering grade II.

Gravely Clay: These soil types constitute the upper most part of residual soil group, in relatively sloped areas. The particle size grading by clay fraction ranges 37-38%, silt sized particles around 24%, sand sized particles 14-17% and gravel sized particles 22-24%. From their liquid limits (36-38%), they are of intermediate plasticity. Also their plastic indexes show they are moderately plastic in nature i.e. 8-11%. The residual gravely clay is brown red in color; the grains show angular and irregular form, with

rough surface characteristics. It is slightly weathered. Its strength is found to be stiff from field tests and laboratory results i.e. consistency indexes are 0.85-.0.90. This clay soil type exhibits weathering grade II.

Sandy Clay: This type is not much frequent as the above two in the residual soil. The sieving analysis of this soil type shows: clay fraction 34-36%, silt sized particles 20-25%, sand sized particles 38-39% and gravel sized 2-4%. From their liquid limits they show intermediate plasticity group, but from their plastic indexes, they have a tendency to show high plastic nature (12-18%).The residual sandy clay is brownish red in color; the grains show angular edges with rough surfaces. It is slightly weathered. Its strength is soft from field test and laboratory results i.e. consistency indexes are around 0.2. This soil mass show some intercalation nature at places and exhibits weathering grade II.

B. Alluvial Deposit

These masses of sediments, deposited long the main Sibilu River valley where there is a decrease in gradient from a hill or a mountain to a plain. These deposits are dissected by deep gully. These deposits include soils, which have been deposited in the channels and flood plains of the rivers and streams. Fine silts and clays are deposited in the thin layers characterize them. At the southern part of the reservoir area some oxbow and meander scar deposits are present (when parts of the meandering channel are cut off from the stream) and are characterized by fine-grained soils, which are near normally consolidated and relatively highly compressible (Table 6.5).

Silty Clay: the upper most part of alluvial deposits characterized by this type of soil. Its grading characteristics are: clay fractions are 46-51%, silt sized particles 37-41%, sand size particles 6-11% and gravel sized 4-5%. From their liquid limits (28-34%), they are of low to intermediate plasticity. Their plastic indexes show they are slightly plastic (2-6%). The alluvial silty clay is brownish red, reddish and pale red in color, the grain show rounded form. It shows a tendency of high erodibility and high weathering. Its strength is measured as soft to firm from field test and laboratory results i.e. consistency indexes are 0.15-0.35. They become very soft near and around seepage surfaces. This soil mass show cracks and fissures and exhibits weathering grade IV.

Clay: most of the alluvial deposits in the study area are composed of this type of soil. In the Sibilu reservoir this alluvial clay are two types: the black cotton clay and dark gray clay.

- The black cotton clay show relatively high clay fraction content and high liquid limit and plastic index. The sieving analysis of the black cotton clay 65-68% of clay fractions, 26% silt sized particles, 3-6% sand sized particles and 3% of gravel sized particles.
- The dark gray variety show clay fractions of 57-64%, silt sized particles 27-31%, sand sized particles 5-9% and gravel sized particles 3-4%. From their liquid limit black cotton clay (104-106%) are of extremely high plastic group and dark gray clay (92-94%) are also of extremely plastic group. Even their plastic indexes (black cotton clay 83-85 and dark gray clay 74%) conform their extremely high plastic nature.

The alluvial clay soil show high degree of compressibility and erodibility. The black cotton soils are stiff (CI= 0.75-0.85) while the dark gray variety are firm (CI= 0.5-0.75) and show decreasing in the strength near and around seepage surfaces from field tests. This alluvial soil mass show cracks and fissures, which are often slickensided. It also exhibits weathering grade IV.

C. Colluvial Deposit

These deposits are soils, which have been eroded and deposited under gravity forces often with the aid of water. These deposits include:

- Soils which are admixture of clay, sand and gravel that, have been moved down slope by combined action of soil creep and erosion by water (slope wash soils).
- Soils with admixture of almost all types of materials from clay to large rock fragments i.e. large boulders embedded in a clay matrix (land slide debris).

The samples collected in these deposit show two types of soils gravely clay and clayey gravel (Table 5.1).

Gravely Clay: is found in less sloppy areas i.e. of the most southern part the study area. The sieving analysis of this soil give: 30-31% of clay fractions, 23-24% of silt sized particles, 13-15% of sand sized particles and 31-34% of gravel sized particles. From their liquid limits (31-37%), they are of slight to

moderately plasticity groups, but from their plastic indexes (6-7%), they have shown slightly plastic nature.

The colluvial gravely clay is reddish brown in color, the grains show sub-angular to sub-rounded form. They are highly weathered and show high degree of erodibility and compressibility. Its strength is measured as stiff from its consistency index (0.75-0.80), but somehow soft to firm from field tests. This soil mass show eroded profiles and cracks and also exhibit weathering grade III.

Clayey Gravel: is a characteristic feature of high-sloped areas. Their sieving analysis result show 12-15% 0f clay fractions, around 16% of silt sized particles, 8-18% sand sized particles and 54-61% of gravel sized particles. From their liquid limits (12-16%) they are of low plastic materials and their plastic indexes (0.5-0.8). indicate that they may be grouped under non-plastic types.

This soil is dark gray in color; the grains show sub-angular to sub-rounded form with rough surface characteristics. Its strength is very soft from its consistency indexes (0.05-0.1) and exhibits weathering grade III.

Table 5.1. Summary of soil sample test results in the reservoir area.

S No.	Depth (m)	Origin	Color	Sieving analysis (%)				Index values (%)				n.m.c (%)*	S.g.	F.s. (%)
				CF*	M*	S*	G*	SL*	LL*	PL*	PI*			
CLAY														
Sa4	1.6	alluvial	Black C	68	26	3	3	9	104	21	83	33.45	2.78	160
Sa5	1.8	alluvial	Black C	65	26	6	3	11	106	21	85	42.25	2.71	152
Sa6	1.8	alluvial	Dark g	62	29	5	3	8	94	20	74	57	2.84	123
Sa7	1.6	alluvial	Dark g.	64	27	5	4	12	92	18	74	47.6	2.90	126
Sa8	1.0	alluvial	Black C	57	31	9	3	9	101	19	83	38.75	2.89	127
Sr1	1.4	residual	Dark g.	63	32	4	1	11	94	17	77	47.8	2.87	97
Sr2	1.2	residual	Dark g.	65	29	5	1	11	89	20	69	54.5	2.91	98
Sr3	1.0	residual	Red. g.	64	28	5	3	14	70	38	32	41.2	2.90	86
Sr4	0.8	residual	Red. g.	65	25	5	5	15	65	35	30	47	2.88	82
GRAVELY CLAY														
Sr7	1.2	residual	red	37	24	17	22	18	36	28	8	28.8	2.74	12
Sr8	1.0	residual	red	38	24	14	24	19	38	27	11	28.65	2.79	56
Sc3	1.5	colluvial	reddish	30	23	13	34	15	31	25	6	26.5	2.78	32
Sc2	1.0	colluvial	reddish	31	24	14	31	17	37	30	7	31.4	2.81	37
SILTY CLAY														
Sa1	1.4	alluvial	Red gray	51	39	6	4	18	34	29	5	33.25	2.71	54
Sa2	1.1	alluvial	Pale red	46	41	8	5	19	32	26	6	30.5	2.86	57
Sa3	1.6	alluvial	brownish	47	37	11	5	18	28	26	2	27.3	2.85	51
SANDY CLAY														
Sr5	1.2	residual	red	36	22	38	4	20	46	24	18	42.4	2.91	54
Sr6	0.8	residual	red	34	25	39	2	25	43	31	12	40.6	2.81	67
CLAYEY GRAVEL														
Sc4	0.6	colluvial	Pale g.	15	16	8	61	-	16	15.5	0.5	15.95	2.61	-
Sc1	1.6	colluvial	gray	12	16	18	54	-	12	11.2	0.8	11.96	2.63	-

Cf – clay fraction (<0.002mm), M- silt sized (0.002- 0.74 mm), S- sand sized (0.74 2.0mm), G- gravel sized (>2mm) particles under US. Standard sieves i.e. No.4- 4.76, No.10-2mm, No.40- 0.42mm, No.60- 0.25mm, No.200- 0.074; SL- shrinkage limit, LL- liquid limit, PL- plastic limit, PI- plastic index, S.g.- Specific gravity; n.m.c.- natural moisture content F.s-free swell;

Black C- black cotton , Dark g. – dark gray

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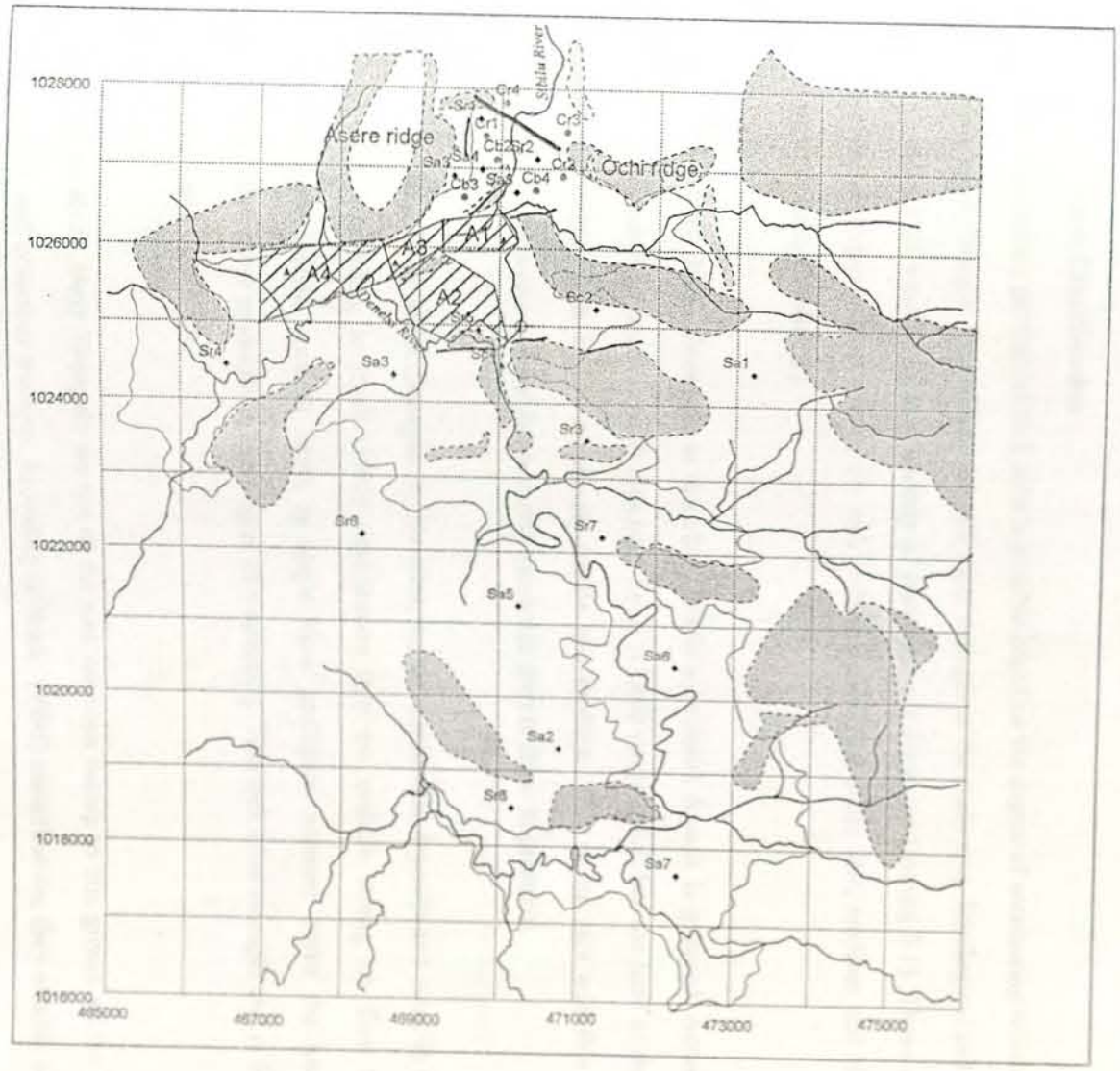

Figure 5.4 Sample Location Map of Sibilu Reservoir Area
(reduced from 1:12,500 scale)

N
W E
S

Scale 1:90,000

LEGEND

- Quaternary deposites
- Basaltic rock
- Trachytic rock
- Pyroclastic deposites
- Reservoir area
- River / stream
- Inferred contact
- Fault
- Dam site
- Clay borrow areas for construction
- Soil samples for physical analysis
- Soil samples for chemical analysis
- AE-HBT soil samples for compaction analysis
- Water samples location
- Sibilu - Deneba gauging station

5.3. Classification of Rocks and Soils in Sibilu Reservoir Area for Engineering Geological Mapping

Engineering geological classification involves grouping of different rock and soil types into categories, which possess similar properties. The classification should take into account both the field and laboratory results used as description parameters. So based on the full description of engineering geological materials, simple classifications of rocks and soils can be drawn by selecting basic parameter (strength, genesis, etc.) in engineering geological maps (Price, 1983). The rock and soil units of the reservoir are mapped into different engineering geological units (Fig 5.6).

5.3.1. Rock Mass Classification

Mapping engineering geological rock units is possible based on the degree of weathering which reflects their rock mass strength. To estimate the rock mass strength in the study area, lithological and textural features, degree of weathering and intensity of fracturing are discussed (section 5.1). Those different engineering geological subgroups of the rock units are classified under low, medium and high rock mass strength units (Table 5.2).

Low Rock Mass Strength: in this class, friable pyroclastic deposit is grouped. According to Hoek (1995) classification, it is weak rock mass i.e. it is knife cut material, but too hard to shape into defined specimens. It is highly weathered, friable and erodable. Due to its rare and thin (6-8m) exposure in the reservoir it is not mapped, only symbol is used to show its presence.

Medium Rock Mass Strength: in this class, welded pyroclastic deposits and massive trachyte are grouped. According to Hoek (1995) classification they are medium strong i.e. firm blow of geological pick indents rock to 5mm; or single blow geological hammer broke the hand held specimens. They show moderate to high degree of weathering. This rock mass strength unit is found on the dam axis and Ochi ridge.

High Rock Mass Strength: the rest of the rock outcrops belong to this group: all the basaltic unit varieties and columnar trachyte. According to Hoek (1995) classification, they exhibit strong to

extremely strong nature i.e. requires blows of geological hammer to break the intact rock specimens. Number of blows used to distinguish between strong and very strong. The fresh parts almost always show extremely strong behavior because they are only chipped under repeated hammer blows and rings when struck. This unit is the most abundant rock mass strength unit in the reservoir area.

Rock mass strength	Engineering subgroups	Strength	Weathering profiles groups
High	Aphanatic basalt	Strong to extremely strong	I-III
	Scoracious basalt	Very strong	II
	Vesicular basalt	Strong to very strong	III-IV
	Halocrystalline basalt	Very strong	II
	Columnar trachyte	Very strong	II
Medium	Massive trachyte	Medium strong	IV
	Welded pyroclastics	Medium strong	II
Low	Friable pyroclastics	Weak	IV

Table 5.2. Engineering subgroups of Sibilu reservoir rocks, their description and classification.

5.3.2. Soil Units Classification

An area is mapped as a soil unit, if the thickness exceeding 1m. (Scoters and Rangers, 1981). If the thickness is less than 1m, the area is mapped as the bedrock. The thickness of 1m is chosen due to the following reasons: first the morphology of the underlying bedrock is usually recognizable when the thickness exceeds 1m; and second, the engineering geological importance of a soil cover with less than 1m thick is rather limited.

Eventhought several soil classification systems are in use, the unified soil classification system (USCS) is employed for classification of soils of the study area (annex-E). The classification method used is based on grading of the constituent particles and plasticity of the fraction of the material consisting of particles finer than 0.425mm.

For the purpose of laboratory classification of soils using USCS (Fig. 5.6), 20 samples were selected from different type of soils with an even distribution throughout the reservoir area (Fig. 5.3). They exhibit clays and silts of different plasticity groups and clayey gravels. According to this classification system the soils of the studied area are classified into MI, ML, OH, CL, CH, CV, CE and GC (Table 5.3).

Inorganic Clays of Very High to Extremely High Plasticity (CV/CE): these types of clay soils cover most of the dam site, central and southern part of the reservoir. They are black clay soils and alluvial and residual in origin. They show extremely high plasticity. Their general properties including their use as a foundation material is largely determined by their clay fractions and mineralogy. Since the clay fraction in these soils is greater than 60% and montimorillonite is the dominant mineral (section 6.3); they have the ability to hold large quantity of water. This characteristic has a great influence on their shear strength, shrinkage and swelling properties.

When they are saturated their strength becomes poor, and fail easily while they are compacted. In dry months, however, their strength increases due to loss of moisture and shrinkage cracks of various dimension appear. During the wet months, they again absorb water and swell to greater degree. This process of swelling and shrinkage are not good as a foundation material and recommended to avoid them as possible (Truitt, 1983).

Organic Clays of High Plasticity (OH): these soils are the red clay varieties and residual in origin. They are dominant in the eastern part of the reservoir flanks. Their organic character may arise from cultivation and tree planting activities (no organic test is done). They are high in dry strength and hard enough and fall in the group of high plasticity. Generally, it is possible to suggest, on the basis of global properties of both CH and OH, for engineering use that they are both impermeable, poor quality as a construction material of high compressible as compared to other groups (Truitt, 1983).

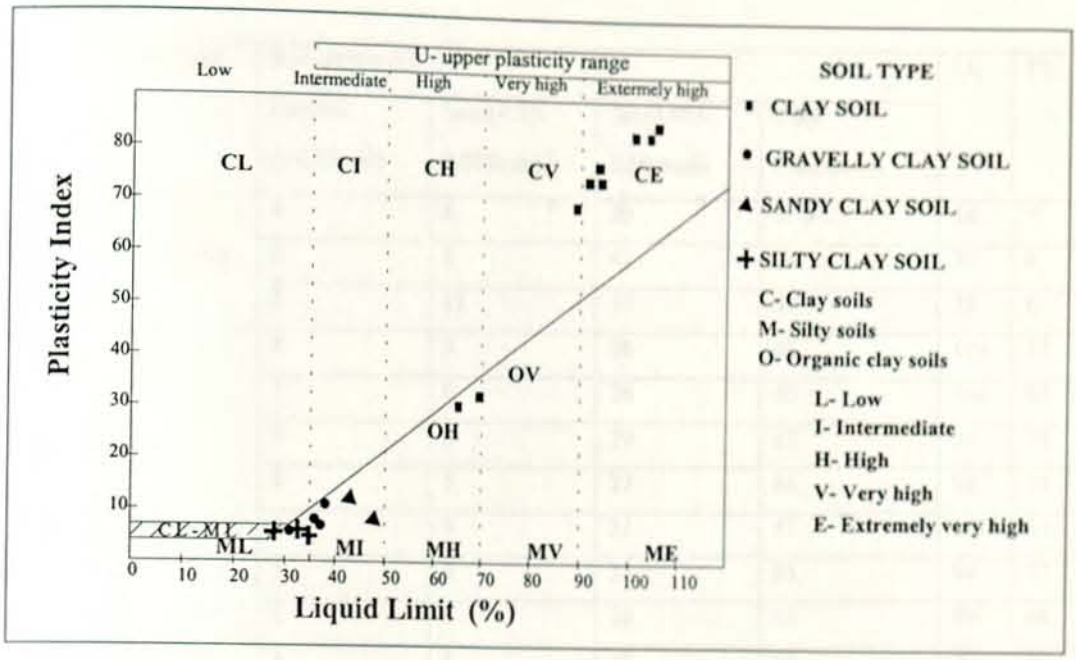

Figure 5.5. Plots of the reservoir soils on the USCS chart for fine-grained soils

Inorganic Silts and Clays of Low Plasticity, Gravelly Clays, Sandy Clays, Silty Clays, and Lean Clays (CL / ML): These soils are dominant in the western part of the reservoir area. CL and ML vary only with their dominant clay or silt percentage respectively. They are mostly light red, reddish brown and red varieties. They are soft to stiff with low plasticity. In terms of origin these soils are grouped mainly into two: those of insitu weathering products and those of alluvial origin, rare colluvial origin are also noted. The degree of cracking as compared to those CE and OH groups is low. The engineering aspects of these soils are low permeable, low compressibility when compacted and saturated, fair as foundation compared with other groups (Truitt, 1983).

Clayey Gravels, Poorly Graded Gravel-Sand-Clay Mixture (GC): this group of soils is found in colluvial deposits and at depth underlying the clay soils. They are rare in the reservoir area and are colluvial in origin. They are permeable, low compressible, fair workability as construction materials and fair to good foundation if seepage is minimal (Truitt, 1983); however in two of the boreholes at the dam axis such types of soils present at shallow depth, so they can act as a seepage line through the foundation. Hence it is recommended to remove or curtain grouting beyond their depth.

Sample No.	Soil type	Soil fractions (%)				LL	PL	USCS
		Gravels (>4.75mm)	Sand(4.75-0.075mm)	Silt(0.075-0.002mm)	Clay. (<0.02mm)			
Sa1	Silty clay	4	6	39	51	34	5	ML
Sa2		5	8	41	46	32	6	ML
Sa3		5	11	37	47	28	6	CL-ML
Sa4	Clay	3	3	26	68	104	83	CE
Sa5		3	6	26	65	106	85	CE
Sa6		3	5	29	62	94	74	CE
Sa7		4	5	27	64	92	74	CE
Sa8		3	9	31	57	101	83	CE
Sr1		1	4	32	63	94	77	CE
Sr2		1	5	29	65	89	69	CV
Sr3		3	5	28	64	70	32	OH
Sr4		5	5	25	64	65	30	OH
Sr7	Gravelly clay	22	17	24	37	36	8	MI
Sr8		24	14	24	38	38	11	MI
Sc3		25	13	23	39	31	6	ML
Sc2		31	14	24	31	37	7	MI
Sr5	Sandy clay	4	38	22	36	48	18	ML
Sr6		2	39	25	34	43	12	ML
Sc4	Clayey gravel	61	8	16	15	16	0.5	GC
Sc1		54	18	16	12	12	0.8	GC

Table 5.3. Classification of the reservoir soils using USCS.

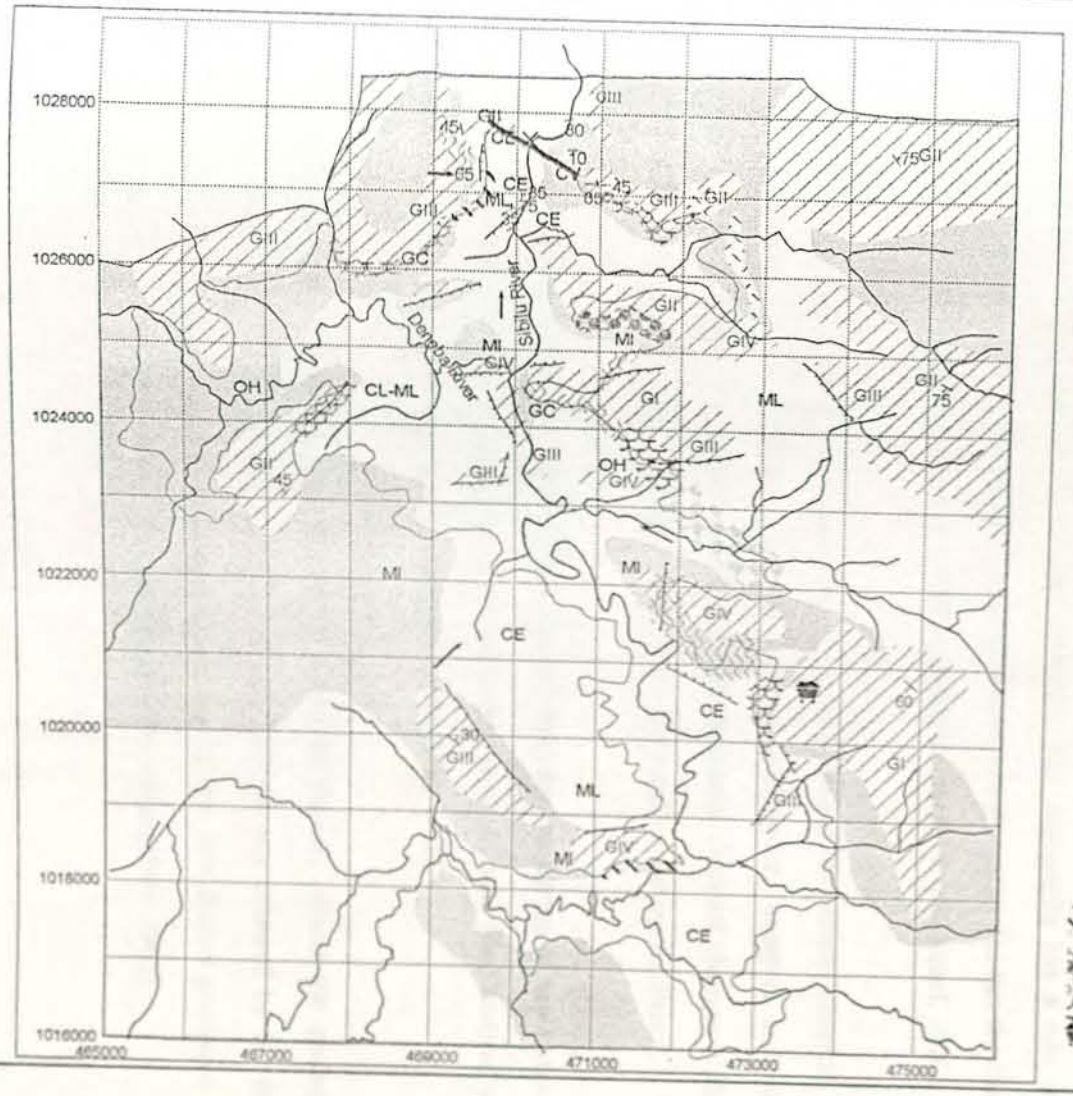

Figure 5.6 Engineering Geological Map of Sibilu Reserviour

(reduced from 1:12,500 scale)

Scale 1:90,000

N
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S

Soil units

- Alluvial deposits
- Residual soils
- Colluvial deposits

Unified soil classification system, Wagner, 1957

CE - Inorganic clays of extremely high plasticiy, fat clays.
CV - Inorganic clays of very high plasticity, flat clays
OH - Organic clays of high plasticity
CL - Inorganic clays of low plasticity, gravely clays, sandy clays, silty clays
ML - Inorganic silts and clays, silty or clayey sands with slight plasticity.
GC - Clayey gravels, poorly graded gravel-sand-silt mixiture.

Rock mass strength units

- High rock mass strength
- Medium rock mass strength
- Low rock mass strength

Weathered rock substance classification, Hosking, 1990

Grade I Rocks show no evidence of weathering, very slight color change
Grade II Rock is slightly discolored, but rings when struck by a hammer
Grade III Rock is discolored, produces only a dull thud when sruck by a hammer
Grade IV Rock is discolored, can be broken and crumbed by hand, but does not readily disintegrated in water
Grade V Materials disintegrates, when shaken in water, i.e. has soil properties

- Landslides, general
- Soil creep
- Toppling
- Rock fall
- Potential land slide
- Quarry site
- Fault
- Reservoir area
- Dam site
- River \ streams
- 45 strike \ Dip
- Local groundwater flow direction

CHAPTER-6 GEOTECHNICAL PROPERTIES OF SOILS IN SIBILU RESERVOIR AREA

6.1. Evolution and Genesis of Soil Formation

Soil is formed as a result of the interaction of many factors that act simultaneously, the most important of which are parental material, climate, topography and time. The processes of weathering profiles and soil formations are governed by the interactions of factors defining the initial state of the soil formation (parental material and relief), the environmental factors (climate and organisms) and the extent of reaction (time).

Soil may be formed by weathering of consolidated rocks or by developing from transported or organic materials, and climate has a direct or indirect impact on soil formation (Graef, 1996). Every climate type favors typical soils depending on the parental materials. Also topography has a role in the interaction of climatic and environmental factors. Time is a dimensional parameter that ties the climate, topography, parent materials and other factors to change the parental material to soil (Graef, 1996).

One of the most important processes for soil formations is the weathering of the parental material. This includes wearing down of the landscape with the help of detachment, transport and initial fragmentation of rock as well. This physical disruption then facilitates chemical changes with the constituent minerals. Water initiates solution and hydrolysis as a chemical weathering facilitator.

The soils in Sibilu catchment are principally residual, derived from the weathering of basic volcanic rocks, which cover much of the area. They do not form significant gravel and sand sized material upon weathering. The soils are invariably clays or silty clays (Morin and Parry, 1971).

The physiography of Sibilu catchment, as a part of the Ethiopian plateau, reflects the geological evolution of the East Africa region. Uplift of east Africa and Ethiopia was followed by the down faulting of the rift valley system. The rift system divides the country into four distinct provinces: the Ethiopia plateau, the eastern plateau, the Main Ethiopia Rift and Afar region (Mohr, 1967).

The Ethiopian plateau is generally above 1000m a.m.s.l., high except for the major river valleys, and much of the area over 2000m a.m.s.l. (Morin and Parry, 1971). It has been covered by lava of predominantly alkaline flood basalts (Mohr, 1971). In Ethiopia, the areas of high rainfall are roughly coinciding with areas covered extensively by volcanic matter (Thompson, 1965). So the mean annual rainfall of the area is 1228.3mm, the mean number of days having over 1mm of rainfall is always above 150 days (NMSA). And its annual temperature (max= 18^0c, min= 8^0c, average 13^0c) is above 12^0c, which reflects the study area has a climatic condition of humid and warm. Then, these climatic features of the area are in favor of high rate of chemical weathering as that of tropical climatic regions.

Drainage density of the catchment varies from poor to good. The good drainage condition is typical for southern and eastern part of the catchment and become poor in the central plain. Thus, the drainage is a good reflection of the topography i.e. well drained areas are corresponding to sloped areas, while the flat and gentle terrains are associated with poor drainage condition.

Though there are local varieties and interactions of the soils of the area, they can be broadly grouped into two types: the red clays and the black clays. The red clay varieties range from red to reddish brown, while the black clays are dark gray clays, black cotton clays and dark brown clays. These soils are also clearly associated with drainage condition; the red clays are mostly observed in well-drained areas and black clays observed in poorly drained areas.

Under mild weathering conditions clay minerals can be inherited from primary silicates (primary clay minerals such as mica and chlorite). But usually under more intense conditions like the study area, they are rather formed after hydrolysis of the primary silicates (neoformation to secondary clay minerals such as illite, kaolinite and montimorillonite). Hence from the governing parameters (climate, topography and parent material) of the area, the probable clay minerals formation can be deduced (Grim, 1968). In this premises, in volcanic terrains of well-drained areas kaolinite and halloysite are most abundant clay products in tropical climatic condition while montimorillonite in poorly drained areas. In between these extremes mixed clays and illites can be predominant (Grim, 1974). This statement is mostly coinciding with the Ethiopian plateau volcanic soils (Morin and Parry, 1971).

Therefore, the black and red verities of clay soils of the area, which are developed over the basalt and trachyte, may be characterized as follows. Montimorillonite is expected to be the predominant clay mineral in the black clays; and kaolinite and halloysite to that of the red clays. The western part may be in between these two extremes and may be characterized by mixed clays and illite. But other tests like X-ray diffraction patterns or differential thermal analysis (DTA) or electro microscope should be used for clear conformations. In this paper, this deduction is further clarified by their geotechnical properties (section 6.3).

Partial chemical analysis of eight samples (four black clays and four red clays) of the Sibilu reservoir, which are analyzed in the National Soil Laboratory, show that the black clays have an average of 41% silica, 14.1% of total iron and 25.7% of alumina. Red clays have got an average of 34% silica, 24.5% of total iron and 24.9% of alumina. The average composition of basalts of the Ethiopia plateau (Barth, 1962) is 44% silica, 13% of total iron and 9% of alumina. The loss of silica in black clays is slight, but more evident in red clays. With these, the area is similar to other Ethiopian volcanic soils and to those tropical soils in general (table 6.1).

The bonding mechanism present in clay minerals is exchangeable cations bonding. The cations, which are held in the space between sheets of clay minerals, can be exchanged for other cations, and in processes, the properties of the clay can be altered. The process is called cation exchange. Cation exchange capacities vary from 54-56.8 milliequivalents per 100g of the red clay soils and from 59.6-65.7 milliequivalents per 100g of the black clay soils (table 6.1). Calcium is the major exchange cations; magnesium, sodium and potassium are also present.

The overall conditions of the clay mineral genesis of the area can lead us to consider the general statement drawn to the Ethiopian volcanic soils by Morin and Parry, (1971) i.e. montimorillonite formed initially in all Ethiopian soils developed over basalt, and in well-drained areas the transformation of montimorillonite to kaolinite has occurred and apparently is continuing at present. Also kaolinite and halloysite are predominantly clay minerals of red soils indicating that alteration of

montimorillonite is more complete in these soils. With these conditions they are similar to that of tropical soils. The red color of the soils is associated with the presence of iron.

Sample No.	Silica (%)	Total iron (%)	Alumina (%)	Exchangeable cations				Cation exchange capacity (millequivalent/per 100g of soil)
				Ca	Mg	Na	K	
ScB1 (black)	41.5	12.6	25	38.14	6.2	9.26	0.92	60.3
ScB2	40.5	15.1	26	35.14	16.04	8.9	0.76	63.1
ScB3	40.8	13.4	26.6	38.12	13.9	9.8	1.3	65.7
ScB4	41.2	15.3	25	41.3	8.2	5.9	0.8	59.6
ScR1 (red)	34	23.8	26.2	41.5	8.88	0.57	0.4	54.85
ScR2	33.8	25.2	23.9	44.2	6.9	0.96	0.5	54.0
ScR3	34.3	24.1	25.1	43.7	9.2	0.8	0.7	56.8
ScR4	34	24.9	24.2	44.2	8.3	0.64	0.22	56.1

Table 6.1. Partial chemical composition and exchangeable cations of Sibilu reservoir clay soils

6.2. Basic Physical Properties

The basic physical properties of soils are very essential in any engineering practices (Cernica, 1995). In dam engineering, soil properties of the reservoir and dam site influence foundation conditions, interaction with the impounding water, siltation problems and their importance for the construction materials (Fell *et al.*, 1992). Information regarding the physical properties of the soils of the studied area was adopted from the soil samples of the present work that are analyzed in Kajima site soil laboratory.

Properties of soils vary not only with soil types but also the grain arrangement and moisture content. So here much emphases is given to the dominant soil groups of the reservoir and dam foundation clays.

6.2.1. Moisture Content

The moisture content of the soil mass is defined as the ratio of the weight of the water to the weight of solid particles. The moisture content determination was carried out in May. The result shows moisture

content varies from 28.6-57%. Black clays varieties have moisture content (38.75-57%) higher than red clay varieties (28.6-42.4%) (table 6.2). This high capacity of holding water in clays corresponds their higher content of clay fractions. From these observations it is clear that black clays higher moisture content values resulted from their greater percentages of clay fractions.

Soil type	Color	Clay fraction (%)	Natural moisture content (%)
Black cotton clay	Black	68	53.45
	Black	65	42.25
Alluvial clay	Dark gray	62	57
	Dark brown	64	47.6
	Black gray	57	38.75
Residual clay	Black	63	47.8
	Dark brown	65	54.5
	Reddish gray	64	41.2
	Red brown	65	47
Alluvial silty clay	Brownish red	51	33.25
	Pale red	46	30.5
	Red-brown	47	27.3
Residual gravely clay	Reddish gray	37	28.8
	Red	38	28.65
Residual sandy clay	Dark red	36	42.4
	Dark gray	34	40.6

Table 6.2. Moisture content of different soils

6.2.2. Specific Gravity

Specific gravity is defined as the ratio between the unit weight of a substance and unit weight of pure water at 4^0c. The result obtained from the present work varies from 2.71-2.91 for clays and clayey gravel 2.61-2.63 (table 5.1); and that AAWSA's samples show the specific gravity of the reservoir soils varies with a range of 2.60 to 2.94. This range is similar to the specific gravities of all tropical soils and within the range of constituent clay minerals as reported by Grim (1968). So the clay fraction proportion governs the reservoir soils property.

6.2.3. Grain Size Distribution and Clay Fractions

Sieve analysis was carried out on the basis of dry and wet sieving. It provides a useful way of classification system for soils. Under such condition, 20 samples were selected from each soil type at different depths and analyses were carried out to determine the range of sizes in which the soil samples fall and their relative proportions (table 5.1). All soil samples are composed of a relative proportion of different size groups although one dominates the other in relative percentages. Clay fractions dominate

and less abundant in transported colluvial deposits. The coarse grain proportion: gravel and sands increase to depth within the soil profiles.

Average grain size distributions of different soil types in the area are plotted using their relative proportions. Clays have 1-3% gravels, 3-9% sands, 25-32% silts and 57-68% clay fractions. Silty clays have 4-5% gravels, 6-11% sands, 37-41% silts and 46-51% clay fractions. Sandy clays have 2-4% gravels, 38-39% sands, 22-25% silts and 34-36% clay fractions. Gravelly clays have 22-31% gravels, 13-17% sands, 23-24% silts and 31-39% clay fractions. Clayey gravels have 54-61% gravels, 8-18% sands, 16% silts and 12-15% clay fractions.

Comparing the black and red clay varieties of the reservoir soils; the black clays (57-68%) have slightly higher clay fraction than the red ones (34-65%).

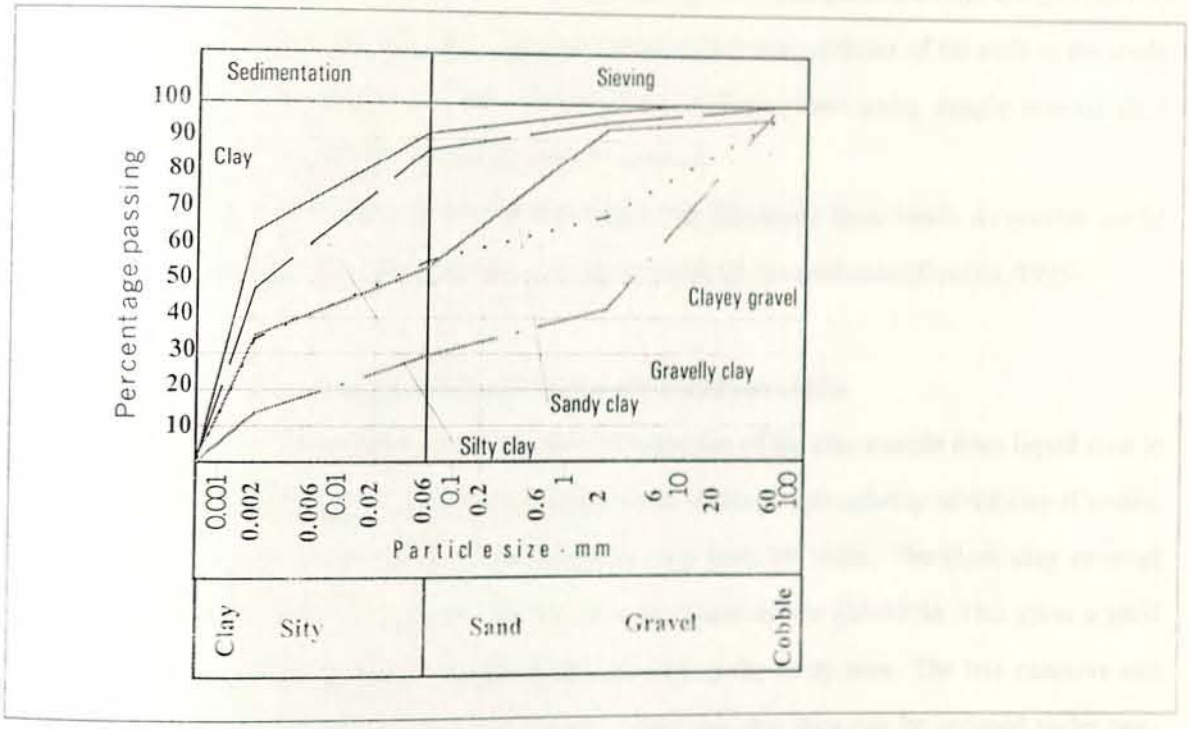

Figure 6.1. Average grain size distribution plots of Sibilu reservoir soils

6.2.4. Consistency Limits and Index Values

For clays and silts the usual classification is derived from their engineering properties under varying conditions of moisture (Cernica, 1995). The Atterberg limits are an empirically developed but widely used procedure for establishing and describing the consistency of cohesive soil. Consistency is a term that is frequently used to describe the degree of firmness (e.g. soft, medium, firm, or hard). The consistency of cohesive soils is greatly affected by the water contents at the soil. A gradual increase of water content may transform dry clay from solid state to semi-solid state, to plastic state and after further moisture increases, into liquid state. The water contents at the corresponding junction points of these states called the shrinkage limit, the plastic limits and the liquid limits respectively. Index properties were determined in Transport Construction Design Enterprise (TCDE) laboratory for AAWSA samples and in Kajima site laboratory samples collected in this present work. Both laboratories followed American Association of State Highway and Transportation Officials (AASHTO) procedure of air-dried samples. Also the degree of coherence between particles of the soils in the study area was roughly determined in the field as soft, firm, stiff and hard using simple manual field identification test and strength characteristics were determined.

The Atterberg limits are of a somewhat empirical nature, but frequently these limits do provide useful information regarding soil strength, behavior, stability and state of consolidation (Cernica, 1995).

A. **Consistency Limits**: Liquid Limits, Plastic Limits and Shrinkage Limits

The *liquid limits (LL),* is the water content at a point of transition of the clay sample from liquid state to plastic state. Liquid limits appear to be directly proportional to the compressibility of the clay (Cernica, 1995). The liquid limits of clay soils in the study area vary from 28-106%. The black clay varieties have values 89-106% while the red clay varieties have got lower values (28-70%). This gives a good evidence for the high compressibility of the black clay soils in the study area. The less cohesive soil clayey gravels have a very low liquid limits 12-16%, signifying that they can be grouped under non-cohesive soils (table 6.4).

The *plastic limit (PL),* is the smallest water content at which the soil begins to crumble. Comparison of the plastic limit with the moisture content of the soils indicates that the soils were above their plastic

state when they are sampled out. The plastic limits of the soils range from 17-38% to which the lower plastic limits are typical for black clays variety (17-21%) and the rest higher values (26-38%)to the red varieties (table 6.4).

The *shrinkage limit (SL),* is the smallest water content below which a soil samples will not reduce its volume any further. The shrinkage limits of the clay soils of the Sibilu reservoir ranges from 8-25%. Also here the lower values are attributed to black clays i.e. 8-11% and higher ones to the red clays (table 6.4).

B. Index Values: Plasticity Index and Consistency Index

The determination of liquid limits and plastic limits are mainly used to determine the valuable indices The *plasticity index (PI)* of soils is essential in dealing with their geotechnical properties. It is used to identify the soil type and describes the soil state of nature (Cernica, 1995) it is given by subtracting the liquid limit to the plastic limit. It is strictly related with its amount of clay fraction.

Plasticity of the soils under investigation shows great variations (table 6.4). All clays of the reservoir soils are high to extremely plastic; the thin top layer of silty clay is slightly plastic and the coarse grained soils are non-plastic. It is possible to say that the high plasticity groups of soils are alluvial and residual in origin.

Comparison between the different group of clays shows that extremely high plasticity is typical to black clays while the red clay soils exhibit relatively lower plasticity. This is clearly shown in the plasticity chart of the reservoir soils. Most of the black clay soils plot above A-line while the red clays plot at and below the A-line of the Casagrande plasticity chart (Fig. 6.2).

The *consistency index (CI)* of a soil helps to describe its strength or degree of firmness. It is given by LL-m/ LL-PL, where m is its moisture content of the soil sample. Though it is an empirical value it is commonly used in describing the degree of firmness. It is also related to its cohesive nature. Consistency indexes of the soils in the study area are given in table 6.4. Most of the clays show firm to

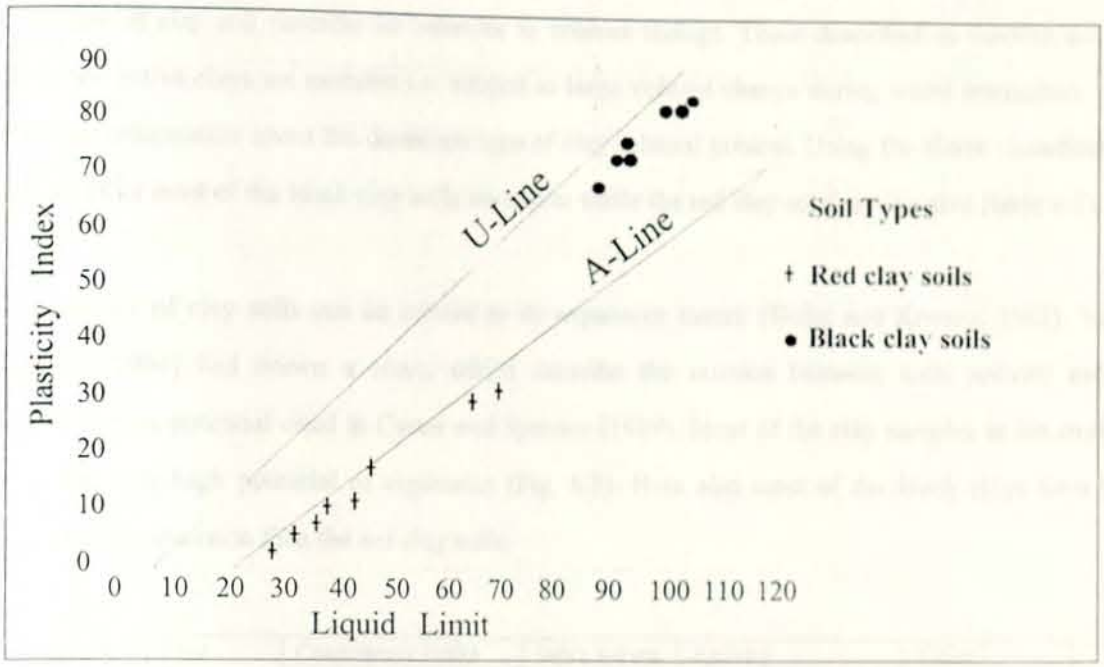

Figure 6.2 Plot of black and red soils on Casagrande Plasticity chart

6.2.5. Activity of Reservoir Soils

Activity of soils is defined as the potential of the soils to interact with water. It usually applied to fine grained soils especially to clays. It is also used to describe its nature when interacted with water. As described above, the plasticity of clay soils is influenced by the amount of its clay fraction since clay minerals greatly affect the amount of attracted water in the soil. Casagrande (1972) proposed a relationship between the plasticity index and the percentage of clay sizes finer than 2μm. This is termed as the activity of clay, which is expressed by: **PL / % finer than 2μm**; He proposed the following classification (table 6.3).

Activity	Clays
< 0.7	Inactive
0.7 – 1.2	Normal
> 1.2	Active

Table 6.3. Activity of clay soils

Activities of clay soil describe its behavior to volume change. Those described as inactive are stable while the active clays are unstable i.e. subject to large volume change during water interaction. It also provides information about the dominant type of clay mineral present. Using the above classification, it is found that most of the black clay soils are active while the red clay soils are inactive (table 6.4).

The activity of clay soils can be related to its expansive nature (Holtz and Kovacs, 1981). Van der Merwe, (1964) had drawn a chart, which describe the relation between soils activity and their expansiveness potential cited in Carter and Symons (1989). Most of the clay samples in the study area have got very high potential of expansion (Fig. 6.3). Here also most of the black clays have higher potential of expansion than the red clay soils.

Sample no.	Clay fractions	Consistency limits			Index values		Activity		Color
		LL	PL	SL	PI	CI	Value	Degree	
Sa4	68	104	21	9	83	0.85	1.22	Active	Black cotton
Sa5	65	106	21	11	85	0.75	1.30	Active	Black cotton
Sa6	62	94	20	8	74	0.5	1.19	Normal	Dark gray
Sa7	64	92	18	12	74	0.6	1.16	Normal	Dark gray
Sa8	57	101	19	9	82	0.75	1.44	Active	Black cotton
Sr1	63	94	17	11	77	0.6	1.22	Active	Dark gray
Sr2	65	89	20	11	69	0.5	1.18	Normal	Dark gray
Sr3	64	70	38	14	32	0.9	0.50	Inactive	Reddish gray
Sr4	65	65	35	15	30	0.6	0.46	Inactive	Reddish gray
Sa1	51	34	29	18	5	0.15	0.09	Inactive	Reddish gray
Sa2	46	32	26	19	6	0.25	0.13	Inactive	Pale red
Sa3	47	28	26	18	2	0.35	0.04	Inactive	Brownish red
Sr7	37	36	28	18	8	0.9	0.2	Inactive	Red
Sr8	38	38	27	19	11	0.85	0.3	Inactive	Red
Sc3	30	31	25	15	6	0.75	0.2	Inactive	Reddish gray
Sc2	31	37	30	17	7	0.8	0.2	Inactive	Reddish gray
Sr5	36	46	24	20	18	0.2	0.5	Inactive	Red
Sr6	34	43	31	25	12	0.2	0.35	Inactive	Red
Sc4	15	16	15.5	14.3	0.5	0.1	0.03	Inactive	Pale red
Sc1	12	12	11.2	10.1	0.8	0.05	0.07	Inactive	Gray

Table 6.4. Summary of consistency limits, index values and activity of the reservoir soils

Swelling in soils is a widely occurring natural processes caused by the wetting of clay and the consequent increase in its volume. So the problem of swell and shrinkage is largely associated with the clay portion of the soil (Carter and Symons, 1989). According to Head (1984) soils with free swell values less than 95% are not likely to show expansive properties. Values of 100% or more are associated with clays, which could swell considerably when wetted; these soils are named as expansive soils. In Sibilu reservoir the clay soils are tested to their swelling properties (table 6.5). Most of the black clay soils (97-160%) are potentially expansive while the red clay soils do not (12-68%).

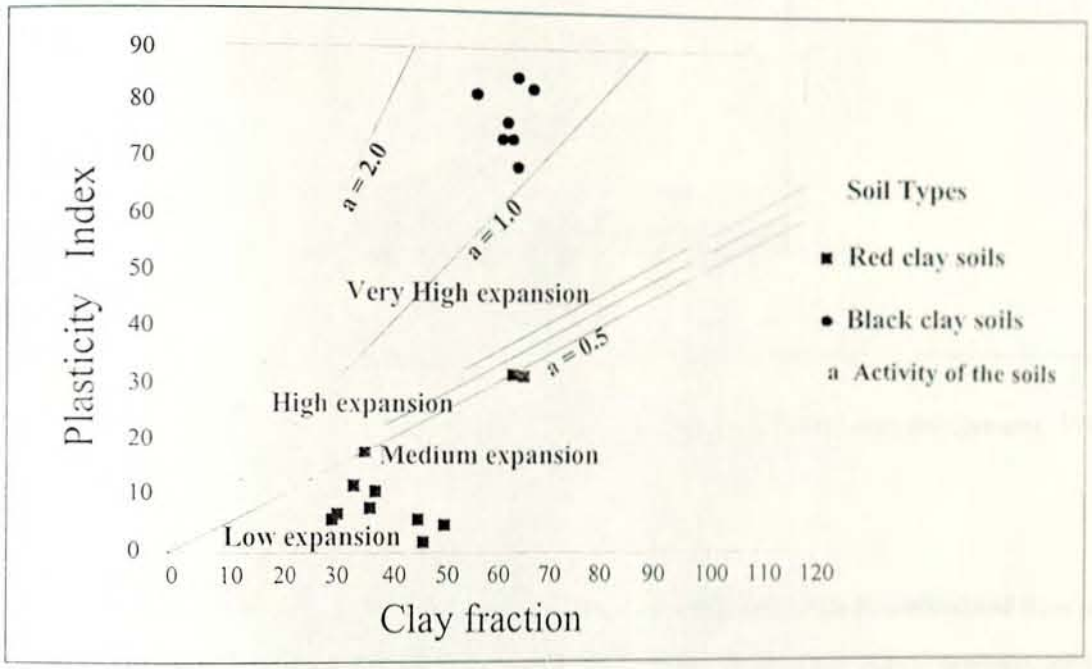

Figure 6.3. Activity and expansion plots of Sibilu reservoir

6.2.7. Compressibility of Reservoir Soils

Soils with a liquid limit greater than 50 are usually show compressibility, although this property is better indicated directly by compressibility measurements. Highly compressible soils are usually associated with alluvial clays and organic clays and always exhibit shrinkage and swelling characteristics with seasonal changes in moisture content (Carter and Symons, 1989) as that of reservoir black clay alluvial soils. Also using the plasticity chart it is possible to estimate their compressibility i.e. results tend to plot above A-line are highly compressible soils while plots below are

the reservoir are highly compressible. Also it is clear that expansive property of the reservoir soils tend to be associated with soils of high compressibility.

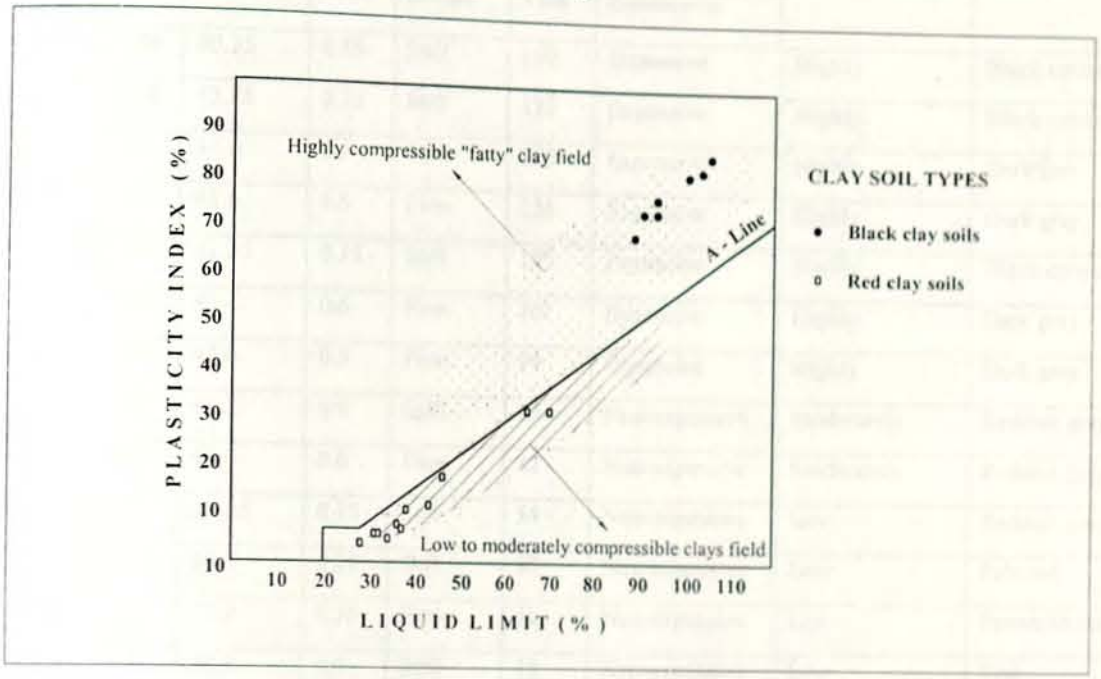

Figure 6.4.Ranges of compressibility plots for Sibilu reservoir soils (after Cater and Symons, 1989)

6.2.8. Shear Strength of Reservoir Soils

Shear strength is the basic geotechnical property of the soils and helps to understand their importance and limitation in engineering practice (Cernica, 1995). There are many sophisticated sampling techniques and laboratory analysis to determine the exact strength, however in the present work simple field observation and indirect quantification of laboratory results i.e. calculating the consistency index are used. It is found that the silty clay and sandy clays are soft, while the gravelly clay and clay soils are firm to stiff. Most of the black clay soils are firm to stiff while the red clay varieties are soft to stiff. But the black clays show high compressibility and high potential of expansion during wetting. These properties make most of the reservoir clays sustain their firm and stiff quality for a short period of time when it is exposed to high moisture conditions (infilling of the dam). So their strength definitely decreases in the long-term.

Sample No.	LL	Moisture content	CI		Free swell		Compressibility	Color
			Value	Strength	Value	Expansiveness		
Sa4	104	60.25	0.85	Stiff	160	Expansive	Highly.	Black cotton
Sa5	106	43.25	0.75	Stiff	152	Expansive	Highly	Black cotton
Sa6	94	51	0.5	Firm	123	Expansive	Highly	Dark gray
Sa7	92	48.6	0.6	Firm	126	Expansive	Highly	Dark gray
Sa8	101	41.25	0.75	Stiff	127	Expansive	Highly	Black cotton
Sr1	94	45.4	0.6	Firm	101	Expansive	Highly	Dark gray
Sr2	89	42.6	0.5	Firm	99	Expansive	Highly	Dark gray
Sr3	70	41.2	0.9	Stiff	86	Non-expansive	Moderately	Reddish gray
Sr4	65	47	0.6	Firm	82	Non-expansive	Moderately	Reddish gray
Sa1	34	33.25	0.15	Soft	54	Non-expansive	Low	Reddish gray
Sa2	32	30.5	0.25	Soft	57	Non-expansive	Low	Pale red
Sa3	28	27.3	0.35	Firm	51	Non-expansive	Low	Brownish red
Sr7	36	28.8	0.9	Stiff	12	Non-expansive	Low	Red
Sr8	38	28.65	0.85	Stiff	56	Non-expansive	Low	Red
Sc3	31	26.5	0.75	Stiff	32	Non-expansive	Low	Reddish gray
Sc2	37	31.4	0.8	Stiff	37	Non-expansive	Low	Reddish gray
Sr5	46	42.4	0.2	Soft	54	Non-expansive	Moderately	Red
Sr6	43	40.6	0.2	Soft	67	Non-expansive	Low	Red

Table 6.5. Summery of Sibilu reservoir soils (strength, compressive, swelling and expansive potential)

6.3. Clay Minerals in Sibilu Reservoir Area

Engineering properties of clay soils are strictly related to the type of clay minerals present. So clay minerals identification and their behavior in the water should be described in dealing and treatment of reservoir soils in dam engineering (Mitchell, 1976). The properties of soils are determined by the properties of the nature and quantity of water in soil. Which help in understanding of clay minerals nature and their interaction condition with the impounding water (Cernica, 1995).

6.3.1. Types of Clay Minerals

The nature of clays, particularly in soil-water environment is determined by the mineralogy of clay present. So clay minerals identification is a part of the main investigation in dam engineering (Fell *et al.*, 1992). In Sibilu reservoir clay minerals identification is done first from their origin and evolution i.e. by observing environmental conditions (climatic, geomorphologic and geologic features) and then from their geotechnical properties. (Fell *et al.*, 1992) proposed clay mineral identification, during dam and reservoir soil evaluation, should be carried out using any two of the following techniques: x-ray diffraction, DTA, electromicroscopy, atterberg limits and activity of soils. Due to inadequate laboratory facilities only the last two methods are practiced for the present work.

Atterberg Limits: As stated above, the property of soils is strongly influenced by the mineralogy of clay present in fine-grained soils. Through experience and understanding of clay minerals properties, it is possible to draw an empirical relation with their atterberg limits. As shown in table 6.6, the atterberg limits themselves can be used as a guide to clay minerals present (Mitchell, 1976).

Mineral	LL (%)	PL (%)	SL (%)
Montimorillonite	100-900	50-100	8.5-15
Illite	60-120	35-60	15-17
Kaolinite	30-110	25-40	25-29
Halloysite	35-55	30-45	
Chlorite	44-47	36-40	

Table 6.6. Atterberg limits of clay minerals.

By comparing the results of soil samples of the study area with the above relation, it was found that there is no strict relation however the black clay soils which have got high values of liquid limit (89-106%) and low values of shrinkage limit (8-12%) and may show that the dominance of montimorillonite while the red clay soils with their relatively lower values of liquid limit (28-70%) and lower plastic limit (25-38%) may indicate that the presence of dominant kaolinite mineral.

The position of the soils on Casagrande plasticity chart can give an indication of the minerals present (Holtz and Kovacs, 1981). As shown in Fig.6.5, there is a good conformation that the black clays constituted by montimorillonite and most of the red clay varieties plotted in kaolinite range.

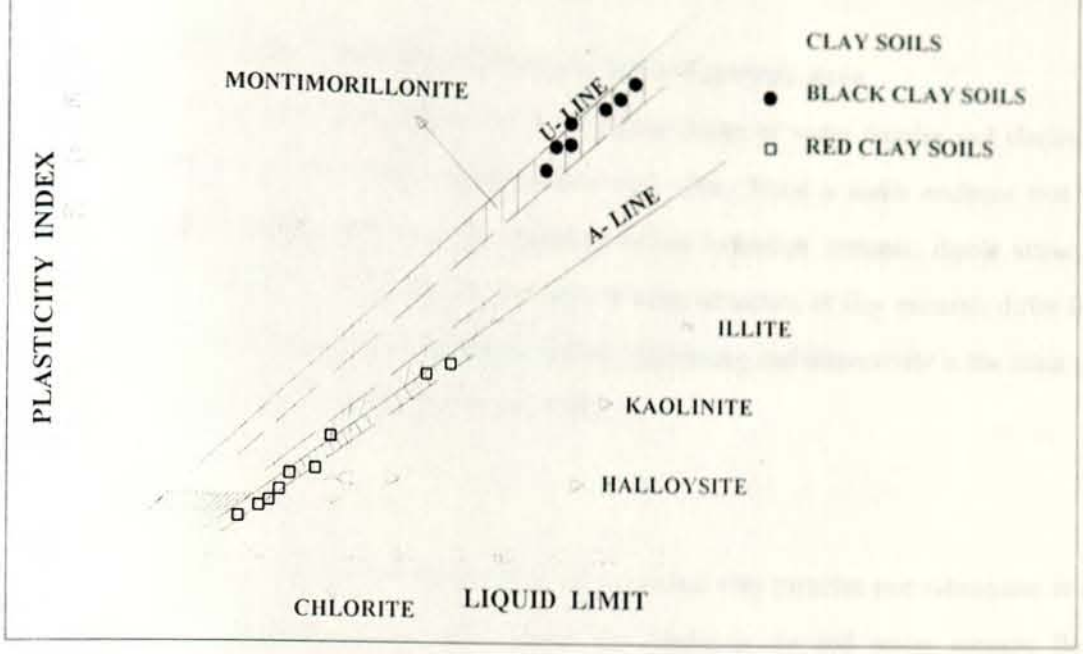

Figure 6.5. Locations of Sibilu reservoir clay minerals on plasticity chart (Holtz and Kovacs, 1981)

Using the atterberg limits, the Sibilu reservoir clays show a good correspondence with previously (from observing their origin and evolution) deducted clay minerals type.

Activity of Clay Soils: Holtz and Kovacs, (1981) done many experiments in different clay minerals to identify their activity ranges; and draw the activity ranges for different clay minerals (table 6.7).

Comparison of the activity of soils with the activities ranges given in the table 6.3, testifies that black clay varieties (1.18-1.46) mainly constituted by montimorillonite while the red clays (0.46-0.5) with the dominant kaolinite mineral. Here also, the activity ranges further conform that the dominant clay minerals in Sibilu reservoirs are montimorillonite and kaolinite, in black and red clay varieties respectively.

Minerals	Activity
Na-montimorillonite	>1.5
Ca-montimorillonite	1.1-1.5
Illite	0.5-1.3
Kaolinite	0.3-0.5

Table 6.7.Activities of clay minerals

6.4. Interaction of Clay Minerals and Water in Sibilu Reservoir Area

Much of the water in soil is adsorbed i.e. the electrical charge of water dipoles and electric charge associated with the surface of clay minerals attract each other. There is much evidence that water is attracted to clay minerals, which can be explained by ion hydration, osmosis, dipole attraction and hydrogen bonding (Fell *et al.*, 1992). The tendency of water attraction of clay minerals differ from one another, sequentially affects their importance in dam engineering and dispersivity is the main property which needs caution in this matter (Fell *et al.*, 1992).

6.4.1. Dispersivity

Dispersive soils are susceptible to separation of the individual clay particles and subsequent erosion of these very small particles through fine fissures and cracks in the soil under seepage flows. So dispersivity of a soil is directly related to its clay mineralogy and chemistry of water that is going to impound i.e. low electrolyte salt concentrations lead to a large diffuse double layer and greater dispersivity (Fell *et al.*, 1992). Dispersive soils are also show effects on their use as a construction material (Mitchell, 1976).

For many years it has been recognized that the presence of dispersive soils either in soils used to construct a dam, or in the dam foundation, greatly increase the risk of failure of the dam by 'piping failure' i.e. development of erosion holes for rapid loss of water from the storage (Cernica, 1995).

There are four laboratory tests, which can be used to determine the dispersivity of a soil: emersion class number (in this method the soil is sieved through a 4.75mm sieve and collected on a 2.36mm sieve and immersed in distilled water and water from the dam area after air dried to check its crumbing nature), double hydrometer (this involves two hydrometer tests on sieved through 2.36mm sieve and carried out with dispersant, and without. The percent of dispersion is the ratio of percentage of soil finer than 0.005mm for the test without dispersent to percentage of soil finer than 0.005mm for the test with dispersent), pinhole dispersive classification (this test used a 1.0mm dia hole performed in soil to be tested, and water passed through the hole under varying heads and for varying durations to check its dispersivity) and chemical tests (Fell *et al.*, 1992).

From laboratory results of AE-HBT joint venture (1997), using double hydrometer and pinhole dispersion, there are some soils that are potentially dispersive (annex-F). Beside, there is also clear field evidence in reservoir and foundation soils i.e. the presence of deep erosion gullies. With these ground, an attempt is made to identify which clay soils are dispersive, using chemical tests, in the present work. Chemical test procedure is presented in annex-G.

In this premise, eight soil samples (four black and four red clay varieties) are analyzed in the National Soil Laboratory and three water samples (surface water, spring water and dug wells) in EIGS laboratory. Based on Sherard *et al.* (1984) relationship of dispersivity and sodium absorption ratio (SAR) (table 6.8).

Dispersivity	SAR
<0.5	Non-dispersive
0.5-1.84	Dispersive and non-dispersive
>1.85	Dispersive

Table 6.8.Dispersivity range in SAR values.

The black clay varieties are dispersive, while the red clays are not. This result even clearly shows their mineralogical features i.e. soils with montimorillonite clays tend to be dispersive, while kaolinite and related clays are non-dispersive. Illite tends to be moderately dispersive (Fell *et al.*, 1992). Hence black clay soils associated with montimorillonite are dispersive.

Ingles and Metcalf, (1972) tried to estimate dispersivity from exchangeable sodium percentage (ESP) i.e. soils with an ESP greater than 2% are susceptible to be dispersive (cited in Fell *et al.*, 1992). They suggested the dispersivity potential of montimorillonite and illite clays during the filling of the storage of the dam i.e. to determine the soil state and whether a change in the pore water chemistry during filling of the reservoir can lead to dispersion (Fig 6.6).

Comparison of the soil samples results (table 6.9) in the above relation, which show that all the black clays have ESP (9.9-15.36%), far greater than 2% and likely to be dispersive while the red clays (1.03-1.78%) are not. The black clay soils fall in zone of potential dispersion with the total ionic

state during the filling of the reservoir; the red clay soils lie on state of stable flocculated zone and those with considerable amount of illite may be liable to be potentially dispersive with the future impoundment of the dam.

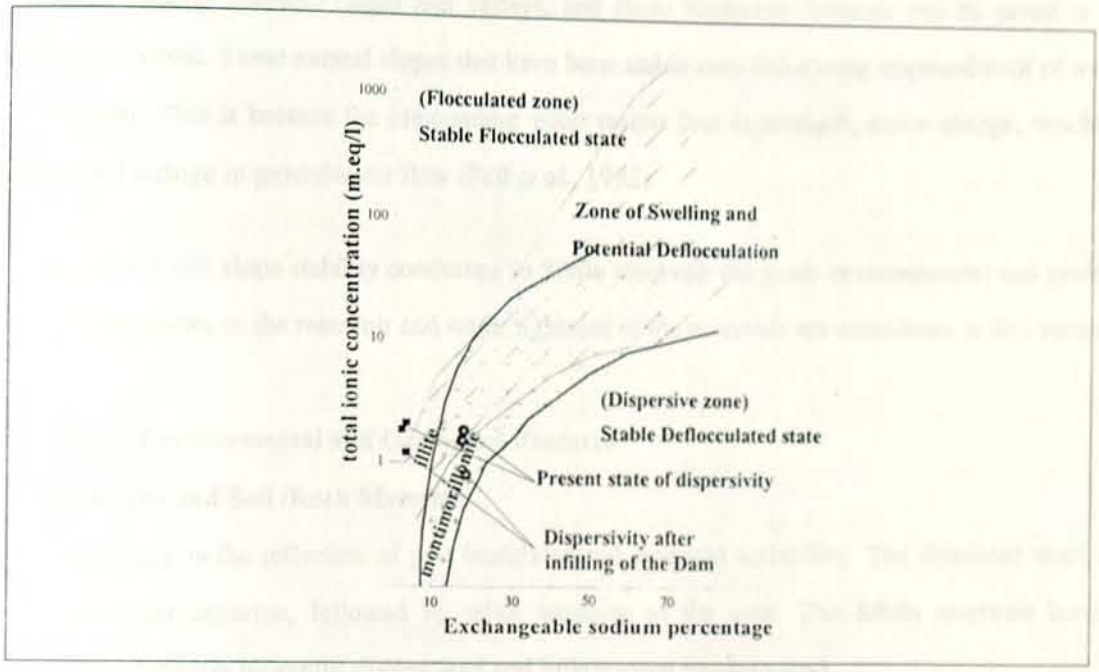

Figure 6.6. Estimation of dispersivity during infilling of the dam, Ingles and Metacalf, 1972

CHAPTER-7 STABILITY AND GEOTECHNICAL FEATURES OF SIBILU RESERVOIR AND DAM SITE

7.1. Stability of Banks in Sibilu Reservoir Area

Reservoirs usually intersect ridges and valleys, and these landscape features can be prone to slope stability problems. These natural slopes that have been stable may fail during impoundment of water in the reservoir. This is because the impounding water causes loss in strength, stress change, weathering, erosion and change in groundwater flow (Fell *et al.*, 1992).

To understand this slope stability conditions in Sibilu reservoir the basic environmental and geological features; landslides in the reservoir and water tightness of the reservoir are considered in this section.

7.1.1. Basic Environmental and Geological Features

A. Landforms and Soil /Rock Materials

Site topography is the reflection of past landslides and potential instability. The dominant slope is the most important criterion, followed by relief intensity of the area. The Sibilu reservoir banks are characterized mostly by gently sloping land and little portion by steep land.

Gently Sloping Land- most of the reservoir flanks are composed of gently sloping landforms, their slope angle ranges 5-20% and it is classified as gentle undulating- rolling according to FAO-UNESCO slope gradient description (table 2.1). It is exposed in the west central and southern portion of the reservoir (Fig.2.1).

These slopes covered by soil materials i.e. mostly clayey in nature, which show high degree of compressibility and swelling potential. The slopes exhibit less degree of dissection since its drainage density is low. Its relief intensity is a maximum of 20m and slope length usually range 75-150m.

Steep Land- reservoir flanks around the dam site, the northeastern part of east central portion of the reservoir are steep. Their slope angle ranges from 25-60%. Those steep lands with slope angles 30-60% are steep and those above 60% are very steep according to FAO-UNESCO slope gradient description.

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Colluvial deposits, rock boulders and fragments cover these steep slopes. Usually the sloped part exhibit jointed and fractured basalts. Their degree of dissection is relatively better than the gently sloping land but its drainage density is quite low. Most of the moderately steep part is gullied, while the rolling part is dissected. Its relief intensity is a maximum of 100m. The slope length ranges 20 to 40m.

B. Degree of Weathering

Weathering of soil and rock materials destroys bonds and reduces shear strength. Weathering may also be accelerated by slope disturbance and by exposure to atmospheric and other agencies (Thompson, 1965).

The gently sloping land is covered by soil masses, which are partly vegetated and cultivated. Mostly these soils are residual. The type of weathering is predominantly chemical rather than physical weathering. The rate of chemical weathering can affect both the short and long-term stability of slopes (Mathewson, 1981). Though it is beyond the scope of this work to deal with details of chemical weathering, it is clear that the formation of clay minerals in the reservoir is governed by the chemical weathering. When these clay soils are subjected to high moisture content, they might cause stability problems. But at the present state, they are almost stable and very few portion show minor soil creep deposits.

The steep and gently sloping lands show high degree of weathering: mechanical weathering and erodibility. The lands with relatively low slope angles exhibit highly weathered basalt, rolled rock fragments and colluvial materials. While the steep part covered by loose and transported colluvial deposits signifies the presence of high degree of weathering (fig 7.1). During reservoir establishment this type of weathering will act at a higher rate in these areas and cause short-term stability problems.

Figure 7.1. Rock fragments and lose colluvial deposits on the reservoir flanks

C. Geological Structures

The exposed rocks in the reservoir flanks are jointed and fractured. These joints are some how systematic but also almost always accompanied by non-systematic joints, which can influence the stability of the slopes. The flow bands or/and thin lamination of basalts when jointed and fractured they become liable to slope stability problems (Fig 7.2). In these aspects the western part of the reservoir, which already show rock rolling are the main ones to mention.

Mostly the joint orientations against the slope angle describe their probability towards stability problems. Only the slightly inclined central E-W joints are explaining such conditions in the reservoir.

Generally the geological discontinuities in the area cause weak environment, which can be easily affected by weathering and erosion. Hence, joints and fractures are the main parameters in dealing with stability problems in the area.

Figure 7.2. Jointed and fractured rock on the reservoir flanks

D. Hydrogeological Conditions

The hydraulic property of the basaltic rock in the reservoir is highly affected by weathering and structural discontinuities. The weathered and fractured basaltic rock is found to be highly permeable (see section 7.2.). Then hydrogeology of the reservoir is associated with weathering and tectonic history of the area.

In the western part of the dam site, at the bottom part of the reservoir flanks there are a series of aligned springs. These springs emerge at the contact line of alluvial deposits and residual/colluvial deposits at the foot of Asere ridge. This condition may indicate that the alluvial clays are relatively impermeable than that of residual/colluvial deposits and also their appearance explained by morphological changes i.e. from steep slope to flat land. Hence, on these sloped landmasses there might be a problem of stability during water impoundment due to a change in pore pressures in the materials forming the slopes.

The rise of groundwater level is expected during the establishment of the dam, which cause reduction of cohesion in the geological materials. To understand its overall effect groundwater level monitoring

should be done. Determination of local groundwater flow direction is also needed to define the overall hydrogeological conditions.

E. Human Activities

In reservoir banks the human activity in disturbing the stability conditions is very limited. The gently sloping land is cultivated by crops, which are a positive effect in slope stability. But at one place the steep slope, south central part of the eastern flank there is a rock quarry; currently excavated for road construction purposes by Kajima Company, which will have a negative effect unless proper attention is given.

All the above parameters should have an influence, in the stated manner, in the slope stability conditions of Sibilu reservoir area. Also data for groundwater fluctuations have a great effect in fully understanding the slope stability conditions.

7.1.2. Landslides in Sibilu Reservoir Area

The presence of unstable slopes in the reservoirs is a major concern for the designers of the dams, which is mostly associated with the mobilization of exiting landslides as a result of submergence of the slide toe during impounding of the reservoir (Mathewson, 1981). Some of the Sibilu reservoir banks show minor landslides; these landslides are creeping and rolling, falling and toppling, and sliding.

A. Creeping and Rolling: are movements of soil and rock masses that are slow. Creeping movements is associated with soil materials, which is difficult to detect easily, while rolling is peculiar to the rocks. This type of movement is very common in steep land and in some parts of sloping parts (Fig. 7.3). They are recognized by the deposits produced i.e. colluvial deposits. They might not cause serious problems in reservoirs.

Figure 7.3. Local peoples protecting the creeping and rolling of geological material in Sibilu reservoir

B. Toppling and Falling: are observed in the Sibilu reservoir. Toppling of columns separated from the rock mass by steeply dipping structural features, which are parallel to the slope face i.e. columnar joints of basalts. This type of movement is observed in northern central part of the eastern flanks of the reservoir (Fig. 7.4). Falling of rocks and boulders on the slope caused by the steep slope and highly jointed and fractured rock nature. Rolling and sliding of loose boulders, on rock slopes, usually accompany it. This type of movement is observed in Ochi ridge. At the southern part, the steep slope of basaltic unit, which is horizontally jointed, also affected by vertical joints to produce blocks to fall down (Fig. 5.2).

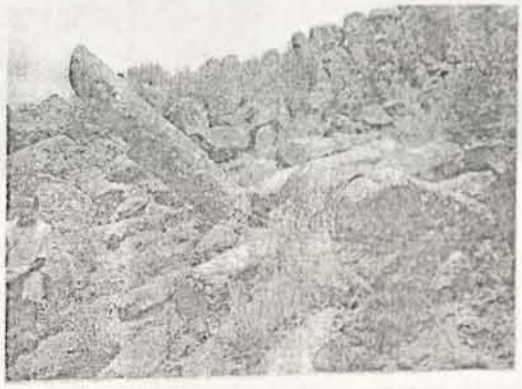

Figure 7.4. Toppling of columnar basalts in Sibilu reservoir

northern part of the reservoir (Fig.7.5). It is characterized by soil and heavily jointed rock slopes i.e. Asere basaltic ridge. In the middle part of this ridge there is a relatively gentle slope followed by thick dome like accumulation that is the displaced landslide debris. This ridge has a slope in the north part 15^0-19^0 and southern part 14^0-20^0 while the middle part has the slope of a maximum of 5^0. The dome shaped accumulation shows 20^0 slopes in the eastern face, which constitute the reservoir bank (Fig. 3.4. geological cross-section across A-A). This is characterized by basaltic rock fragments and loose soil materials which overlain the thin and relatively weak pyroclastic rock unit. Even from the aerial photographs this convex spoon shaped failure is clearly observed. The vegetation type in displaced mass and the middle slope is different. The relief is also surface vegetation type, clearly different from the adjacent unstable slopes. The unstable slope is well vegetated than the others characterized by big trees and shrubs while the stable slope show only grass and the displaced accumulation characterized by grass and some shrubs and small trees (Fig. 7.6).

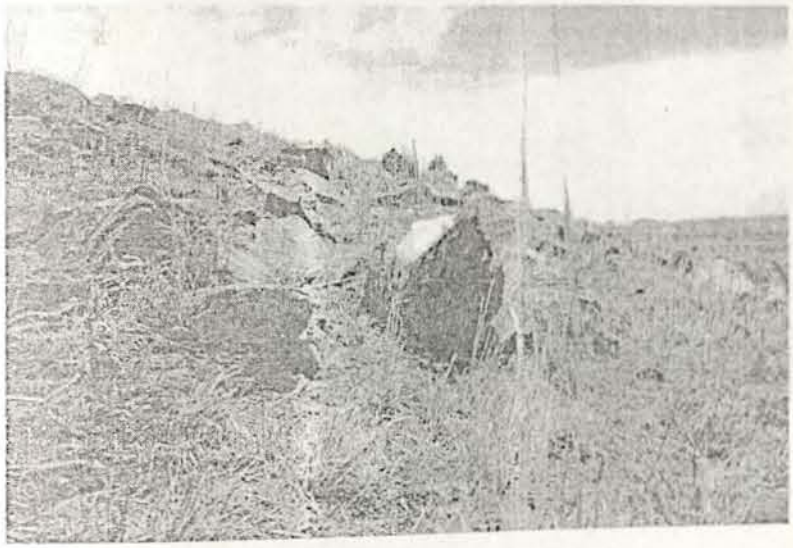

Figure 7.5. Rockslide in Sibilu reservoir

The overall observations indicate that there is a possibility of exiting a landslide with past history (Fig.3.4). During impounding of the reservoir this area may cause serious problems. To define very clearly and propose a remedial action slope height, angle and orientation; dip and strike of structural features; and groundwater distribution in slope are discussed as follows.

of 14^0-20^0 and it is N-S oriented in the northern part and NE-SW oriented in the southern part. The ridge is characterized by N-S, E-W, and NW-SE sets of joints and non-systematic joints. The middle part is jointed by mostly N-S joints, which dip to the east at angle of 65^0-85^0. From the series of springs also it is clear that the groundwater is at shallow depth and its flow direction is to the east, which may cause internal erosion during rainy seasons. Also the displaced mass overlain on the relatively weak pyroclastic units, which might act as, a slippery planes during the rise of the groundwater i.e. impounding of the reservoir.

Using this and other geological and environmental factors it is possible to develop acceptable criteria to reduce its risk in the future.

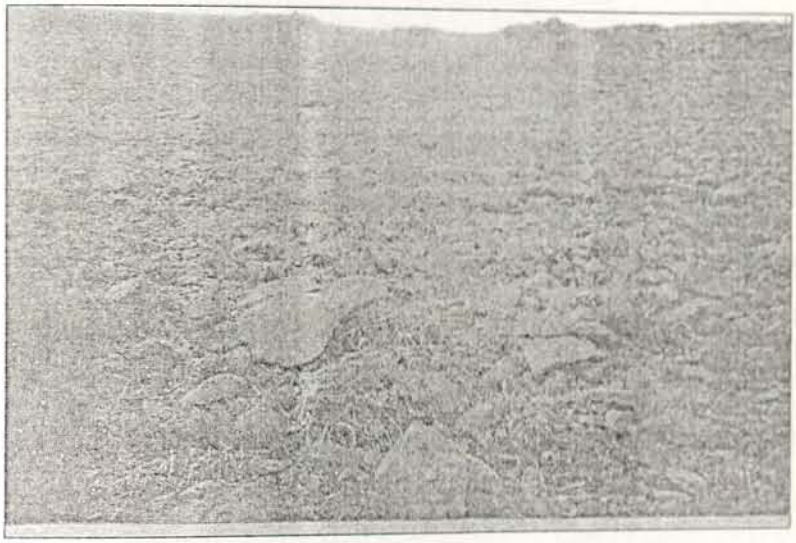

Figure 7.6. Past land slide trace on Asere ridge of Sibilu reservoir

7.2. Water Tightness of Sibilu Reservoir Area

This is the basic investigation in the reservoir area. Water can escape from the reservoir through the flanks of the reservoir, faults in the reservoir and below the dam. Here the possible leak zones in the reservoir are given much emphasis; the permeability of the dam foundation is discussed in section 7.2.

direction, the impounding water will have an access to escape away from the reservoir. So investigation should be carried out in all reservoir flanks to find out the joint orientation and weather the valley side covered by slope deposits which are either of low permeability or impermeable so that they can appreciably reduce the loss of water. It should be ascertained at the same time weather the stability of slope deposits would be distributed by the raising water level. Seepage of water from the reservoir valley is also possible in the rocks, which are cut by continuous fissures trending approximately at right angles to the valley (through the shattered rocks of broad fault zones).

Water can escape from the Sibilu reservoir through riverbanks of slightly inclined permeable joints; the slope covered by slope wash; unstable river flanks; shattered rocks, open joints and fractured zones; and very fragmented circular basaltic dome.

A. Riverbanks with Slightly Inclined Permeable Joints

At the central part of the Sibilu reservoir, at the junction of the Denba River with the Sibilu River there is an exposure of the basaltic unit, which show slightly inclined two horizontal, wet joints (Fig 7.7). These joints are dipping against the river course, closely spaced (30cm), with aperture of 25cm and 32cm. They are continuous and persistence throughout the exposure of around 80m. They are observed in the eastern bank of the river and covered by clay soil, which are loose and soft. These features can be a potential leak zone.

Figure 7.7. Slightly inclined open joint in central part of Sibilu River

B. The Slope Covered by Colluvial Deposits

Colluvial deposits cover most of the river slope flanks. These deposits are characterized by:

- Rock fragments, which break off cliffs or areas of steep outcrops, and fall by gravity and roll down slope; and
- Admixture of clay, sand, gravel which have been moved down slope by combined actions of soil creep (due to gravity forces) and erosion by water.

These materials are likely to be highly permeable, reflecting the presence of voids and loose structure. They are also likely to be highly erodable. Impounding water into these materials cause development of debris flow; as a result unstable conditions may be created in the slopes.

C. Unstable Reservoir Flanks

The unstable flanks of the reservoir may also facilitate water movement outside the reservoir. Especially the unstable conditions arise from the joints and fractures, which dips against the reservoir. In this respect the southern unstable basaltic unit, which is jointed by orthogonal set of joints will be prominent. In the Asere ridge, though some joints favor the water movement against the reservoir, local groundwater flow direction is towards the reservoir. So this ridge might not be a problem for water seepage outside the reservoir. The quarry site dip orientation i.e. against the reservoir will facilitate water escape from the reservoir, so attention should be given during reservoir operations.

D. Shattered Rocks, Open Joints and Fracture Zones

Shattered rocks are characterizing features of strongly jointed and fractured rock zones. In the Sibilu reservoir these shattered rocks observed in the rolling slopes and highly jointed rocks observed usually by non-systematic orientation and minor fractures. Unless the penetration to the depth is known, they are grouped under potential leakage zone.

Open joints, which are found in the central reservoirs covered by soil materials that can be eroded during impounding especially those E-W open joints, which have a strike length 40m in central reservoir should be sealed or clarified there three dimensional conditions.

Fault zones are the most dangerous leak zones. From inferred faults in the reservoir the one found in the eastern bank (Fig. 5.5) of the reservoir running N-S dips to the west (against reservoir) might be a leak zone. The other faults that are E-W and NE-SW are dip towards the reservoir and might not be leak zone, but their depth and fault plane should be clearly defined to underestimate their presence.

7.3. Geotechnical Features of Sibilu Dam Site

7.3.1. Geomorphological and Geological Setting of Dam Site

The Sibilu Dam, which will have a length of 980m with a height of 27m, is located at $9^0$17.7" N and $38^0$43.8" E. An area of 2.8 km^2 around the dam is considered as the Sibilu dam site (Fig.3.8). The area lies between altitude 2,530m at the riverbed and 2,590m at the Ochi and Asere ridges above mean sea level. The mean slope of the river in the dam site area is 0.5% (SEURECA, 1991). The slope of the dam site at the left abutment is quite steep while the right abutment is gentle with an average slope of 11%. A steep slope is encountered where the trachyte layer is exposed. In the dam site residual and alluvial deposits of clayey materials and the basaltic and trachytic rock units are encountered. Previously the dam site area was covered by thick lower Ashangi basalt that overlies Mesozoic sediments uncomfortably. Then, local deposition of trachyte and basalt took place (Tefera Eshete, 1995). Particularly the dam site is made up of different types of volcanic rock, residual soil and alluvial deposits (AE-HBT joint Venture, 1997).

Around the dam axis there are 11 boreholes, to which three (Bh-10, 11, 12) are located in the western side of Sibilu River, while the rest (Bh-13, 14, 15, 16, 17, 18, 19, 20) in the eastern side (Fig. 3.8) and their detail log and section presented in annex-H.

Bh-10, Bh-11 and Bh-12

These boreholes show reddish brown residual soils of less than 1m thick. It is plastic, firm clays with silt and sand admixtures. The underlying basaltic units exhibit scoracious and aphanatic textures; its upper part is highly fractured, weathered and jointed. Joints are open and filled with clay and calcite; their intensity decrease with depth, so do weathering. The strongly fractured and weathered basalt

thickness is not exceeded 1m in all three boreholes. The static water table is shallow in these boreholes (2.25m, 1.81m and 1.63m respectively).

Bh-13, Bh-14 and Bh-15

These boreholes are located on the flat plain of the eastern side of the river on the alluvial deposits. They show thick (3.5-6m) deposits of black expansive, highly plastic and compressible clay soils. The underlying unit is fragmented and, weathered basalt, which is followed by jointed and fractured basaltic unit. The intensity of fracturing and jointing localized at different depth. There is also 1-3m thick, reddish, fissured and hard clay paleosoil intercalated within the basaltic unit. The static water table is deep in these boreholes (12.77m, 11.7m and 14.69m respectively).

Bh-16

This borehole is located on the sloped side of the eastern side of the river. It shows around 9m thick weathered trachyte, underlay by paleosoil. The fragmented and highly weathered basaltic rock underlying the paleosoil and then the fresh and slightly jointed basalt is shown. The static water level in this borehole is 19.34m deep.

Bh-17, Bh-18, Bh-19 and Bh-20

These boreholes show thick deposits of residual soils (~5m). It is reddish brown, plastic and firm. This soils unit overlying strongly weathered basaltic fragments of 4-5m thick. Bh-17 and Bh-18 show around 1m thick paleosoil underlying it. The slightly weathered and jointed basaltic rock constitutes the depth of these boreholes. The static water table is deep in these boreholes (14.8m, 16.78m, 12.8m and 14.45m respectively).

Generally the basalt exposed at the dam site exhibits scoracious and aphanatic textures, it is also intercalated with the pyroclastic deposit at the left bank of the river on the dam axis. As a whole the outcrops in the dam sites are:

- Clayey alluvial on the lowland with thickness not more than 6m.
- Clayey colluvial on the foothills and slopes, thickness <1.5m.
- Clayey residual on lowland and plateau, thickness not more than 5m.
- Basaltic boulders on the ridges and hilltops.

The boreholes results show a basalt layer, which its upper part is fragmented and highly weathered and lower part being sounder underlie these formations. Paleosoil was encountered underlying the aphanatic and scoracious basalt.

7.3.2. Foundation Conditions of Sibilu Dam and Spillway

Based on borehole drilling carried out (annex-H) and observation of the surfacial material, the following has been given:

A. The Sibilu dam foundation consists of the following features:

Shallow deposits of residual and alluvial soil with thickness of 0.5-6m are exposed (Fig 7.9). The properties of these deposits are variable but can be generally described as moist, dark gray and reddish brown, firm to stiff, highly plastic and expansive clays.

Scoracious and aphanatic basalts are weathered but generally the degree of weathering decreases with depth. The strength of the rocks varies from medium strong to very strong. The scoracious rock outcrops at the riverbed at the right abutment close to Ochi hill and aphanatic rock outcrops at the end of the left abutment.

Trachyte unit outcrops at the right abutment of the dam. The thickness of the unit is 9m. It is limited in width being exposed about 20m in the dam axis direction. The trachyte is medium strong and highly weathered. It has a steep slope on the exposed section. It was observed from the borehole that the weathering increases with depth. Presences of paleosoil are observed in some of the boreholes and have a thickness of 1-4m. It was encountered underlying the aphanatic and scoracious basalt. The paleosoil is reddish in color highly plastic when wet, clayey in composition.

Lineament interpretation indicated that the fractures are oriented in E-W, N-S and NW-SW trend; the E-W lineaments are well pronounced. Most of the joint spaces are closely spaced implying that the fracture index is high. From the joint systems E-W are open and persistent. The N-S is also frequently observed and closely spaced but mostly tight. Other sets of joints are not that much frequent. Joints in

open joints can be the possible routes of seepage under the dam foundation.

From relief forms of the dam site, it was interpreted that the presence of faults i.e.

- The ridges approximate parallel to the river and covered by angular boulders and blocks of basalts
- The difference in elevation between the two banks of the river.

However the boreholes did not conform the presence of faults. Beside, the geophysical survey using Vertical Electrical Sounding (VES) gave the same result (SEURECA, 1991); though the data is not available for the present work.

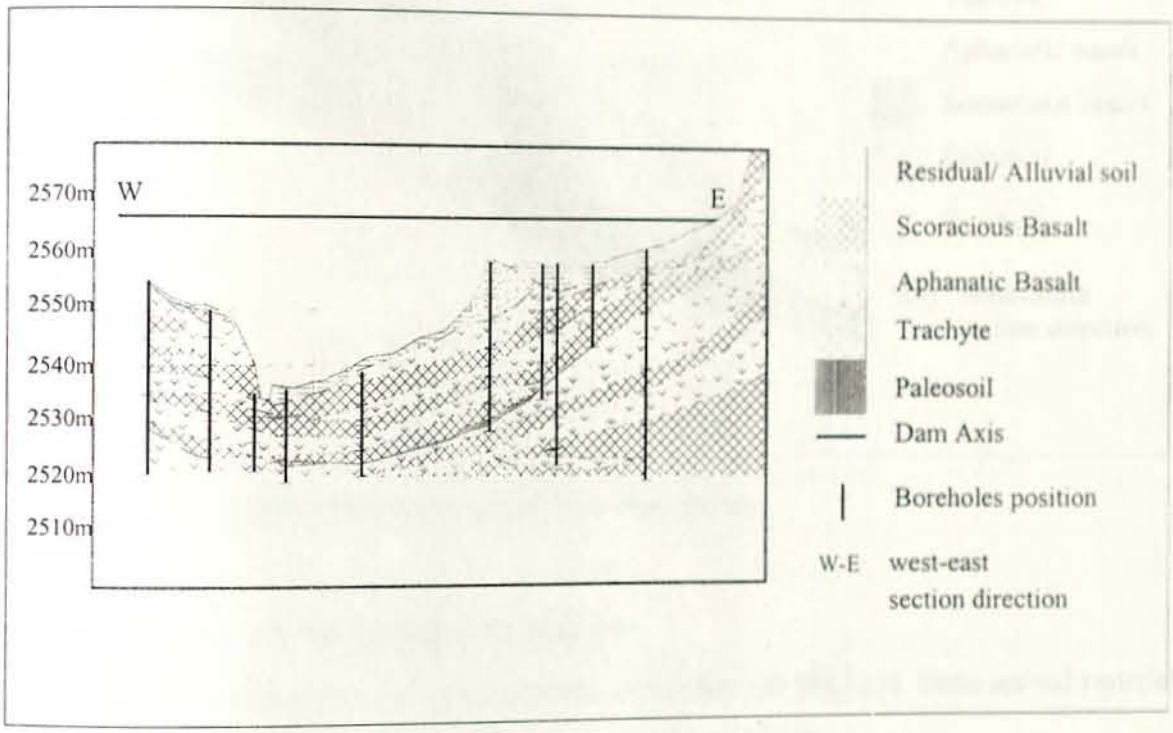

Figure 7.8. Sibilu dam stratigraphic and geologic cross-section

B. The Sibilu spillway foundation consists of the following features:

A residual deposit of highly expansive clay was encountered at the upper portion of the spillway foundation and generally it is described as moist, light reddish to brown, firm to stiff and highly plastic

soil, and have got similar properties as the dam foundation. Trachyte outcrop were also observed at the middle section of the spillway to a maximum depth of 3.5m (Fig. 7.10).

Lineament interpretation included within the dam foundation and here also most of the joint spaces of the rocks in the area are closely spaced implying that the fracture index is high.

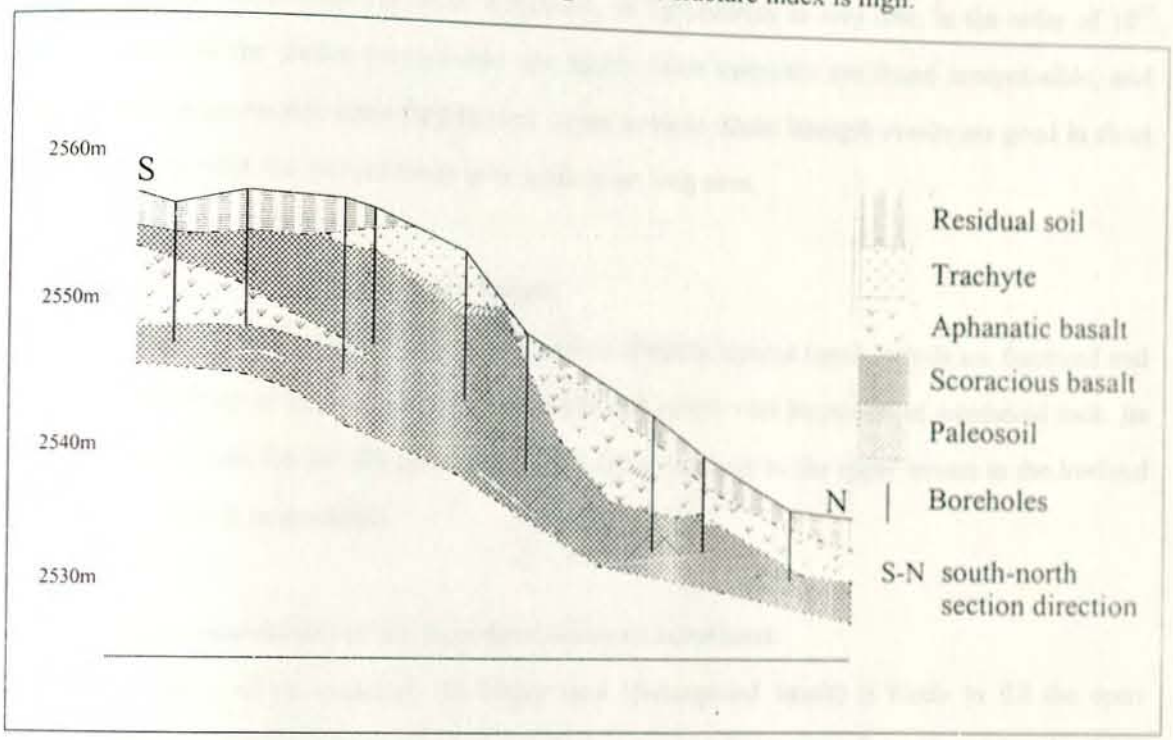

Figure 7.9. Sibilu spillway stratigraphic and geologic cross-section

7.3.3. Geotechnical Cross-Section of the Dam Site

From geotechnical viewpoint there are three layers at the dam site (fig.7.11). These are soil materials, highly weathered and fragmented soft basalts and jointed sound basalts.

A. Soil Materials

Deposits of residual and alluvial materials in the area are considered as the soil materials. their thickness varies between 0.5-6m and exposed close to the river channel, on gently sloped areas and on

the right abutment at the spillway axis. The properties of these clayey materials are variable. It is stiff in the deeper portions than the upper part (AE and HBT joint venture, 1997).

Laboratory test results showed that the soil materials are highly expansive; such expansive clay is particularly impervious when saturated. At present, its permeability is very low, in the order of 10^{-7} cm/sec, based on the packer permeability test result. These materials are found compressible, and become more compressible when they become darker in color. Shear strength results are good in short term because of cohesion, but are likely to be weak in the long term.

B. Highly Weathered and Fragmented Basalts

It is a heterogeneous layer; some parts are composed of thinly layered basalt, which are fractured and the rest are made up of clayey sand (decomposed basalt) mixed with fragments of weathered rock. Its thickness varies from 0.5-2m. It's thickness become more and more in the upper stream in the lowland where alluvial soil is encountered.

To deal with the permeability of this layer three factors are considered:

- The nature of the material: the clayey sand (decomposed basalt) is likely to fill the open discontinuous, cracks, fractures and voids between the fragments of weathered basalts. This material is generally impervious ($K < 10^{-8}$ m/sec) and semi-pervious ($10^{-8} < K < 10^{-6}$ m/sec).
- The results of packer tests: packer tests are not well adapted to this type of material. To derive exact permeability value from packer test, the media tested should be homogenous, and it is not the case. However the data obtained give a loss of water 6 to 17 liters per meter per minute which is compatible with semi-pervious material of pervious material of 10^{-8} cm/sec .
- The water table in boreholes: most of the water table is below this unit, and some of them show artesian nature, which might indicate that this layer is impervious or semi-pervious.

Hence, a permeability of 10^{-8} cm/sec is taken in accordance with all the above observation.

This layer is not or little compressible under the stress of 30m high dam. But its heterogeneity makes it possible to have differential settlement, which could not be tolerated by a too rigid structure; so the

rock fill dam is the good choice. Shear strength is high enough because of the fragments included in the decomposed materials.

C. Jointed Sound Basalts

This layer is composed with scoracious and aphanatic basalt, which is overlain by the above layers. The degree of weathering varies from high to fresh; but generally the rock is fresh to moderately weathered. The thickness of this layer is not known because only its top part has been reached by the boreholes and extended to depth.

The permeability of this layer varies from 10^{-6} cm/sec to 10^{-4} cm/sec. Most of the water table is encountered around upper part this layer. It implies that the upper part of this layer is pervious. The lower part is less pervious because less fractured and less weathered as shown by the packer tests. So, for design purpose the upper part is neglected because in any case the design will include a grout curtain till the slightly fractured basalt with a permeability of less than 10^{-8} cm/sec. This layer is practically incompressible and able to use as a sound foundation rock.

7.3.4. Permeability

When dams are constructed the foundation permeability conditions should be thoroughly investigated and help to maintain the embankment stability including the effect on the soil strength, and to prevent seepage problems those are erosion and piping failure through the foundation (Fell *et al.*, 1992).

The permeability of the Sibilu foundation exposed and the underlying sections are highly variable. For ease of understanding, excluding the top fine clays, permeability of the foundation materials are categorized in 8m intervals.

- The first part, between depths of 0-8m, has a coefficient of permeability of 10^{-4} to 10^{-3} cm/sec on average, which consists of highly fractured basaltic layer.
- The second part, between depths of 8-16m, has a coefficient of 10^{-5} cm/sec on average.
- The third part, between depths of 16-24m has a coefficient of permeability of 10^{-6} cm/sec on average.

cm/sec.

The above were categorized based on the packer permeability test results done by AE and HBT joint venture (1997).

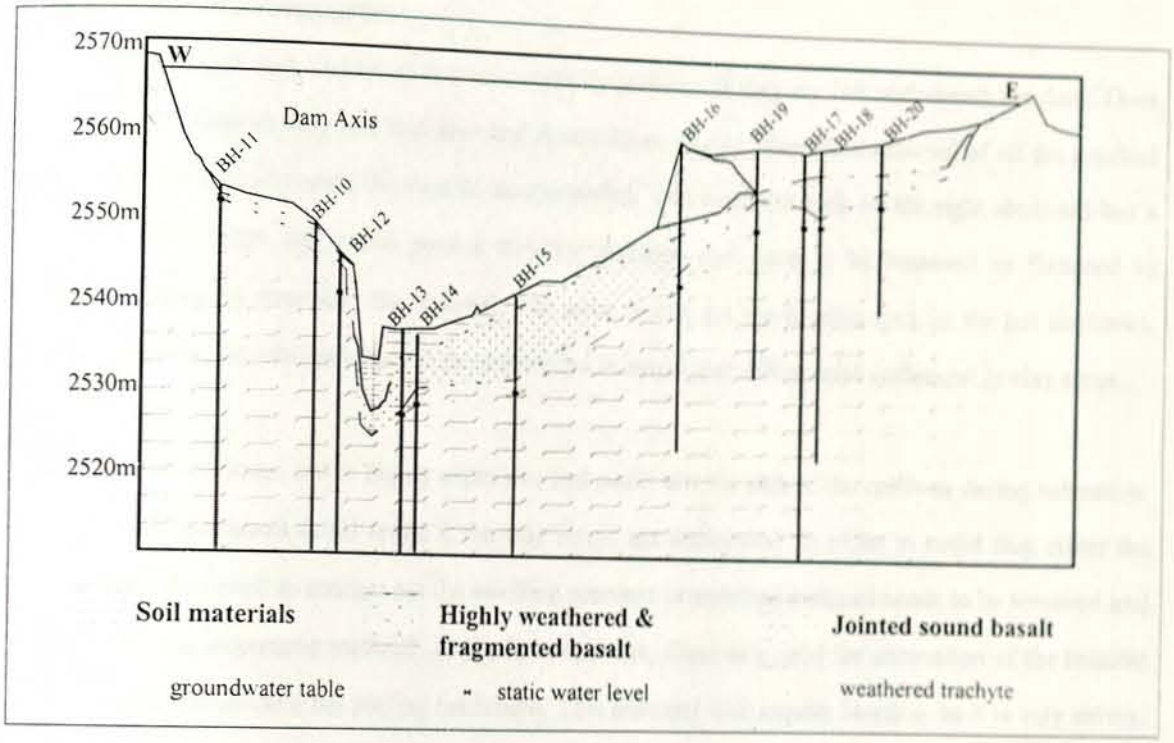

Figure 7.10. Geotechnical cross-section of Sibilu dam

7.3.5. Seepage Loss Through Foundation

By virtue of viscous friction exerted on the water flowing through the soil pores, an energy transfer is achieved between the water and soil, which is referred to seepage. The seepage of water under the foundation responsible for the phenomenon called quick sand and is of importance in stability analyses of earth structures, which are subjected to the action of seepage (Casagrande, 1972). Seepage beneath a dam foundation should be allowed to exit in a controlled manner (Fell *et al.*, 1992). A seepage analysis in Sibilu dam foundation is done, using Seep/W software by AE and HBT joint venture (1997), to determine water loss through the foundation. Then it was estimated to be in the order of 1000m^3/day. In

order to cater for unforeseen geological conditions and further lower the seepage, a one-line curtain grouting is recommended to be done close to the center of clay core.

7.3.6. Foundation Preparation

Dam: The residual and alluvial soils pose a stability problem if they are left underneath the dam. Their existence will require very flat upstream and downstream slopes. Therefore removal of all the residual and alluvial soils underneath the dam is recommended. The trachytic rock on the right abutment has a nearly vertical slope and could pose a stability problem and need to be removed or flattened to acceptable slope by removing the material. The same is true for the basaltic rock on the left abutment. Flattening of the foundation slopes is recommended to avoid also differential settlement in clay cores.

Spillway: The residual soil is highly expansive and could left the slab of the spillway during saturation. A crack and settlement could result if the clay layers are desiccated. In order to avoid this, either the slab shall be designed to counter act the swelling pressure or residual material needs to be removed and replaced by non-expansive material. At the lower portion, there is a need for excavation of the basaltic material to accommodate the stilling catchment. This material will require blasting, as it is very strong. With controlled blasting, the basaltic material could be used in rock fill section of the Sibilu dam.

All in all it is needed to conduct general excavation (of compressible and low strength soil and weathered rock as is necessary to form a surface sufficiently strong to support the dam and to limit settlement to acceptable values) and cutoff excavation (below the general excavation level to remove highly permeable rocks).

CHAPTER-8 CONSTRUCTION MATERIALS OF SIBILU DAM

8.1. General

One of the main objectives of engineering geological investigation for rock-fill dams is to find adequate rock and soil materials for the construction of the dam within reasonable distance of the site. The rock should ensure the stability and watertightness of the dam and not liable to the volume changes i.e. the main requirement for the stone relates to its strength. Materials of poorer quality would break and crush under pressure, possibly giving rise to undesirable settlements. The shape of the rock material is also important; elongated flat fragments are undesirable in high dams since cavities may remain under them. While the soil should ensure the impermeability quality for the core i.e. it should be economically compatible and stable under future conditions (Prince, 1983).

The Sibilu rock-fill dam is designed to satisfy the topographic and foundation conditions at the site (SEURECA, 1991) and the need of construction materials around the vicinity area should be examined for its economic workability. But before discussing the construction materials appraisal in the Sibilu area, it is better to describe its parts and the generally accepted construction materials, which usually used as a guide in the construction materials assessment. It is learned from the preliminary design of the Sibilu dam (SEURECA, 1991), the following parts are incorporated (Fig 8.1). As shown in the design, the dam has got five main components: clay core, filter and drain, random rock-fill, well packed rock-fill and riprap. These components need specified construction materials type depending on their utility. Jovanovic (1974) described typical construction materials used for the different parts of the rock-fill dam (table 8.1)

Clay core is the component used to control seepage through the dam. So it should be impermeable and well compacted to be stable. Rock-fill zones, flank the core upstream and downstream should be strong and durable, to provide stable and free drain for the rock-fill dam permanently. Filter zones are provided between the core and the rock-fill to control internal erosion while the riprap used to prevent erosion of the upstream slope of the rock-fill dam from the water wave action (Fell *et al.*, 1992).

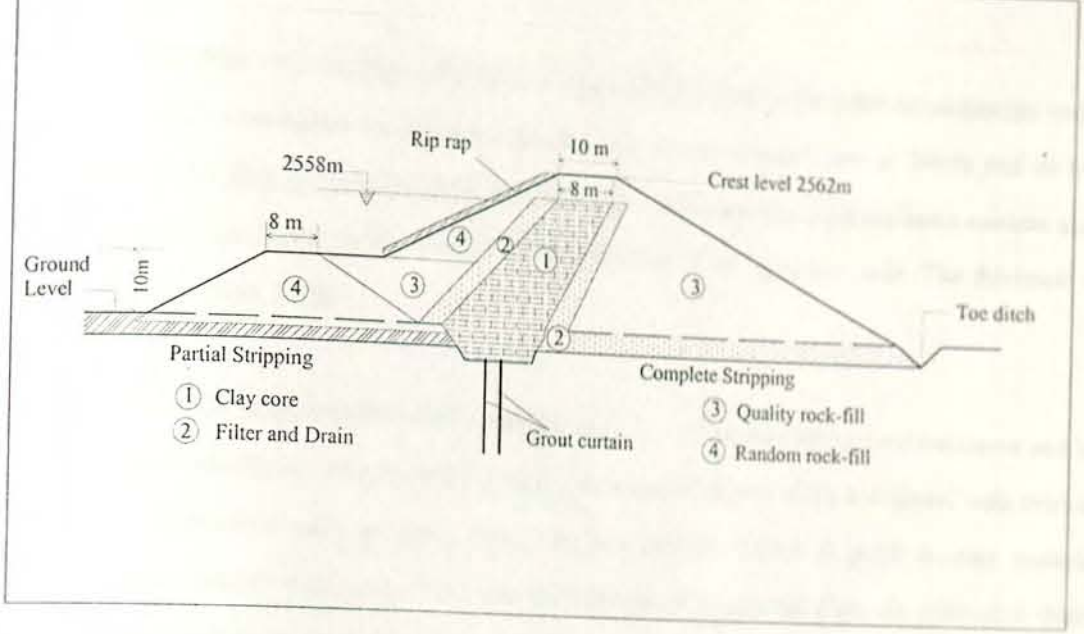

Figure 8.1. The preliminary design of Sibilu rock-fill dam (SEURECA, 1991)

Usually it is emphasized that good dam engineering involves use of the materials available at the site rather than to look for the materials with preconceived ideas needed. Then in the Sibilu dam construction the materials needed should be examined in the near distance like in the reservoir and field visits in the area showed presence of impervious clay materials and rock sources in close proximity to the dam. With this in mind close inspections were done and the presence of sufficient amount was reported by AE-HBT joint venture (1997). The present work tries to assess their suitability as a quality material and their limitation for usage from scientific viewpoint.

8.2. Core clay materials

The impervious core is the most important element in the dam. As long as the impervious core remains intact, with no cracks or other concentrated leaks, the dam is safe. Therefore the materials used for the core material should be given priority.

Most of the reservoir is covered by clay soils of alluvial and residual origin. The clay borrow areas investigated are located within the reservoir. A total of four borrow areas were under investigation by

the AE-HBT joint venture (Fig. 5.4) and as described before these soils (alluvial sediments and residual soils) have different nature i.e. alluvial deposits occur along the main river of Sibilu and its tributaries upstream of the dam are highly plastic, black in color, compressible, high moisture content and active. They are more extensive in the vicinity of the dam site to the upstream side. The thickness of these deposits varies from 2-5m.

Residual soils are relatively less plastic, reddish in color, non-compressible, less moistures and inactive. This clay soil usually are mixed with the rock fragments of varying sizes and found with thickness run up to 6m. Reservoir soils generally have low permeability, which is good as core material. The suitability of soil for impervious core can be appreciated in general from its grain-size distribution curve and more from its geotechnical properties.

From soil mechanics viewpoint soils designated in GC, ML and CL in USCS are suitable for impervious part of the dam (Terzaghi, 1968). Comparing with the reservoir soils it can be seen than most of the gravelly clay and silty clay (CL and ML), sandy clay (ML) and clayey gravel (GC) are suitable materials. Most of these soils are residual in origin but the alluvial soils (CH) are not preferred as a core material. Beside this, comparison showed that red clay soil varieties are more suitable than the black clay soils.

The moisture of the soils also affects their workability. Soils with higher water content are usually difficult to compact them. Moreover, the alluvial soils of the area have excessive water content, which makes them even less suitable. Soils with a high content of clay particles are unsuitable for impermeable core, since they are difficult to handle (Terzaghi, 1968). The liquid limit should therefore not exceed 50% and the tendency to swelling is another unfavorable properties of these soils i.e. plastic clays cause shrinkage cracks within the core so non-plastic nature is preferred.

Activity curves also give some idea about the preference of soils for core material i.e. inactive soils are better than the active soils, with this also the red clay soils become more preferred than the black soils. Other property should to be considered is dispersivity i.e. non-dispersive soils are preferred. It is known

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that the red clay soils are not potentially dispersive, while the black clay soils are dispersive, so the red ones still favored. Generally the residual soils are better than the alluvial soils for core materials in the Sibilu reservoir.

Component	Construction materials
Clay core	Clay, sandy clay, clayey sand, silty clay possibly with gravel. Usually more than 15% passing 75μm, perfectly more.
Filter	Sand or gravelly, with less than 5% (preferable less than 2%) fines passing 75μm. Fines should be non-plastic. Manufactured by crushing, washing, screening and recombining sand-gravel deposits and quarried rock. They are designed to strict particle size grading limits to act as a filter.
Rock-fill	Quarry run rock-fill; possibly with oversize removed and preferably dense, sound, free draining after compaction. Compacted in 0.5 to 1m layers with the maximum particle size equal to compacted layer thickness. Most igneous rocks and metamorphic rocks yield these properties.
Riprap	Selected dense durable rock-fill sized to prevent erosion by wave action with preferably high durable quality than the rock-fill.

Table 8.1. Rock-fill dam typical construction materials, (Jovanovic 1974)

To use these soils for the needed purpose, their geotechnical properties should be further improved i.e. advancing their engineering performance. The more common technique available for soil improvement is compaction.

Compaction

The primary objective of compaction is to improve the engineering behavior of the soils and it has been recognized that soil compaction process affects the physical properties, such as moisture and density and the engineering properties include compression, permeability and strength. Compaction of soils, for the impermeable core, is needed to reduce its compressibility and permeability and increase its strength.

To assist the compaction effort for the core construction using the reservoir soils laboratory results are required.

Sample from CL, depth 120-200cm, natural moisture content is 41.65%									
Wet density	1.54	1.59	1.68	1.70	1.82	1.81	1.79	1.76	1.70
Moisture content (%)	26.5	28.11	30.43	33.02	35.9	36.5	38.5	40.78	43.91
Dry density (g/cc)	1.22	1.24	1.29	1.31	1.34	1.33	1.29	1.25	1.18
Sample from ML, depth 190-250cm, natural moisture content is 36.4%									
Wet density	1.50	1.58	1.65	1.70	1.75	1.74	1.73	1.70	1.69
Moisture content (%)	23.15	25.41	29.53	32.16	33.94	35.0	38.2	41.8	44.2
Dry density (g/cc)	1.22	1.26	1.27	1.29	1.31	1.29	1.25	1.20	1.17
Sample from GC, depth 190-250cm, natural moisture content is 27.5%									
Wet density	1.54	1.57	1.64	1.68	1.73	1.88	1.83	1.76	1.73
Moisture content (%)	25.44	26.40	27.41	28.29	31.48	34.0	37.5	39.2	42.0
Dry density (g/cc)	1.23	1.24	1.29	1.31	1.32	1.40	1.33	1.27	1.22

Table 8.2. Laboratory results of dry density and moisture contents

Many compaction laboratory tests were conducted by AE-HBT joint venture from which three representative samples were selected from the soils that are believed to be more suitable (ML, CL, and GC) for core materials. This is done to show their average maximum dry densities and optimum moisture contents needed for the proper compaction of the core using the reservoir soils. The following table shows the laboratory results of the selected soil samples.

The test results plotted as dry density versus water content (Fig 8.2) and can be used to select the compaction procedure. The curves are unique for the given soil type and then compaction effort. The peaks of the curves correspond to the maximum dry densities and optimum moisture contents. Typically, the optimum water content is a few percent less than the soils' plastic limit i.e. the optimum water content corresponds to approximately 80% saturation and the zero air void line shows average envelope at saturation of 100%.

The values (below on the graph) used to determine specific compaction effort; type of compaction, equipment type and amount of moisture content for the given soil at which the desired compaction is effective.

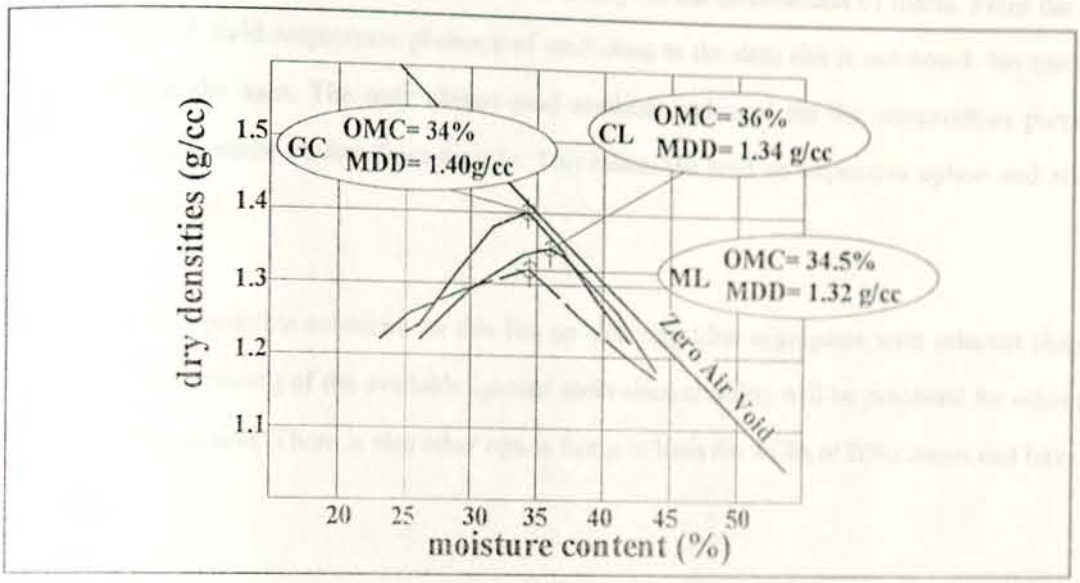

Figure 8.2. Plots of moisture contents verses dry densities

8.3. Filter Materials

As said before, filters are provided in the dams to control internal erosion of the dam, arise from the forces generated by seepage through and under the dam. These filters are essential to the performance of the dam. Their failure to perform satisfactory, can lead to piping failure of the dam. From many failures experience the filter should be the most important element, which needs maximum attention. By providing a conservative filter, it is possible to quit worrying about the possible concentrated leaks through the core (Sherard *et al.*, 1976).

The basic requirements of filters are; they should be sufficiently fine grained and permeable to prevent erosion of the soil and to allow drainage of seepage water. As described in table 8.1 materials of non-plastic sand or gravelly, with less than 5% fines passing 75□m are generally needed for the filter.

Certainly filters are designed using the grain size distribution of the soils that are being suspected to be eroded and disturb the stability of the dam.

A source of high quality sand and gravel is necessary for the construction of filters. From the geology of the area and field inspections presence of sand close to the dam site is not noted. No natural sand was found in the area. The only closest sand available and used for the construction purpose was located at Mojo some 150km from the site. This makes the sand an expansive option and alternative source is required.

To recommend possible solutions for this lies on obtaining filter aggregates with selected shape using crashing and screening of the available igneous rocks since crushing will be practiced for other parts of the dam construction. There is also other option that is to limit the width of filter zones and have natural sand.

8.4. Rock-fill and Riprap Materials

The designing of the rock-fill dam is usually associated with the availability of rock, which can be quarried to yield free draining for the dam. Most igneous and many metamorphic rocks, e.g. basalt, diorite, granodiorite, granite, marble, greywacke, quartzite will when fresh, yield free draining rock-fill.

The basaltic rock in the area is found to be suitable for the rock-fill dam from the tests conducted by AE-HBT joint venture. The tests focus on its strength and durability. Due to sampling and laboratory problems it is not possible to conform the results to other tests in the present study.

AE-HBT joint venture conducted investigation on a rock quarry namely Buba, which is located about 40m off the road that connects Chancho and Derba and is some 500m downstream of the dam axis. The Buba hill is about 110m high and mainly consists of volcanic scoracious and aphanatic basalt. They are fresh and massive. The strength of the rock was measured to be very strong using uniaxial compressive strength test (298-387 MPa.) also the slake durability tests showed that (slaking durability index greater than 97.3%). The material is suitable for use as rock-fill.

The riprap is an element of the dam that prevents erosion of the upstream face by water wave action. The rock source of the rock-fill can also suit to the riprap too, since the material is dense and durable. The difference between the rock-fill and riprap mainly lies on their size, of which the riprap is greater. Also the riprap materials should be resistant for the water wave action and such quality is tested with abrasion test. The strength of the Buba hill basalts against abrasion is found to be excellent from the test results conducted by AE-HBT joint venture in 1997. It can be concluded that the rock source for the Sibilu dam construction is available in the required quality.

CHAPTER-9 CONCLUSION AND RECOMMENDATIONS

In the studied catchment geomorphological, geological, hydrological and engineering geological studies were conducted to characterize the area in terms of engineering geology and to analyze the geological conditions effect in the Sibilu dam.

The catchment has climatic conditions, which can be grouped, as warm humid tropical climatic region. In the catchment four landforms: level, gentle sloping, steeping and composite lands and different slope classes were identified. With topographic slope analysis it was possible to show that all surface water converges to the reservoir area.

Using aerial photos interpretation it was also possible to draw the relief and landforms, slope and geomorphological maps of the Sibilu catchment at the scale of 1:50,000. The warm and humid climate, volcanic parent materials and its topographic features used to deduct the possible clay minerals formations, governing the genesis of the soil in the area. For further analysis montimorillonite and kaolinite were found to be the dominant clay minerals in the soils of the Sibilu catchment.

Sibilu catchment geological map was prepared at the scale of 1:50,000. The rocks of the northern part are correlated with the general stratigraphic units of Addis Ababa drawn by Hailesellase Girmay and Getaneh Assefa (1989) using their textural features. Geological map of the reservoir area at the scale of 1:12,500 was developed through large-scale (1:8,000) aerial photo interpretation and intensive field surveys.

The structural features of the catchment were interpreted from aerial photographs. The NW-SE and NE-SW lineaments are found to be the dominant lineaments in the catchment. Joint sets orientations interpretation in the reservoir and dam site showed that the N-S and E-W are the dominant joint sets over NW-SE and NE-SW. Beside their concentration these joint sets, especially the E-W, are open and continuous which are liable to cause stability problems in the reservoir and dam site.

By referring 25 years (1975-1999) rainfall records in the catchment, the mean annual rainfall depth of the catchment was calculated to be 1228.3mm. Using the Thornthwaite empirical formula (1948) the potential evapotranspiration of the catchment calculated to be 588.9mm. However, this result is extremely low estimate compared to other forwarded estimates in the surrounding areas under more or less same climatic conditions. Therefore, it is not used for further actual evapotranspiration calculations. Instead the values promoted for Addis Ababa and surrounding areas by Food and Agricultural Organization of the United Nations (FAO) is used. Applying this (1120mm) value with effective monthly rainfall, the actual evapotranspiration is found to be 791.5 mm using Thornthwaite and Mather (1957) soil-water balance method. The runoff depth calculation in the catchment gave 388 mm. Graphic separation of the surface runoff and base flow of the two components showed that 54 % of the flow is contributed by base flow. Comparison between the calculated surplus value and base flow shows that the surplus value (222.9mm) is greater than the base flow (209.5). This condition indicates that there is no out flow of groundwater from the catchment through other routes, which is in favor of the reservoir condition.

Some features of the groundwater in the area are also discussed. The depth of static water level is observed mostly in the weathered and fragmented part of the bedrock in the dam site using the borehole data of the area. These data was also used to estimate the general groundwater flow direction to be south to north as that of the surface water. The waters in the area are a little alkaline, hard water and less content of sulphate indicating they are not causing significant negative effect in the concrete structure of the dam. The river water has high Na cation while the ground water has high content of Ca, which used to explain the mineralogy of the reservoir soils formations.

The rocks of the area were described using their lithological features as main classes: basalts, trachyte and pyroclastic deposits. But detail engineering description within these main groups relay on the assemblage of basic engineering behaviors. Engineering subgroups of the basaltic, trachytic and pyroclastic deposit units are highly influenced by their textural, joint and compaction natures respectively. Through this it was possible to describe eight engineering subgroups in the reservoir area:

aphanatic, scoracious, vesicular and halocrystalline basalts, massive and columnar trachyte, friable and welded pyroclastic deposits; according ISRM (1981) descriptive scheme.

The soils of the area are genetically classified using their morphologic set up as residual, alluvial and colluvial. For better geotechnical description of the soil units in the area 20 soil sample test results were used. Using their grain size distributions it was possible to describe five engineering subgroups of the soils in the reservoir: silty clay, clay, gravelly clay, sandy clay and clayey gravels; according ISRM (1981) descriptive scheme.

These full descriptions of the rocks and soils are used to classify them into basic engineering geological units, which then represented on the engineering geological map of the reservoir area. The rock units classified based on their strength and weathering grades as high, medium and low rock mass strength with spot weathering grades. The genetically designated soils were classified using the USCS, i.e. with their grain size analysis and plasticity nature, as ML, MI, CL, OH, CH, CV, CE and GC. All these information were used to establish the engineering geological map of the reservoir area at the scale of 1:12,500.

The evolution and genesis of soils in the Sibilu catchment are discussed in terms of the basic controlling factors: topographic, geologic, climatic and environmental features. As a result, volcanic soils of black and red clay varieties of soils have been identified in the area as the two major soil formations, with different geotechnical behaviors. Black clay soils are found in areas of flat terrains and poor drainage conditions, while the red clay soils have developed in sloppy and good drainage areas. With the help of chemical analysis, it was found that the loss of silica is slight in the black clay soils, but more evident in the red clays. The black clay soils have dominant montimorillonite, while the red clay soils contain kaolinite as the principal clay mineral. This result is further conformed by their general geotechnical properties. In the midst of these arguments it may be feasible to conclude that montimorillonite formed initially in volcanic soils of the area and then with intense leaching kaolinite formed as the result of montimorillonite alteration. This was also described in characterizing the volcanic soils of the country. The soils of the reservoir are similar to other Ethiopian volcanic soils.

With regard to the geotechnical properties of the Sibilu reservoir soils, it was found that black clay soils have higher moisture contents, higher clay fractions, higher values of liquid limits and plasticity index and lower values of plastic and shrinkage limits than the red clay soils. Comparison of the activity of these soils indicates that black clay soils are more active than the red clay soils. Most of the black clay soils are potentially expansive, while the red clays do not. Since the expansive nature is associated with the compressibility nature, the black clays are highly compressible than the red ones.
The main concern of dealing the clay minerals in the dam engineering is to define their dispersivity. So the black clay soils, of high content of montimorillonite, are potentially dispersive and needs more caution as a foundation material.

There are small-scaled landslides in the reservoir flanks of which the one on Asere ridge may need serious attention. From the borehole data, it was possible to establish the stratigraphy of the dam and spillway sites. It was also possible to identify three geotechnical layers in the dam site: soil materials, highly weathered and fragmented soft basalts, and joined sound basalt. Excavation is needed by considering these layers and observing the dam site geomorphological setting. The permeability and fracture intensity of the foundation materials show that, the requirement of further treatment during construction of the dam is crucial to control seepage through the foundation.

The rock and soil materials for the construction of the dam are almost available in the vicinity of the area. For the clay core, the reservoir soils are examined and the red clay soils are preferred than the black clay soils by their geotechnical properties. The compaction efforts for the preferred soils are also discussed. The Buba hills basalts fulfill the requirements as the construction material for the dam. In the construction materials only sands for filter material are not available in the surrounding area, which make the search of other sources, vital for economic consideration.

Based on the this study the following recommendations are forwarded:

- The analyses of the E-W open joints and fractures in terms of depth should be identified in reservoir flanks and dam site to define the stability and leakage problems.
- Proper water balance assessment in the catchment should be done to analyze the water resource in the area.
- Long-term peziometeric readings in the reservoir flanks and dam site are needed to evaluate the groundwater fluctuations in solving the stability and geotechnical problems easily.
- Depth of the unstable landmasses on the reservoir flanks should be known by drilling to understand their effect in the reservoir and dam conditions.
- Slope stability analysis should be done in the Asere ridge landslide to define the remedial measure.
- Excavation is recommended to the depth of sound rock with curtain grouting to reduce seepage through the dam foundation.
- Filter design should be made to determine the proper size of the crushed aggregate in substituting the sand material.
- Environmental impact assessment should be clarified before and after the project establishment.

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Annex-A: Measurements of Joint Sets Orientations- dips, aperture and spacing

Station-01

Strike (°)	Dip direction (°)	Dip (°)	Aperture (cm)	Spacing
330	60	80	0.3	
335	65	75	0.2	
340	70	65	0.4	
330	60	60	1	
351	81	75	1.4	1.5-
355	85	65	1.6	7cm
355	265	70	0.8	
340	250	72	0.75	
345	255	50	0.24	
345	255	57	0	
330	240	64	0.91	
350	80	70	1.2	
340	70	75	0.6	
330	240	50	5	4-
340	250	55	1.2	5.2cm
70	340	65	0.4	
80	350	55	0	0.4-
75	345	65	0	2cm
75	345	60	0	
335	245	60	1.2	
340	250	70	0.8	1-5cm
350	240	65	0.4	
70	160	75	0	
80	170	70	0	
345	75	45	2.1	
335	65	45	2.2	10mm-
335	65	54	2.1	2cm
280	190	70	2	
285	195	75	0	
290	200	85	0	
285	195	80	0	
290	200	80	0	
285	195	85	0	
280	190	75	0.4	
275	185	70	0.5	
280	190	75	0	
280	10	65	2	
290	20	60	0.1	
285	15	55	1.2	
285	15	60	1.4	
290	20	65	2	
295	25	75	0.5	
300	30	70	0.4	
280	190	90	0	
285	195	90	0	1m-
290	200	90	0	2.1m
290	200	85	0	
300	30	55	1.2	

Strike (°)	Dip direction (°)	Dip (°)	Aperture (cm)	Spacing
300	30	55	1.2	
290	200	75	0.4	
285	195	80	3.1	
270	20	80	2.1	6m-
280	10	85	0	7.1m
285	15	55	0	
280	190	75	0	
290	200	75	0	
285	195	80	1.4	
290	200	85	2.4	
260	350	20	0.2	
275	05	30	0.4	
265	170	25	1	
275	185	35	0.5	
280	190	25	0.5	1.2cm-
285	185	30	0.6	3m
290	200	35	0.7	
295	205	40	0.3	
340	250	45	0.4	
330	240	65	0.3	
300	210	65	0.85	
310	220	75	0.9	
315	225	65	0.85	
325	235	75	1.2	2m-
315	225	50	1.4	3.2m
310	220	60	1.3	
320	230	65	1.2	
330	240	65	1.3	
325	235	70	1.4	
310	220	60	1	
315	225	75	1.1	
320	50	70	0.5	
320	50	75	0.5	
330	60	75	0.4	
320	50	60	0.4	
315	45	40	0	10cm-
325	55	50	0	17cm
330	60	45	0	
340	80	60	0	
270	Vertical	90	0.03	
280	"	90	0.03	
275	"	90	0.1	
295	"	90	0.3	
290	"	90	0	
300	"	90	0	
290	"	90	0	
285	"	90	0	
285	"	90	0.02	
290	"	90	0.02	

Strike (°)	Dip direction (°)	Dip (°)	Aperture (cm)	Spacing
05	95	65	1.2	
355	85	75	1.1	
0	90	75	1.5	
358	88	80	0.2	
350	80	85	1.4	
355	85	85	1.3	2-
5	95	65	1.5	9.8cm
10	100	75	1.1	
0	90	70	0.8	
2	92	65	0.8	
5	95	70	0.9	
10	100	75	0.5	
12	102	85	0.2	
0	Vertical	85	1.1	
10	"	90	2	
05	"	90	0.4	
360	"	90	0.5	
355	"	90	1.2	
340	"	90	1.4	0.4-
355	"	90	1.3	2.7cm
350	"	90	1.2	
05	"	85	1.1	
05	"	87	0.9	
10	"	85	0.8	
355	"	85	0.9	
355	"	90	0.7	
0	"	90	0.5	1-2cm
05	"	90	0.6	
10	"	90	1.4	
15	"	90	1.4	
10	"	90	1.2	
15	"	90	1.3	
05	"	90	1.4	
0	"	90	1.5	
02	"	90	1.6	
0	"	90	1.2	
10	"	90	1.8	
355	"	90	1.5	0.8-
350	"	90	1.4	1.5cm
0	"	90	1.3	
358	"	90	0.8	
357	"	90	0.75	
0	"	90	0.75	
355	"	90	0.75	
360	"	90	0.7	
355	"	90	0.5	
0	"	90	0	
10	"	90	0	
10	"	90	0	
15	"	90	0	
05	"	90	0	2-30cm
12	"	90	0	
15	"	90	0	
350	"	90	0	
355	"	90	0	

Strike (°)	Dip direction (°)	Dip (°)	Aperture (cm)	Spacing
340	250	65	0.2	
340	250	75	0.4	
345	255	55	0.5	
350	260	60	0	
345	255	65	0	
340	250	50	0	
330	240	55	0	
330	240	55	0	
340	250	60	0	
345	255	65	0	5-38cm
340	250	70	0	
340	250	65	0.1	
335	245	75	0.1	
320	230	75	0	
335	245	60	0	
340	250	75	0.6	
340	250	60	0.5	
330	240	75	0.7	
350	260	60	0.4	
335	245	70	0.6	
345	255	55	1.2	
350	260	50	1.3	
330	240	60	1.2	
340	250	65	0.9	
85	355	45	0.03	
90	0	50	0.1	
90	0	40	0.12	
95	185	45	0.3	40-
90	180	30	0.45	120mm
90	180	25	0	
85	355	40	0	
90	0	45	0	
90	0	30	0	
85	355	35	0	
87	357	30	0	
88	358	45	0	
90	190	65	0	
95	185	65	10	2.5-
90	180	75	20	5cm
95	185	70	15	
90	190	65	17	
90	180	50	18	
85	355	65	30	
90	360	65	35	
95	05	75	40	
85	355	75	13	
90	360	65	15	
90	360	75	12	
92	02	80	10	
95	05	85	8	
95	05	75	12	
0	Vertical	90	0	30-
05	"	90	0	45mm
355	"	90	0	
0	""	90	0	

Strike (°)	Dip direction (°)	Dip (°)	Aperture (cm)	Spacing
0	Vertical	90	1.2	
05	"	90	1.3	
0	"	90	1.6	80cm-
05	"	90	1.65	2.2m
0	"	90	2	
0	"	90	2.3	
355	"	90	2.3	
358	"	90	2.3	
05	"	90	1.5	
0	90	65	1.4	
0	90	85	1.8	
355	85	75	0.6	
360	90	70	0.7	
360	90	70	0	
0	90	75	0	
05	95	75	0	
10	100	85	0.5	
05	95	65	0.65	1.5-
05	95	60	0.80	4cm
10	100	65	0.7	
10	100	75	0	
0	90	75	2.1	
360	90	60	1.2	
360	90	75	1.5	
340	70	30	0	
340	70	35	0	
330	60	20	0	
335	65	15	0	
340	70	15	0	70cm-
340	70	20	0	1.2m
345	75	30	0	
350	80	35	0	
340	70	15	0	
340	70	20	0	
10	100	60	0.2	
20	110	65	0.4	
15	105	75	0.3	
20	110	80	0.5	
05	95	85	0.6	
15	105	60	0.7	
10	100	65	0.4	10cm-
10	100	75	0.2	2m
15	285	75	0	
10	280	80	0	
15	255	80	0	
05	275	65	0	
20	290	60	0	
10	280	65	0	
0	Vertical	90	0.4	
05	"	90	0.2	
360	"	90	0.1	
355	"	90	0.2	30-
360	"	90	0.1	110mm
05	"	90	0.1	
05	"	90	1.4	
10	"	90	1.3	
360	"	90	1.2	
15	"	90	1.8	4.5cm-
350	80	85	2.4	16cm
355	85	80	1.3	
360	Vertical	85	2.8	
360	"	65	2.8	
360	"	75	3	
80	170	45	1.2	
90	180	50	2.1	
95	185	40	1.8	
90	180	45	3.1	
85	175	70	3.2	
90	180	75	1.8	
90	180	50	20	1.2-
95	185	45	31	65cm
90	190	30	36	
85	175	35	41	
90	180	20	50	
90	180	45	50	
95	185	65	50	
85	175	70	54	
90	180	75	15	
95	185	80	24	
90	190	85	26	
85	175	75	34	
80	170	75	33	
90	180	80	24	

Station –03

Strike (°)	Dip direction (°)	Dip (°)	Aperture (cm)	Spacing
90	Vertical	90	1.4	
85	"	90	0.5	3-
90	"	90	0.8	50cm
90	"	90	1.2	
15	105	85	0	
20	110	75	2	
25	115	85	4	
40	130	80	0	
40	130	80	0	16-
25	115	85	10	30cm
40	130	75	10	
15	105	65	5	
20	110	75	0	
25	115	80	0	
90	Vertical	90	1.4	
70	"	90	1.2	45-
90	"	90	0.8	63cm
80	350	85	0.5	
90	0	85	0.8	
85	355	80	0.8	
0	90	70	17	
355	85	65	8	
360	90	70	5	2cm-
350	80	75	10	1.2m

Strike (°)	Dip direction (°)	Dip (°)	Aperture (cm)	Spacing
0	Vertical	65	8	
360	"	70	14	
355	265	70	13	
2	272	65	15	
5	275	75	16	
10	280	80	15	
10	280	80	17	
20	290	75	0	2-
25	295	85	0	40cm
25	295	75	0	
25	295	85	0	
40	130	65	0	
30	120	75	0	
20	110	75	0	
25	115	75	0	50cm-
35	125	80	0	3m
30	120	80	5	
40	130	85	2	
45	135	80	10	
30	120	85	0	
35	125	85	8	
80	Vertical	90	7	
90	"	90	8	
90	"	90	5.6	
85	"	90	5.8	
90	"	90	12.3	
95	"	90	6.9	
90	"	90	7.5	15-
85	"	90	14	30cm
95	"	90	28	
95	"	90	30	
95	185	85	25	
90	180	85	12	
90	180	80	5.4	
90	180	80	8.5	
0	90	65	1.3	
355	85	75	2.3	
5	95	75	2.4	
10	100	75	2.6	2-
350	80	65	2.5	35cm
355	85	70	1.3	
5	95	70	1.6	
5	95	65	13	
360	90	80	0.2	
360	90	75	0.2	
0	270	85	0	
355	265	80	0	
355	265	65	0	
340	250	65	0	
340	250	60	0.8	
360	270	40	0.9	36-
80	350	30	0.2	48cm
80	350	30	0.2	
0	90	65	10	
355	95	75	12	
360	90	75	7	
350	80	65	17	2-
5	95	70	16	62cm
10	100	80	12	
15	105	85	15	5-
10	100	80	14	60cm
5	95	65	12	
350	80	60	10	
360	Vertical	90	0	
0	"	90	0	2-
360	"	90	0	10cm
10	"	90	0	
15	"	90	0	
40	"	90	0	
35	"	90	0	
35	"	90	0	
40	"	90	0	
15	"	90	0	
20	"	90	0	8-
15	"	90	0	17cm
10	"	90	5	
15	"	90	2	
35	"	90	7	
30	"	90	8	
40	"	90	4	
35	"	90	2	
20	"	90	5	
25	"	90	2	
20	"	90	1	
90	180	65	0.5	
85	175	70	0.6	
95	185	65	1.2	
80	170	75	0.5	8-
90	180	75	0.8	96cm
85	175	70	0.8	
90	180	65	0.8	
95	185	65	0.8	

In central reservoir area

Strike (°)	Dip direction (°)	Dip (°)	Aperture (cm)	Spacing
0	90	60	0.3	
5	95	75	0.2	
5	95	70	0	0.5-
0	90	80	0	1.3cm
360	270	10	0	
355	265	20	0	
355	265	70	0	
90	0	75	13	
90	0	80	12	
90	0	85	2	1.5-
95	05	80	4	2.1cm
95	05	85	1	
95	05	90	0.8	
100	10	90	12	
90	0	90	11	
95	05	90	0.8	

In central reservoir area

Strike (°)	Dip direction (°)	Dip (°)	Aperture (cm)	Spacing
45	325	20	1.2	
40	320	25	1.4	
45	325	25	2	0.2-0.6cm
47	327	30	0	
40	320	30	0	
40	320	30	0	
90	0	90	1.2	
80	350	90	1.4	
85	355	90	1.3	
90	360	90	1.1	
85	355	75	2	
85	355	60	5	
88	358	75	1.4	
90	360	75	2	
90	360	70	1	1.3-17cm
95	05	70	1.4	
85	355	65	2	
85	355	70	2.6	
90	360	65	0.7	
90	360	70	0.8	
90	360	70	0.5	
05	95	70	0	
0	90	65	0	
05	275	75	0	
05	275	70	0.3	
05	275	70	0.2	
10	280	70	0.1	0.8-1.5m
360	270	65	0	
355	265	65	0	
360	270	60	0	
0	270	90	0	
360	270	90	0	
0	270	90	0	
90	180	90	2.4	
85	175	90	15	
85	175	90	1.2	
87	357	90	30	5cm-1.6m
85	355	90	40	
90	360	90	52	
95	05	90	27	
90	360	90	30	

In southern reservoir area

Strike (°)	Dip direction (°)	Dip (°)	Aperture (cm)	Spacing
330	30	20	0	
335	35	25	0	
330	30	30	0	
337	37	35	0	
339	39	40	0	1.1-2.3cm
355	85	45	0	
335	245	20	0.1	
335	245	25	0.4	
330	240	30	0.5	
335	245	35	0.1	
330	240	20	0.1	
335	245	25	0	
0	90	80	10	
05	95	85	20	
05	95	75	10	
0	0	80	7	
05	95	75	2	
05	95	75	1.5	
05	95	80	1.6	
0	270	85	1.4	0.2-7cm
10	280	75	1.2	
10	280	70	2.1	
07	97	60	1	
05	275	65	4	
05	275	70	5	
05	275	75	0.8	
90	0	70	1.5	
90	0	75	2.4	
95	05	90	0.2	
90	0	90	0.1	
95	05	90	0.4	
95	05	90	0.6	
90	180	90	0.7	
90	180	90	1	
97	187	90	2	
90	180	90	2	50cm-7m
95	185	90	6	
85	175	90	12	
88	178	90	1.4	
86	176	90	1.6	
85	175	90	0	
90	180	90	0	
90	180	90	0	
85	175	90	0	
85	175	90	0	
85	175	90	0	
90	0	90	0	
85	355	90	0	

Latitude 9:02:00N Longitude 38:45:00E Altitude 2408m

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1975	0	0.4	14.4	86.4	55.5	136	312	228	213	27.4	0	0	1073.1
1976	19.3	61.4	44	170	83.4	121	281	278	158	3	93.6		1312.7
1977	34.7	57.2	80	125	69.8	238	354	399	220	35.5	6.6	- 0	1619.8
1978	1.4	55.4	78.8	121	49.6	131	196	376	147	39.1	0	3.4	1198.7
1979	128	19.1	73.6	84.5	103	135	289	204	225	0	0	16.6	1277.8
1980	23.2	36.6	45.3	88.5	44.5	126	283	297	118	1.5	0	0	1063.6
1981	0	75.5	176	82.9	73.6	50.1	266	311	215	15.5	0	5.2	1270.8
1982	4.87	80.9	57.8	104	75.6	131.9	259	258	212	14.4	43.2	11.9	1253.6
1983	18.3	21.7	48.7	117	237	109	199	244	198	26.3	0	8.8	1227.8
1984	0	8	9.7	42.3	128	221	296	296	142	9.8	4.4	16.3	1173.5
1985	14.2	0	17.5	96.3	83.7	112	270	328	156	13.8	3.3	1.2	1096
1986	0	35.7	88	146	89.3	120	280	264	128	14.3	0	0	1165.3
1987	0.5	63.4	249	82.4	97.4	92.9	296	254	187.8	21.3	4.8	10.3	1359.8
1988	9.7	53.4	5.3	88.6	46.3	106	278	299	156	39.9	0	0	1082.2
1989	0.8	75.9	76.5	96.3	64.7	120.9	257.6	301.6	188.7	14.5	8	17.6	1223.1
1990	0.8	155.9	59.2	106.4	85.3	129	218.7	268.6	184	16.2	6	0	1230.1
1991	0	74.5	106.6	54.7	75.3	191.1	248.9	262.6	126.4	3.4	0	50	1193.5
1992	20.2	33.7	20.2	44	85.6	109.1	248.5	244.7	209.4	69.7	0	2.9	1088
1993	10.8	67.2	16.1	157.9	97.2	169	274	326.7	243.3	62.1	0	4.5	1428.8
1994	0	0	82.4	82.6	63.3	123.4	208.9	225	141.3	0	14.7	0	941.6
1995	0	69	41.5	174.4	68.2	102.9	190.2	314.9	136.1	0	0	48.4	1145.6
1996	28.1	5.2	106.8	128.2	122	258.5	266.4	338.8	294.2	0.2	0.2	0	1548.6
1997	39.2	0	24.5	51.3	38.5	104	272.6	194	213.8	62.4	50.3	1.5	1052.1
1998	55.2	20.5	49	48.5	154.2	124.4	285.4	260	213.6	116.9	0	0	1327.7
1999	22.3	28.3	86.5	94.2	88.3	134	256.9	284	140.8	71.3	0	1.6	1208.2
Ave.	17.263	43.956	66.296	98.936	87.172	135.85	263.48	282.28	182.7	27.14	9.404	8.3417	1222.8

Monthly Rainfall Data (in mm)
Station- Sululta
Latitude 9:11:00N Longitude 38:46:00E Altitude 2604m

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1975	0	27	22.5	72	19.5	221	258	273	266	32.5	25.3	5.5	1222.3
1976	23.5	82.8	156	225	24	257	284	376	183	15	63	0	1689.3
1977	1	52.5	44.6	115	19.4	279	281	287	270	32.8	0	14.9	1397.2
1978	7.1	18.9	44.9	81.2	63.7	225	383	400	102	35.1	8.9	11.2	1381
1979	0	18.3	23.6	74.4	109	202	275	301	219	12.5	0.2	9.7	1244.7
1980	19.4	19.4	173	190	79.1	130	168	168	160	3.45	0	19.5	1129.9
1981	22.5	10.5	118	65	106	164.2	249	209	138	32.5	0	0	1114.7
1982	0	10.2	51.2	39.7	58	140.1	278.6	379.5	161	13	3.4	0	1134.7
1983	21.3	22.7	45.7	119	24.5	207	211	254	151	27.1	1.2	9.1	1093.6
1984	0	70.6	9.2	10.1	95.2	201	311	291	141	0	0.8	12.3	1142.2
1985	12.1	22.7	17.5	90.3	84.7	211	214	278	206	51	3.3	1.2	1191.8
1986	0	35.2	80	192	32.5	270	293	261	128	9.5	0	0	1301.2
1987	2	56.4	272	81.2	24.2	90.9	299	257	115	19.3	1.2	0.3	1218.5
1988	8.5	63.1	3.5	126	93.2	100.2	275	301	231	30	0	0	1231.5
1989	0	79.2	81.2	135.2	110	101	379.1	321.3	191.7	14.1	0	7.6	1420.4
1990	1.2	160.9	60.2	116.4	18.9	112.2	212.4	281.6	211	16.2	6	0	1197
1991	0	71.2	111.2	23.7	56.3	197.1	257.6	256.1	120.4	3.4	0	5.1	1102.1
1992	6.5	64.8	31.9	32	53.2	101	310.5	341.2	136.5	2.3	1.2	2.1	1083.2
1993	31.2	68.7	1.6	96	44.9	121.3	371.3	356.1	169.4	6.5	0	6.4	1273.4
1994	3.2	9.76	48.9	151	56.9	123	314.4	301.6	198.2	4.6	0	2.6	1214.2
1995	4.3	9.75	51.2	57	61.4	115.8	257.1	278.9	158	5.8	1.8	5.2	1006.3
1996	0	112.3	136.5	38.3	22.2	147	218.7	297	195.3	9.7	17	4.5	1198.5
1997	0	118.3	123	53.3	126	125.6	221.3	321.5	177.6	10.4	4.6	2.1	1283.7
1998	2.1	116.3	98.7	24	48.2	129.4	311	297.6	196.5	3.7	3.5	3.4	1234.4
1999	2.5	105.3	106.2	58	38.4	197.3	207.2	305.4	169.7	5.8	4.1	2.7	1202.6
Ave.	6.736	57.072	76.492	90.632	58.776	166.76	273.61	295.75	175.81	15.85	5.82	5.016	1228.3

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1975	0.4	55.3	47.2	108	26	206	260	247	56.7	0	2.8	0	1009.4
1976	20.4	1.7	45.1	32.7	6.2	79.9	215	302	273.8	26.4	2.7	10.3	1016.2
1977	15.1	42.6	30.1	53	45.7	97.2	223	335	215	27.4	15.6	13.6	1113.3
1978	19.3	0	14.7	139	81.4	180	428	431	394	0.9	0	0	1688.3
1979	13.4	1.7	8.4	287	61.5	265	472	425	328	0	2.2	0	1864.2
1980	56	0	21.1	211	32.3	299	398	401.2	321	0	0	0	1739.6
1981	0	0	65.2	10.7	75.9	175	347	308	282	19.9	0.8	0.2	1284.7
1982	0	1.8	19.5	92	93.8	195	282	325	83.6	7	0	0.3	1100
1983	0	20.4	41.3	126	26.8	185	277	300	186	12.5	3	0.5	1178.5
1984	33.5	0	25.5	55.8	73.2	159	295	369	257	21.9	3.5	16.9	1310.3
1985	0	1	97.5	45.2	65.3	138	283	341	216	41.3	0	0	1228.3
1986	67.5	109	153	95.8	123	128	226	300	109	0	0.3	0.1	1311.7
1987	0	0.4	21.6	37.4	35.4	268	314	180	98.8	0	0	2.25	957.85
1988	80.5	29.9	80.6	67.4	108	158	290	279	108	22.6	5	0	1229
1989	27.3	28.2	108	57.6	122	75.9	243	241	96.5	23.1	11.2	4	1037.8
1990	28.5	36.5	54.7	55.8	56.8	212	381	364	64.4	13.1	0	0	1266.8
1991	13.6	0	32.4	71.8	96.6	96.5	294	324	164	1.3	0	1.8	1096
1992	0	95.4	67.4	67.4	149	68.9	143	189	216	32.5	9.4	0	1038
1993	0	71.6	182	84.2	88.1	69.3	208	247	82.5	14.4	0	2.4	1049.5
1994	0	44.5	112	96	23.8	125	256	278	175	35.4	8.4	0	1154.1
1995	2.1	63.8	163	112	25.3	158.8	264.2	301	171	38	0	0	1299.2
1996	17.7	120.6	48.4	116	37.8	103.6	280.2	223	117.3	5.8	1.2	1.2	1072.8
1997	0	270.6	62.4	116.4	45.6	165.7	263.7	309	113.3	12.6	1.6	0.5	1361.4
1998	28.5	36.8	54.7	55.8	56.8	112	381	364	64.4	13.1	0	0.9	1168
1999	1.8	33.3	15	147	17.5	183	238	275	139	9.2	2	0	1060.8
Ave.	17.024	42.604	62.832	93.64	62.952	156.15	290.48	306.33	173.29	15.136	2.788	2.198	1225.4

Monthly Mean Maximum Temperature (0^C)
Station Sululta

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	mean
1975	18.8	20.2	21.1	19.1	20.1	18.1	14.2	14.7	16.5	18	18.5	18.7	
1976	20.2	18.7	22.2	18.7	21.2	17.1	15.5	15.1	16.3	18.1	18.4	18.6	
1977	17.6	18.4	18.1	19.7	22.1	17.3	16.1	15.2	16.2	18.1	18.4	18.6	
1978	16.7	18.1	19.2	19.6	21.1	17.8	15.1	15.1	16.1	18.3	18.8	18.5	
1979	18.2	20.1	19.8	19.7	19.5	16.7	15.3	15.3	16.7	17.6	18.3	18.3	
1980	18.1	19.2	19.7	20.3	19.7	17.8	15.7	14.7	16.8	17.7	18.1	18.4	
1981	18.7	19.1	18.7	21.1	20.9	17.9	15.9	14.6	16.9	17.7	18.2	18.6	
1982	19.2	19.3	18.9	18.1	20.5	18.1	16.1	15.1	16.5	18.1	18.4	18.7	
1983	18.1	19.4	19.1	18.4	20.1	17.2	15.6	15.1	17.1	18	18.5	18.2	
1984	18.3	19.8	20.1	18.5	18.9	17.3	15.2	15	14.9	18	19	19.5	
1985	18.3	20.7	20.2	19.2	19.7	17.4	15.4	15.6	15.2	18	19.3	19.9	
1986	17.2	21.7	19.5	19.8	20.1	17.6	15.1	15.1	15.1	17.9	19.7	19.3	
1987	17.4	18.3	19.4	19.5	20.1	17.8	15.6	15.1	15.2	18.3	19.7	20.1	
1988	19.1	20.1	19.3	19.7	19.7	17.8	15.5	16.1	15.3	18	20.1	19.1	
1989	18.8	19.1	19.1	19.7	20.8	17.5	15.3	15.3	15.6	18	18.1	19.2	
1990	19.2	19	19.5	19.6	19.2	18.1	14.2	16.1	15.1	18.8	19.2	19.6	
1991	17.1	18.6	19.7	18.2	19.1	17.2	15.9	15.1	15.3	18.2	19.2	19.3	
1992	17.6	19.3	19.6	18.7	19.8	18.1	15.1	14.3	16.1	17.1	18.2	19.4	
1993	18.1	19.4	20.1	19.7	19.2	17	15.2	15.2	17.1	17.3	18.3	18.5	
1994	18.3	19.7	20.1	19.8	19.5	17	15.4	15.3	18.1	17.4	18.3	18.5	
1995	18.7	19.1	18.9	19.2	20.1	17.2	15.8	15.1	17.8	18.8	18.4	18.6	
1996	18.4	19.4	18.7	19.5	20.3	16.9	15.8	15.4	17.8	18.2	18.5	18.7	
1997	18.7	19.2	19.4	19.7	19.9	16.8	15.7	15.1	17.4	18.5	18.5	19.3	
1998	18.6	19.1	19.6	20.1	20.4	17.1	15.2	15.2	17.2	18.6	18.7	19.1	
1999	18.7	19.3	19.7	20.2	20.8	17.2	15.1	15.3	17.8	18.5	18.3	18.7	
Ave.	18.324	19.372	19.588	19.432	20.112	17.44	15.4	15.168	16.404	18.048	18.684	18.936	18.076

					May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	mean
1975	7.6	8	9	9	9.5	7.3	7.2	7.2	7	6.9	6.8	7	
1976	7.5	8.1	9.2	8.8	9.6	7.4	7.1	7.1	7.1	6.8	6.7	6.9	
1977	7.4	8.3	9.6	8.7	9.1	7.5	7.3	7.1	7.4	7.4	6.2	7.3	
1978	5.2	7.8	8.1	8.4	10.1	7.6	7	7.2	7.6	6.9	6.8	7.2	
1979	8.1	7.9	8.3	8.9	8.9	7.7	7.2	7.1	7.7	7	6.9	7	
1980	8	7.7	8.2	8.9	8.9	8.1	6.9	7.2	7.2	7.1	7	7.1	
1981	7.3	8.1	9	8.9	10.7	7.3	7.3	7.1	7.1	6.5	7.4	7.2	
1982	7.4	8.2	8.4	9	9.4	7.2	7.2	7.1	7.4	7.2	7.1	7.7	
1983	6.1	8.3	8.5	9.1	9.3	7	7.1	7.3	7.5	6.3	7.3	7.4	
1984	6.4	8.4	8.9	8.8	9.2	7.9	7.7	7.4	7.2	6.9	7	7	
1985	7.8	8.5	8.6	8.4	10.2	7.8	7.4	7.1	7.8	6.8	7	7.1	
1986	7.8	8.6	9.1	8.7	10.4	7.1	7.2	7.3	7.8	6.5	6.4	7.3	
1987	8.1	7.7	9.2	9.1	10.6	7.9	7.3	7.2	7.8	7.5	6.1	7.1	
1988	7.2	8.3	8.8	9.2	9.1	8	7.5	7.1	7.9	6.9	6.8	6.9	
1989	7.3	8.1	8.2	9.1	9.6	7.7	7.7	6.5	7.6	7	6.8	6.9	
1990	7.4	8.2	8.3	9.7	9.6	8.1	8.1	6.9	7.7	7.4	6.2	7.1	
1991	7.5	7.6	9	8.9	9.4	8	8.2	6.8	7.5	7.3	7.1	7.3	
1992	7.7	7.4	9	8.9	9.7	8.1	8.3	7.7	7.6	7.4	7.1	7.4	
1993	8.1	7.3	8.1	8.8	9.3	8.2	7.6	7.8	7.7	6.9	6.8	6.9	
1994	7.1	7.3	8.2	8.6	10.5	8.2	7.9	7.2	7.8	6.8	6.7	6.6	
1995	7.2	7.3	8.3	8.4	10.4	7.8	7.8	7.3	7.2	6.9	6.8	6.9	
1996	6.3	7.4	8.6	8.3	10.7	8.1	7.7	7.4	7.5	7	6.9	6.8	
1997	6.9	7.2	8.7	8.2	10.2	7.2	7.2	7.2	7.5	7	6.5	6.7	
1998	8.9	8.1	8.6	8.8	9.3	8.1	7.4	7.1	7.3	6.5	6.3	6.9	
1999	7.3	8	8.6	9.3	9.4	7.3	7.1	7.1	7.4	6.4	6.8	7.3	
Ave.	7.9	8.06	8.66	9.2	10.3	8.7	7.456	7.4	7.492	6.932	6.78	7.08	7.9967

Monthly Flow data of Sibilu River (cubic meter per second)
Station number : 112014 Name R. Sibilu near Deneba
Latitude 9:15:00N Longitude 38:43.6:00E
Area 376.6 sq. km Altitude 2550m

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
1981	0.435	0.427	0.593	0.618	0.481	1.052	12.1	24.4	16.6	4.98	0.941	0.545	
1982	0.661	0.432	0.435	0.459	0.481	1.068	13.69	25.2	11.2	2.32	1.05	0.578	
1983	0.434	0.456	0.467	0.636	0.545	1.34	17.89	28.1	17.7	4.65	0.934	0.624	
1984	0.453	0.414	0.402	0.387	1.31	1.94	20.6	29.9	16.8	5.3	0.688	0.538	
1985		0.425	0.346	0.353	0.405	1.5	14.1	27.9					
1986				0.89									
1987	0.648	0.489	0.624	0.4	0.92	2.63	18	28.7	19.28	4.4	0.78	0.61	
1988	0.467	0.458	0.425		0.41	1.42	13.4	32.9	15.1	3.22	1.04	0.534	
1989	0.521	0.443	0.422	0.353	0.423	1.53	11.5	31.2	25.3	4.65	1.19	0.664	
1990	0.468	0.535	0.398	0.369	0.496	1.278	22.4	26.3	19.8	2.12	1.09	0.645	
1991	0.68	0.529	0.397	0.387	0.447	1.082	16.7	23.5	21.6	3.85	0.94	0.709	
1992	0.457	0.416	0.404	0.464	0.504	2.4	18.9	28.8	24.3	3.47	1.22	0.597	
1993	0.501	0.511	0.479	0.547	0.593	1.252	15.5	24.2	20.6	4.16	1.011	0.653	
1994	0.483	0.526	0.47	0.539	0.654	1.35	15.6	25.5	17.3	5.7	0.906	0.572	
1995	0.575	0.457	0.591	0.579	0.533	2.26	19.1	23.2	13.05	1.07	0.803	0.579	
1996	0.54	0.524	0.523	0.429	0.577	9.7	15.18	22.7	14.45	2.78	0.609	0.551	
1997	0.455	0.498	0.404	0.398	0.401	2.04	21.2	25.1	19.7	3.02	0.688	0.538	
1998	0.563	0.611	0.654	0.97	0.723	3.4	16.8	26.1	9.28	3.98	0.83	0.61	
1999	0.476	0.467	0.431	0.46	0.372	6.4	19.9	27.1	17.4	3.65	1.02	0.534	5.9

Annex-C: Groundwater Level Data

WATER LEVEL IN SIBILU CATCHMENT

	Bh-N	E(m)	N(m)	G. E	S.w.l.	E. w.l.
Sibilu Resevoir	Bh-01	470087	1026992	2537	19.8	2517
Sibilu dam site	Bh-04	470150	1026988	2538	20.1	2518
	Sb-01	470666	1027813	2536	3.6	2532
	Sb-11	470118	1027850	2553	1.81	2534
	Sb-13	470240	1027645	2537	12.77	2534
	Sb-14	470380	1027705	2536	11.7	2534
	Sb-15	470370	1027568	2541	14.69	2536
	Sb-10	470160	1027712	2539	2.25	2537
	Sb-02	470680	1027745	2540	3.2	2537
	Sb-03	470699	1027699	2543	5.1	2538
	Sb-16	470520	1027425	2558	19.34	2544
	Sb-12	470195	1027645	2549	1.63	2544
	Sb-04	470682	1027594	2549	4	2545
	Sb-19	470675	1027220	2559	12.8	2546
	Sb-22	470658	1027445	2558	10.8	2547
	Sb-06	470661	1027469	2558	10.2	2548
	Sb-07	470657	1027370	2559	9.6	2549
	Sb-20	470772	1027155	2562	11.45	2551
	Sb-18	470625	1027213	2561	16.78	2554
	Sb-08	470655	1027315	2558	3.6	2554
	Sb-09	470652	1027215	2559	1.2	2558
Gerbi Dam site	GB-05	464052	1012312	2651	20.14	2631
	GB-08	463961	1012295	2645	1.96	2643
	GB-06	463929	1012277	2645	1.66	2643
	GB-09	463888	1012321	2648	4.5	2644
	GB-07	463878	1012253	2645	1.11	2644
	GB-12	463840	1012372	2666	20.74	2645
	GB-11	463881	1012377	2668	21.75	2646
	GB-02	463727	1012192	2655	6.9	2648
	GB-10	463846	1012376	2677	27.52	2649

Geographic positions(UTM)
E(m)= easting
N(m)= northing
G.E= Ground elevation above mean sea level
S.w.l= Static water depth (m)
E.w.l= Elevation water level above mean sea level

Reading took in :-
Sibilu Reservoir in March 1994
Sibilu dam site in Sepetember 1997
Gerbi dam site in May 1997

proposed by International Society of Rock Mechanics (ISRM), (1981)

Lithologic name is of primary importance because it genetic rock group and provides basic information on mineral composition and grain size. Supplementary features may be extremely useful as a means of discriminating between different rocks that have the same lithological name.

Descriptive of Rock Material: i) Color can be quantitatively evaluated using, the rock color chart published by Geological Society of America (Anon, 1963). (Table.1)

LIGHTNESS	CHROME	HUE
Light	Pinkish	Pink
Dark	Reddish	Red
	Yellowish	Yellow
	Brownish	Brown
	Greenish	Green
	Bluish	Blue
	Grayish	Gray

Table .1 terms of color description

ii) Texture: of the textural elements used for description and classification, the most important is grain size. Because it considerably affects the physical properties of a rock should always be indicated directly in the rock description rather than relying on the grain size implication in the rock name. Many other aspects of rock texture may be used to amplify the description, such as: relative grain size, grain shape fabric and porosity.

2. State of Weathering: Description of the state of weathering of the rock material is of particular importance in describing engineering rocks because weathering has profound effects on the physical and mechanical properties of the rock material. In present work, Hosking (1990), weathered rock substances classification is used during field investigation. (Table.2)

Strength: is the basic parameter of the rock material in engineering works. To determine the strength of the rock material, uniaxial compression test and point load test are commonly used. Due to sampling problems, it is not possible to make these tests to the rocks of the study area. However, an attempt was made to designate the strength of rocks of the area using field estimates of unaxial compressive strength (Hoek et al, 1995).

Description of the Rock Mass: i) Structure of the rock mass is related to the larger scale interpretations of textural features and the association of one or more rock types in the mass. Terms used to describe igneous rocks are massive, flow banded, etc.

ii) Discontinuities are surfaces within a rock mass that is open or potentially open able under the stress levels applicable in engineering because the tensile strength across the surface is lower than that of the rock material. Description of discontinuities is aimed at determining their nature, orientation, spacing, persistence, roughness, wall strength, aperture, filling, seepage, number of sets, and block size.

3. Orientation: of the planar feature being measured with reference to magnetic or true north. Alternatively, the dip and dip direction of the plane may be determined.

Term	U.c.strength (MPa)	P.load test(Mpa)	Field estimate of strength
Extremely strong	>250	>10	Rock material only chipped under repeated hammer blows, rings when struck
Very strong	100-250	4-10	Requires many blows of a geological hammer to break intact rock specimens
Strong	50-100	2-4	Hand held specimens broken by a single blow of geological hammer
Medium strong	25-50	1-2	Firm blow with geological pick indents rock to 5mm, knife just scrapes surface
Weak	5-25	-	Knife cuts material but too hard to shape into triaxial specimens
Very weak	1-5	-	Material crumbles under firm blows of geological pick can be shaped with knife

Table.2 field estimates of uniaxial compressive strength

Spacing: the term refers to the mean or modal spacing of the set of joints that is perpendicular distance between adjacent discontinuities. Descriptive terms for discontinuity spacing are given in table 3.

Medium spaced	600mm-2m
Closely spaced	200mm-600mm
Very closely spaced	60mm-200mm
	under 60mm

Table 6. Discontinuity spacing

Persistence: is a measure of the aerial extent of a discontinuity from its inception to its termination in the solid rock against another discontinuity. For major joints, the plane may extend beyond the limits of the exposure and then the maximum trace length. Should be recorded.

Roughness: a discontinuity surface my be planer, undulating or stepped and descriptive terms (table 7) are based on two scales of observation

TERM	CATEGORY
Rough (or irregular), stepped	I
Smooth, stepped	II
Slickensided, stepped	III
Rough (or irregular), undulating	IV
Smooth, undulating	V
Slickensided, undulating	VI
Rough (or irregular), planar	VII
Smooth, planar	VIII
Slickensided, planar	IX

Tables 7. Roughness categories for discontinuity surface (ISRM, 1977)

Aperture: the mean perpendicular distance between adjacent walls of a discontinuity, in which the space is filled with air or water, is referred to as aperture. The mean separation may be described using the terms in table 8.

TERM	APERTURE
Very wide	Over 200mm
Wide	60-200mm
Moderately wide	20-60mm
Moderately narrow	6-20mm
Narrow	2-6
Very narrow	0ver 0-2mm
Tight	Zero

Table 8. Aperture of discontinuity surfaces

Infilling: the infilling between discontinuity surfaces may be soil introduced into the opening, minerals such as calcite, or in the case of faults clay gouge or breccia.

Seepage: water flow free moisture visible in individual discontinuities should be described and the rate of flow estimated.

Number of Sets: discontinuities may be irregular, of small persistence, without any arrangement into distinct sets: they are rather then referred to as non-systematic. Systematic joints will usually be persistent, with individual joints in each set parallel or sub-parallel. Systematic joints may be present in one or more sets, and influence rock mass blockiness and block size.

Block Size and Shape: the spacing of discontinuities may be described with reference to the size and shape of the rock blocks bounded by discontinuities and by the persistence of different discontinuity sets. Matula and Holzer (1978) have given models of rock mass blockiness (table 9), and the size of the blocks bounded by discontinuity may be described using the terms in table 10.

The Weathering Profile: weathering of the rock mass may be described in terms of the distribution and relative proportions of fresh rock and discolored, decomposed and disintegrated rock, and the effects on discontinuities.

Weathering eventually converts rock to an engineering soil and the weathering profile may be described in terms of basic units: rocks, rock-ad-soil, and soil. On rock masses consisting of one rock type these units will form a distinct succession with rock depth being overlain in turn by rock-and-soil and soil at the surface if a complete weathering

Type	Name	Description
Po-type	Polyhedral blocks	Irregular discontinuities without arrangement into distinct sets, and of small persistence
Ta-type	Tabular blocks	One dominant set of parallel discontinuities, with other non-continuous joints; thickness much less than length
Pr-type	Prismatic blocks	Two dominant sets of discontinuities almost orthogonal and parallel, with third irregular set; thickness much less than length
Eq-type	Equidimensional blocks	Three dominant sets of discontinuities, almost orthogonal, with occasional irregular joints, giving equidimensional blocks.
Rh-type	Rhomboidal blocks	Three (or more) dominant sets of discontinuities, mutual oblique, giving oblique-shaped, equidimensional blocks
Co-type	Columnar blocks	Several, usually more than sets of continuous, parallel joints crossed by irregular joints: length much greater than other dimensions.

Table 9. Rock mass block shape description.

TERM	AVERAGE DIMENSION
Very large	Over 2m
Large	600mm-2m
Medium	200mm-600mm
Small	60mm-200mm
Very small	Under 60mm

Table 10. Description f block size in the rock mass

Term	Description	Grade
Fresh	No visible sign of rock material weathering; perhaps slight discoloration on major discontinuity surfaces.	I
Slightly weathered	Discoloration indicates weathering of the rock material and discontinuity surfaces.	II
Moderately weathered	Less than 35% of the rock material is decomposed and/or disintegrated to a soil. Fresh or discolored rock is present either as a continuous framework or as corestone.	III
Highly weathered	More than 35% of the rock material is decomposed and/or disintegrated to a soil. Fresh or discolored rock is present either as a continuous framework or as corestone.	IV
Extremely weathered	All the rock material is decomposed and/or disintegrated to a soil. The original mass structure is still largely intact.	V
Residual soil	All the rock material is converted to soil. The mass structure and material fabric are destroyed.	VI

Table 11. Weathering grades for the rock mass.

The soil descriptive scheme has been proposed by International Society of Rock Mechanics (ISRM), (1981)

Descriptive Soil Name: i) Genetic type describe the type of geological formation and the environment of origination. Examples are: alluvium, eluvium, colluvium, Aeolian, marine, deltaic, tidal, and etc.
ii) Basic soil types are named after soil particle sizes falling within specified limits. These are boulders over 200mm, cobbles (20-60mm), gravel (6-2mm), sand (0.2-0.06mm), silt (0.006-0.002) and clay under 0.002mm.
iii) Composite soil types: most soils are composite types, containing a range of basic soil types. The proportion by weight of each component is then used as the basic for naming the soil (table 12).
iv) Plasticity: clay and silt, alone and in the mixture with coarse material, may be classified in terms of plasticity (Table 13).
As an alternative, a classification may be made in terms of plasticity index (table 14).

		0.06)		symbol	
Coarse soils (<35% is b/n 0.06-60mm)	Gravel	0-5	Gravel	G	Gravel
		5-35	Gravel, silty Gravel with fines Gravel, clayey	GM GF GC	Silty gravel Clayey gravel
	Sand	0-5	Sand	S	Sand
		5-35	Sand, silty Sand with fines Sand, clayey	SM SF SC	Silty sand Clayey sand
Fine soils (>35% is b/n 0.06-60mm)	Silty & clays Gravelly or sandy	35-60	Silt, gravelly Fine soil, gravelly Clay, gravelly	MG FG CG	Gravelly silt Gravelly clay
			Silt, sandy Fine soil, sandy Clay, sandy	MS FS CS	Sandy silt Sandy clay
	Silty & clays	65-100	Silt Fine soil Clay	M F C	Silt Fine soil clay
Organic	Organic sand, silt or clay			O	
Peat	Predominantly plant remnants			Pt	

Table 12.Composite soil type naming in engineering geology. (ISRM, 1977)

Term	Range of liquid limit (%)
Of low plasticity	Under 35
Of intermediate plasticity	35-50
Of high plasticity	50-70
Of very high plasticity	70-90
Of extremely high plasticity	Over 90

Table 13 terms for description of plasticity of fine soils and soil fractions in coarse soils

Terms	Plasticity index (%)
Non-plastic	Under 1
Slightly plastic	1-7
Moderately plastic	7-17
Highly plastic	17-35
Extremely plastic	Over 35*

*For very "fat" clays

Table 14. Terms for the description of plasticity index classes for fine soils and soil fractions in coarse soils.

Description of Soil Material: i) Color: soil may be evaluated quantitatively using the simple system recommended for rocks (table 1).

ii) Practical Shape and Composition: where appropriate, particle shape may be described by reference to the general form of the particles, their angularity which indicates the degree of rounding at the corners and edges, and their surface characteristics.

- Form: equidimensional, flat, elongated, irregular
- Angularity: angular, rounded
- Surface characteristics: rough, smooth

iii) State of Weathering: describe the degree of weathering i.e. the extent of departure from the parent rock, must be recognized and given semi-quantitative values. Various researchers use degree of weathering as a basis for

engineering identification of laterite soils. (Gidigase, 1984 sighted in Journal of Engineering Geology, 19 (1985/86) pp. 133-148).

iv) Strength: may be estimated by simple field tests on disturbed and/or undisturbed samples or by laboratory tests on the disturbed samples.

- Field tests for fine soils; consistency may be estimated using simple manual tests (table 15) on the disturbed samples.
- Undrained shear strength of fine soils may be classified and described as in table 16.
- If numerical, laboratory values for moisture content (m), liquid limit (LL), and plastic limit (PL) are available, the physical state of fine soils can be closely expressed by the consistency index:

Consistency index CI= LL – M/ LL – PL

A scale in terms of consistency index is given in table 17.

Term	Field test
Very soft	Exudes between fingers when squeezed in hand
Soft	Can be molded by light finger pressure
Firm	Can be molded by strong finger pressure
Stiff	Cannot be molded by strong finger pressure; can be indented by the thumb
Very stiff/ Hard	Can be indented by the thumb nail

Table 15.Field tests for the consistency fine soils

Term	Undrained shear strength kN/m^2
Very soft	Under 20
Soft	20-40
Firm	40-75
Stiff	75-100
Very stiff	Over150

Table 16. Classification of fine soils in terms of undrained shear strength

Term	Consistency index
Very soft	Less than 0.05
Soft	0.05-0.25
Firm	0.25-0.75
Stiff	0.75-1
Very stiff	Over 1

Table 17. Classification of fine soils in terms consistency index.

Description of the Soil Mass: requires information additional to the description of the soil as a material. A soil mass should first be described as a soil material, or as a combination or a mixture of soil types, followed by information of engineering significance concerning the soil mass. Such information includes:

- The geological structure and the distribution of the soil types in the soil mass
- The characteristics of the discontinuities in the soil mass
- The weathering profile

Features of the soil mass can only are determined by field observation or from a sufficient number of samples.

i) Structure: the larger aspects of structure are related to stratified deposits. Intercalation and lenses of softy clayey or organic matter, or of soluble materials, should be described in detail because of their important influence in engineering properties and the behavior of the soil mass.

ii) Discontinuity: in soils in fissures and shear planes should be described and quantified using the terms already given rocks. (ISRM, 1977).

iii) The Weathering Profile: weathering of the soil mass including the gradation to rock if the soil profile has resulted from weathering of the rock. However, table 11. has to be modified if it to be generally applicable to all soils, other than very stiff or hard, jointed and fissured fine soils.

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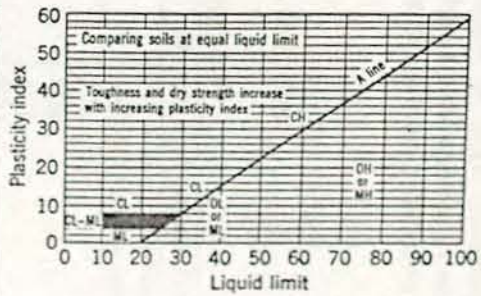
Unified Soil Classification

Field Identification Procedures (Excluding particles larger than 3 in. and basing fractions on estimated weights)				Group Symbols [a]	Typical Names	Information Required for Describing Soils	Laboratory Classification Criteria	
Coarse-grained soils: More than half of material is *larger* than No. 200 sieve size[b] (The No. 200 sieve size is about the smallest particle visible to naked eye)	Gravels: More than half of coarse fraction is larger than No. 4 sieve size (For visual classification, the ¼ in. size may be used as equivalent to the No. 4 sieve size)	Clean gravels (little or no fines)	Wide range in grain size and substantial amounts of all intermediate particle sizes	*GW*	Well graded gravels, gravel-sand mixtures, little or no fines	Give typical name; indicate approximate percentages of sand and gravel; maximum size; angularity, surface condition, and hardness of the coarse grains; local or geologic name and other pertinent descriptive information; and symbols in parentheses	Use grain size curve in identifying the fractions as given under field identification	$C_U = \frac{D_{60}}{D_{10}}$ Greater than 4; $C_C = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3
			Predominantly one size or a range of sizes with some intermediate sizes missing	*GP*	Poorly graded gravels, gravel-sand mixtures, little or no fines			Not meeting all gradation requirements for *GW*
		Gravels with fines (appreciable amount of fines)	Nonplastic fines (for identification procedures see *ML* below)	*GM*	Silty gravels, poorly graded gravel-sand-silt mixtures	For undisturbed soils add information on stratification, degree of compactness, cementation, moisture conditions and drainage characteristics	Determine percentages of gravel and sand from grain size curve. Depending on percentage of fines (fraction smaller than No. 200 sieve size) coarse grained soils are classified as follows: Less than 5% *GW, GP, SW, SP*; More than 12% *GM, GC, SM, SC*; 5% to 12% *Borderline* cases requiring use of dual symbols	Atterberg limits below "A" line, or *PI* less than 4 — Above "A" line with *PI* between 4 and 7 are *borderline* cases requiring use of dual symbols
			Plastic fines (for identification procedures, see *CL* below)	*GC*	Clayey gravels, poorly graded gravel-sand-clay mixtures			Atterberg limits above "A" line, with *PI* greater than 7
	Sands: More than half of coarse fraction is smaller than No. 4 sieve size	Clean sands (little or no fines)	Wide range in grain sizes and substantial amounts of all intermediate particle sizes	*SW*	Well graded sands, gravelly sands, little or no fines	Example: *Silty sand*, gravelly; about 20% hard, angular gravel particles ½-in. maximum size; rounded and subangular sand grains coarse to fine, about 15% nonplastic fines with low dry strength; well compacted and moist in place; alluvial sand; (*SM*)		$C_U = \frac{D_{60}}{D_{10}}$ Greater than 6; $C_C = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3
			Predominantly one size or a range of sizes with some intermediate sizes missing	*SP*	Poorly graded sands, gravelly sands, little or no fines			Not meeting all gradation requirements for *SW*
		Sands with fines (appreciable amount of fines)	Nonplastic fines (for identification procedures, see *ML* below)	*SM*	Silty sands, poorly graded sand-silt mixtures			Atterberg limits below "A" line or *PI* less than 5 — Above "A" line with *PI* between 4 and 7 are *borderline* cases requiring use of dual symbols
			Plastic fines (for identification procedures, see *CL* below)	*SC*	Clayey sands, poorly graded sand-clay mixtures			Atterberg limits below "A" line with *PI* greater than 7
Fine-grained soils: More than half of material is *smaller* than No. 200 sieve size (The No. 200 sieve size is about the smallest particle visible to naked eye)	Identification Procedures on Fraction Smaller than No. 40 Sieve Size							
		Dry Strength (crushing characteristics)	Dilatancy (reaction to shaking)	Toughness (consistency near plastic limit)				
	Silts and clays: liquid limit less than 50	None to slight	Quick to slow	None	*ML*	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands with slight plasticity	Give typical name; indicate degree and character of plasticity, amount and maximum size of coarse grains; colour in wet condition, odour if any, local or geologic name, and other pertinent descriptive information, and symbol in parentheses	
		Medium to high	None to very slow	Medium	*CL*	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays		
		Slight to medium	Slow	Slight	*OL*	Organic silts and organic silt-clays of low plasticity	For undisturbed soils add information on structure, stratification, consistency in undisturbed and remoulded states, moisture and drainage conditions	
	Silts and clays: liquid limit greater than 50	Slight to medium	Slow to none	Slight to medium	*MH*	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts		
		High to very high	None	High	*CH*	Inorganic clays of high plasticity, fat clays	Example: *Clayey silt*, brown; slightly plastic; small percentage of fine sand; numerous vertical root holes; firm and dry in place; loess; (*ML*)	
		Medium to high	None to very slow	Slight to medium	*OH*	Organic clays of medium to high plasticity		
Highly Organic Soils		Readily identified by colour, odour, spongy feel and frequently by fibrous texture			*Pt*	Peat and other highly organic soils		



Plasticity chart for laboratory classification of fine grained soils

From Wagner, 1957.

[a] *Boundary classifications.* Soils possessing characteristics of two groups are designated by combinations of group symbols. For example *GW-GC*, well graded gravel-sand mixture with clay binder.

[b] All sieve sizes on this chart are U.S. standard.

Field Identification Procedure for Fine Grained Soils or Fractions

These procedures are to be performed on the minus No. 40 sieve size particles, approximately 1/64 in. For field classification purposes, screening is not intended, simply remove by hand the coarse particles that interfere with the tests.

Dilatancy (Reaction to shaking):

After removing particles larger than No. 40 sieve size, prepare a pat of moist soil with a volume of about one-half cubic inch. Add enough water if necessary to make the soil soft but not sticky.

Place the pat in the open palm of one hand and shake horizontally, striking vigorously against the other hand several times. A positive reaction consists of the appearance of water on the surface of the pat which changes to a livery consistency and becomes glossy. When the sample is squeezed between the fingers, the water and gloss disappear from the surface, the pat stiffens and finally it cracks or crumbles. The rapidity of appearance of water during shaking and of its disappearance during squeezing assist in identifying the character of the fines in a soil.

Very fine clean sands give the quickest and most distinct reaction whereas a plastic clay has no reaction. Inorganic silts, such as a typical rock flour, show a moderately quick reaction.

Dry Strength (Crushing characteristics):

After removing particles larger than No. 40 sieve size, mould a pat of soil to the consistency of putty, adding water if necessary. Allow the pat to dry completely by oven, sun or air drying, and then test its strength by breaking and crumbling between the fingers. This strength is a measure of the character and quantity of the colloidal fraction contained in the soil. The dry strength increases with increasing plasticity.

High dry strength is characteristic for clays of the CH group. A typical inorganic silt possesses only very slight dry strength. Silty fine sands and silts have about the same slight dry strength, but can be distinguished by the feel when powdering the dried specimen. Fine sand feels gritty whereas a typical silt has the smooth feel of flour.

Toughness (Consistency near plastic limit):

After removing particles larger than the No. 40 sieve size, a specimen of soil about one-half inch cube in size, is moulded to the consistency of putty. If too dry, water must be added and if sticky, the specimen should be spread out in a thin layer and allowed to lose some moisture by evaporation. Then the specimen is rolled out by hand on a smooth surface or between the palms into a thread about one-eight inch in diameter. The thread is then folded and re-rolled repeatedly. During this manipulation the moisture content is gradually reduced and the specimen stiffens, finally loses its plasticity, and crumbles when the plastic limit is reached.

After the thread crumbles, the pieces should be lumped together and a slight kneading action continued until the lump crumbles.

The tougher the thread near the plastic limit and the stiffer the lump when it finally crumbles, the more potent is the colloidal clay fraction in the soil. Weakness of the thread at the plastic limit and quick loss of coherence of the lump below the plastic limit indicate either inorganic clay of low plasticity, or materials such as kaolin-type clays and organic clays which occur below the A-line.

Highly organic clays have a very weak and spongy feel at the plastic limit.

AAWSA soil samples were processed on TCDE laboratory to evaluate dispersivity using double hydrometer test. Soil with values 50% are dispersive and cause piping effect; soils with < 15% are non dispersive; while the ones in between are potentially dispersive (Fell *et al.*, 1992).

Lab No. 1090/88- 1097/88
Project: Sibilu dam site
Submitted by: AAWSA stage IIIA on 01-5-96
Test required: Double hydrometer
Reported to AAWSA stage IIIA, on 22-5-96

Double Hydrometer Test				
Sample	Depth (cm)	(A) Without dispersent and mechanical stirring omitted	(B) Standard hydrometer	% dispersent A/B x 100
Sb-A1-stpa4-2A	100-200	5.25	24	21.88 (?)
Sb-A1-stpa4-4A	300-400	4.00	12	33.33 (?)
Sb-A2-stpa4-2A	100-200	9.25	15.25	60.66 (??)
Sb-A2-stpa4-4A	300-400	2.00	36.00	5.56
Sb-A3-stpa4-2A	100-200	4.75	32	14.84
Sb-A3-stpa4-4A	300-400	10.00	42.5	23.53 (?)
Sb-A4-stpa4-2A	100-200	10.25	48	21.35 (?)
Sb-A4-stpa4-4A	300-400	4.00	17.5	22.88 (?)

(?)- Potentially dispersive (??)- Dispersive and cause piping effect

AAWSA soil samples were processed on Ministry of Water Resource Soil Mechanics Laboratory (Physical and Strength analysis of Soil) to evaluate dispersivity using pinhole. PD1 that are dispersion >50% are potentially dispersive and cause may piping effect and ND1 are not dispersive (Fell *et al.*, 1992).
Project: Sibilu dam site
Sheet No. 03
Date of receipt sample 05-07-96
Test date 10-07-96
Reported to: AAWSA stage IIIA, on 25-7-96

PINHOLE							
Field No.	Classification	Head (mm)	Time for test (Min)	Rate of flow (Ml/s)	Color	Hole diameter after time (mm)	Dispersion (%)
SA1-P4(4A)	ND1	820	5	4<4.5>5	Clear	1	36
SA1-P1(2A)	ND1	820	5	4<4.3>5	Clear	1	31
SA2-P5(3A)	ND1	820	5	3.6	Clear	1	12
SA2-P1(2A)	ND1	820	5	4<4.2>5	Clear	1	25
SA4-P3(3A)	PD1	820	5	0.8	Not clear	1	63 (?)
SA4-P1(3A)	PD1	820	5	0.9	Not clear	1	57 (?)
SA1-P4(4A)	-	-	-	-	-	-	Without dispersion
SA1-P1(2A)	-	-	-	-	-	-	"
SA2-P5(3A)	-	-	-	-	-	-	"
SA2-P3(4A)	-	-	-	-	-	-	"
SA4-P1(2A)	-	-	-	-	-	-	"
SA4-P3(3A)	-	-	-	-	-	-	"
SA1-P1(2A)	-	-	-	-	-	-	

(?)- Potentially dispersive and may cause piping effect

Based on correlation with many dam failure Sherard et al (1976) proposed chemical relations to determine the dispersivity of the soil. The Sodium adsorption ratio (SAR) and Exchange sodium percentage (ESP) are defined below and determined by chemical analysis of the soil samples.

- Sodium adsorption ratio (SAR)= $Na^{+}/[0.5\,(Ca^{++} + Mg^{++})]^{1/2}$
- Exchange sodium percentage (ESP)= $Na^{+}/Na^{+} + +Ca^{2+}+Mg^{2+}$ X 100%

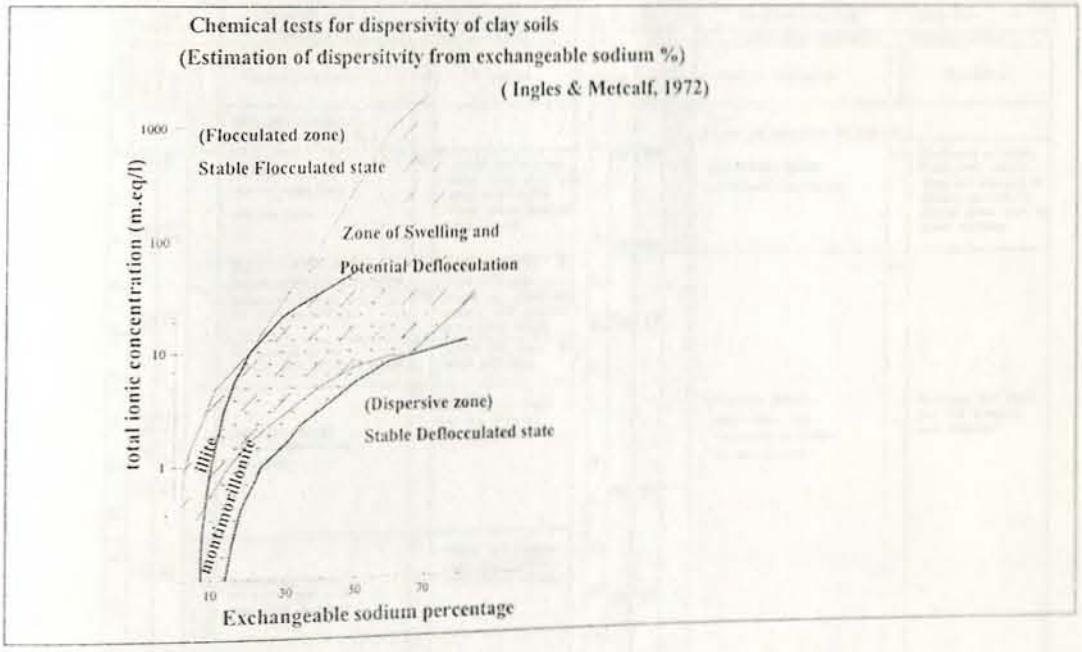
In which Na^{+}, K^{+}, Ca^{++} and Mg^{++} are measured in milliequivalents per liter 0.5 liter
Considering the SAR values in dispersivity Sherard et al gives the following table

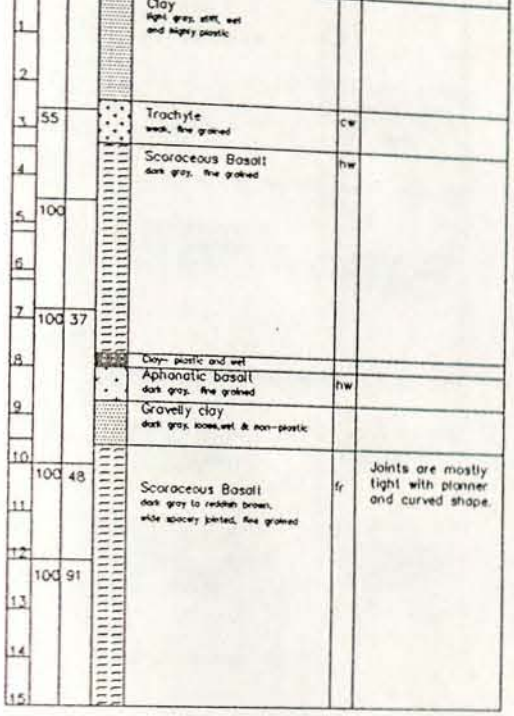
Dispersivity	SAR
<0.5	Non-dispersive
0.5-1.84	Dispersive & non-dispersive
>1.85	Dispersive

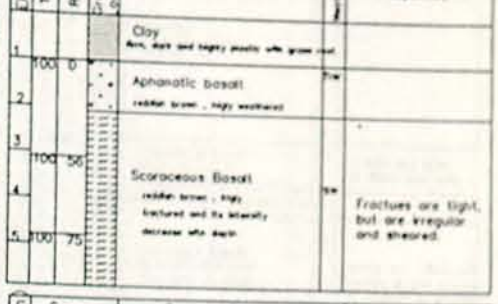
Table1. Dispersivity range in SAR values

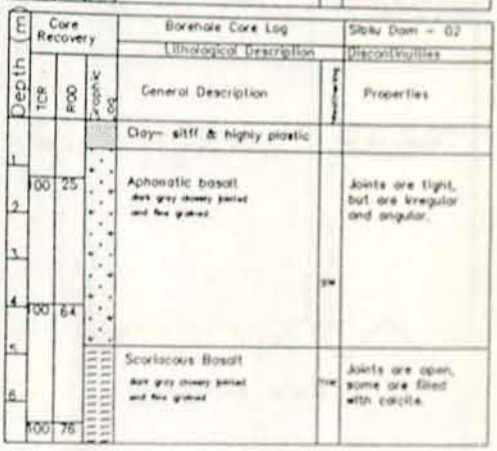
And soils with an ESP greater than about 2% are susceptible to dispersion.

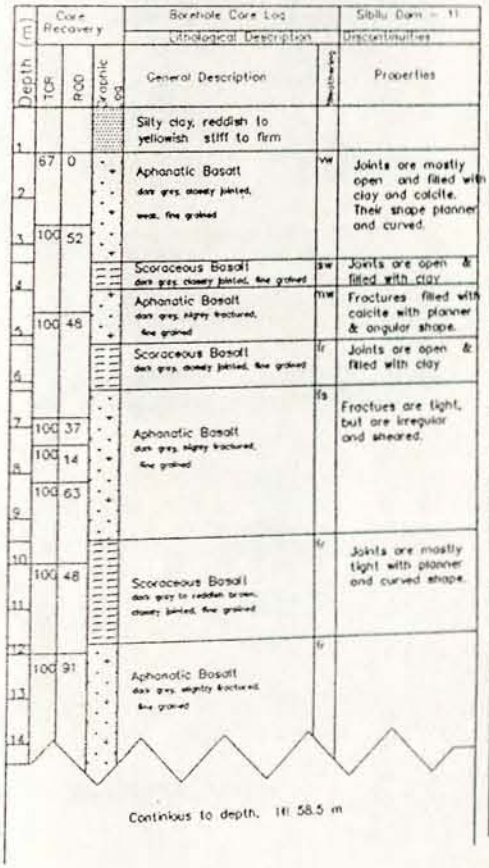
Ingles & Metcalf (1972) suggest that to assess dispersivity potential, the exchangeable sodium percentage and total concentration of the impounding water should be determined. Then for montimorillonite and illite clay, Figures 01 is used to determine whether the soil is in a flocculated, or dispersed (deflocculated) state, and whether a change in water chemistry during the filling of the reservoir can lead to dispersion.

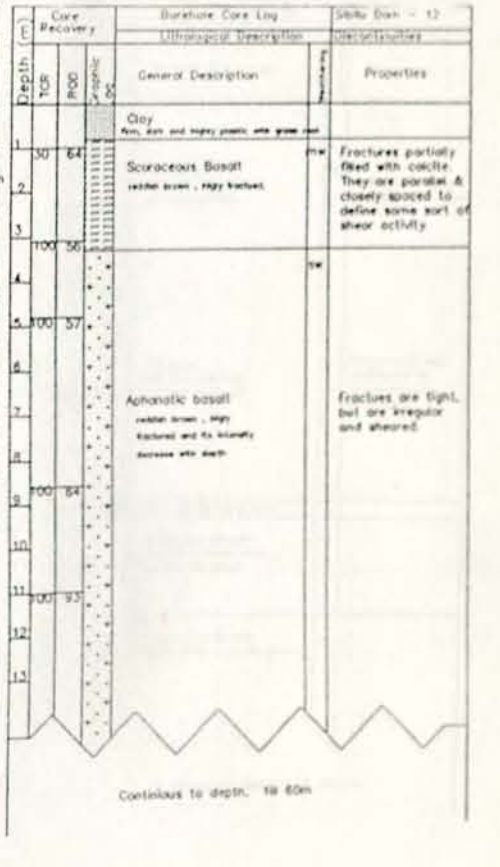


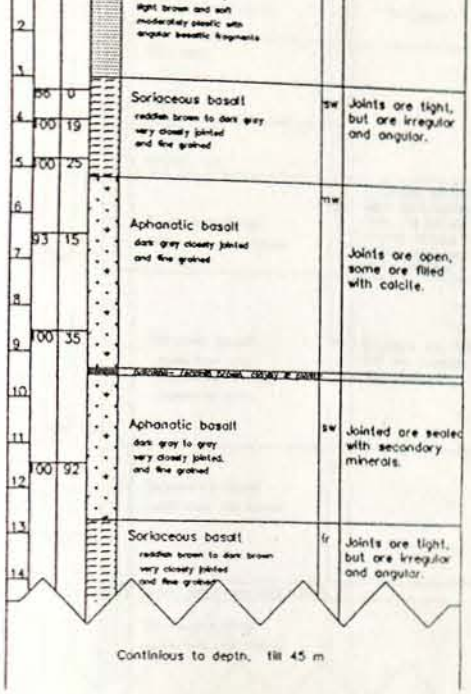

Clay
light grey, stiff, wet and highly plastic
Trachyte
weak, fine grained
cw
Scoraceous Basalt
dark grey, fine grained
hw
Clay- plastic and wet
Aphanatic basalt
dark grey, fine grained
hw
Gravelly clay
dark grey, loose, wet & non-plastic
Scoraceous Basalt
dark gray to reddish brown, wide spacery jointed, fine grained
fr
Joints are mostly tight with planner and curved shape.
55
100
100 37
100 48
100 91

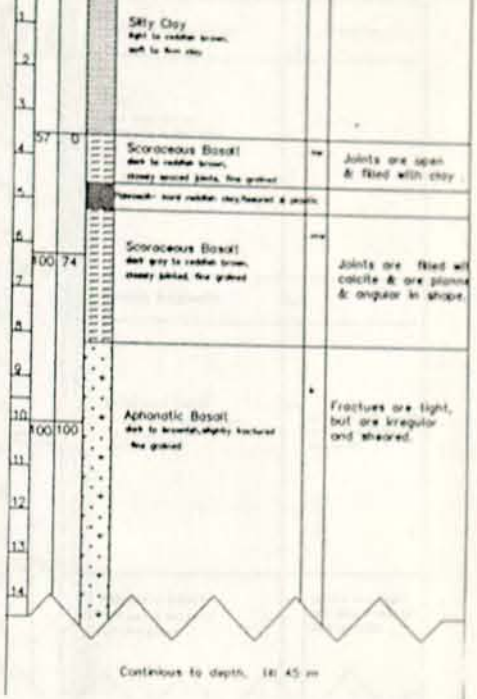

Clay
Aphanatic basalt
Scoraceous Basalt
Fractures are tight, but are irregular and sheared.
100 0
100 56
100 75

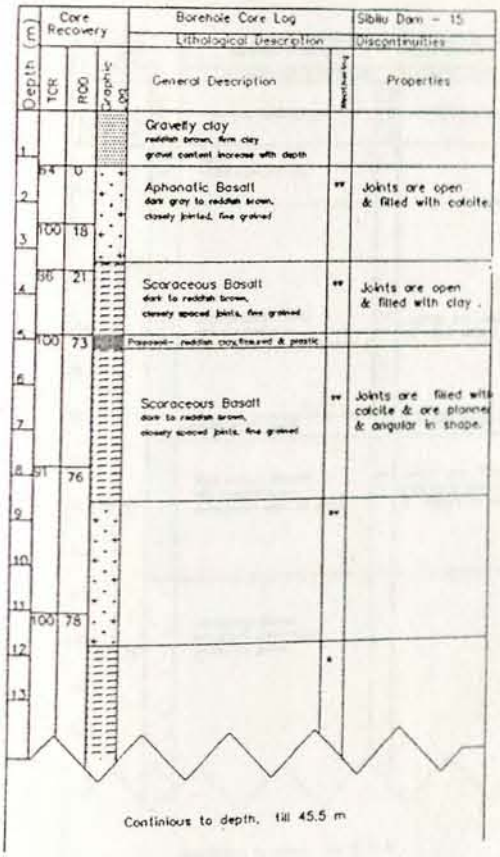

Core Recovery
Borehole Core Log
Lithological Description
Discontinuities
Sibilu Dam - 02
Depth (m)
TCR
RQD
Graphic log
General Description
Properties
Clay- stiff & highly plastic
Aphanatic basalt
dark grey closely jointed and fine grained
Joints are tight, but are irregular and angular.
Scoriacous Basalt
dark grey closely jointed and fine grained
Joints are open, some are filled with calcite.
100 25
100 64
100 76

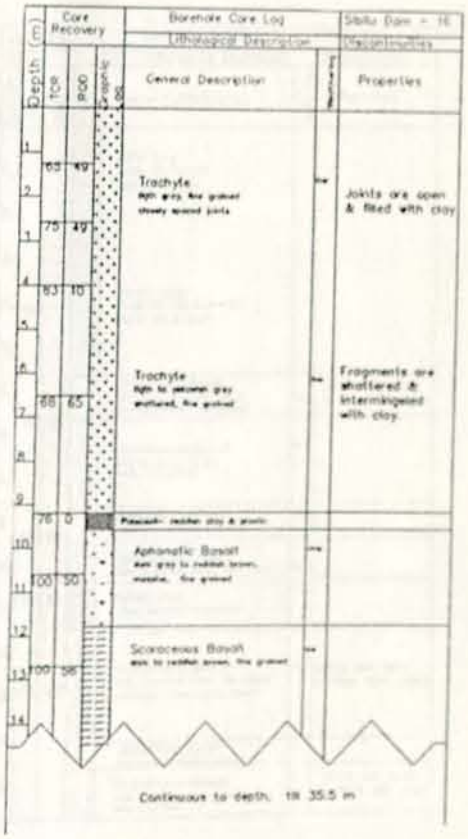

Core Recovery
Borehole Core Log
Lithological Description
Discontinuities
Sibilu Dam - 11
Depth (m)
TCR
RQD
Graphic log
General Description
Properties
Silty clay, reddish to yellowish stiff to firm
Aphanatic Basalt
dark grey, closely jointed, weak, fine grained
vw
Joints are mostly open and filled with clay and calcite. Their shape planner and curved.
Scoraceous Basalt
dark grey, closely jointed, fine grained
sw
Joints are open & filled with clay
Aphanatic Basalt
dark grey, slighty fractured, fine grained
mw
Fractures filled with calcite with planner & angular shape.
Scoraceous Basalt
dark grey, closely jointed, fine grained
fr
Joints are open & filled with clay
Aphanatic Basalt
dark grey, slighty fractured, fine grained
fs
Fractures are tight, but are irregular and sheared.
Scoraceous Basalt
dark gray to reddish brown, closely jointed, fine grained
fr
Joints are mostly tight with planner and curved shape.
Aphanatic Basalt
dark grey, slightly fractured, fine grained
fr
67 0
100 52
100 48
100 37
100 14
100 63
100 48
100 91
Continious to depth. till 58.5 m

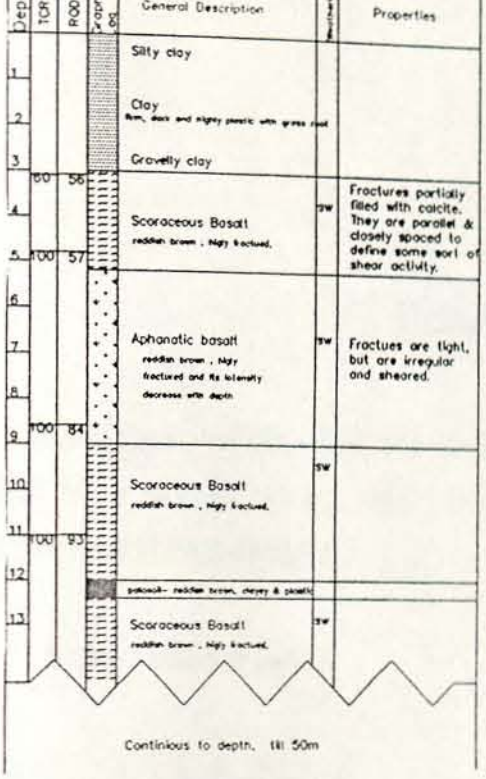

Core Recovery
Borehole Core Log
Lithological Description
Discontinuities
Sibilu Dam - 12
Depth (m)
TCR
RQD
Graphic log
General Description
Properties
Clay
Scoraceous Basalt
reddish brown, slighy fractured
mw
Fractures partially filled with calcite. They are parallel & closely spaced to define some sort of shear activity
Aphanatic basalt
reddish brown, slighy fractured and its intensity decrease with depth
sw
Fractures are tight, but are irregular and sheared.
30 64
100 56
100 57
100 84
100 93
Continious to depth. till 60m

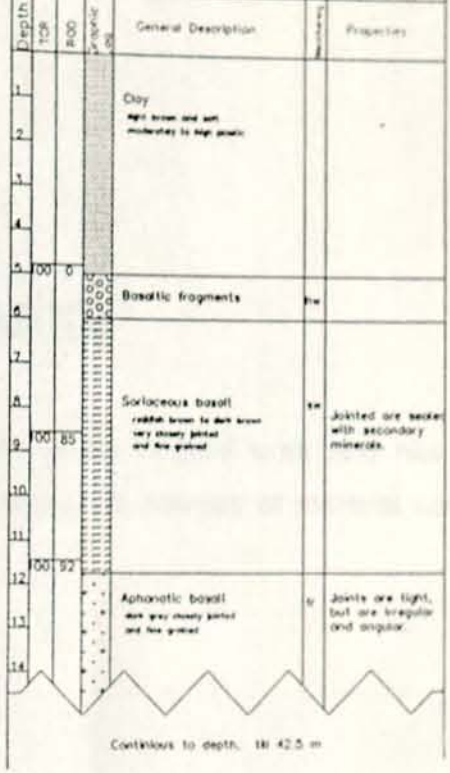

Soriaceous basalt
reddish brown to dark gray
very closely jointed
and fine grained
sw
Joints are tight, but are irregular and angular.
Aphanatic basalt
dark gray closely jointed
and fine grained
Joints are open, some are filled with calcite.
Aphanatic basalt
dark gray to gray
very closely jointed,
and fine grained
sw
Jointed are sealed with secondary minerals.
Soriaceous basalt
reddish brown to dark brown
very closely jointed
and fine grained
fr
Joints are tight, but are irregular and angular.
Continious to depth, till 45 m

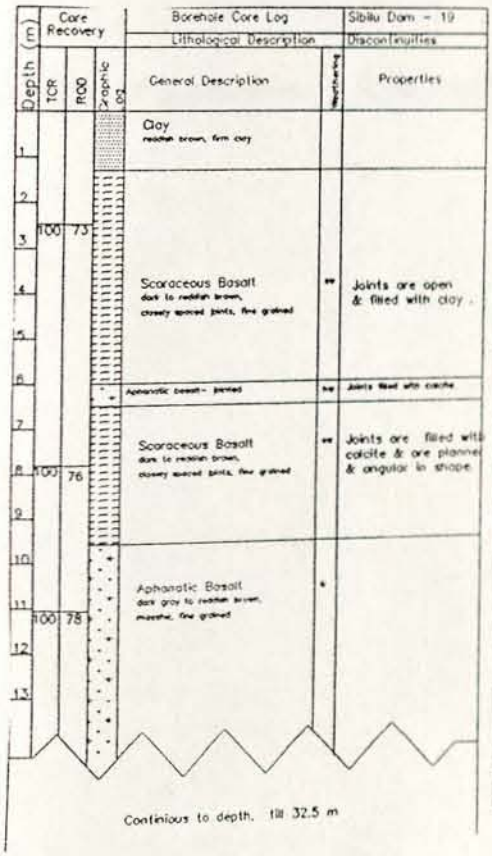

Silty Clay
Scoraceous Basalt
Joints are open & filled with clay.
Scoraceous Basalt
dark gray to reddish brown,
closely jointed, fine grained
Joints are filled with calcite & are planar & angular in shape.
Aphanatic Basalt
Fractures are tight, but are irregular and sheared.
Continious to depth, till 45 m

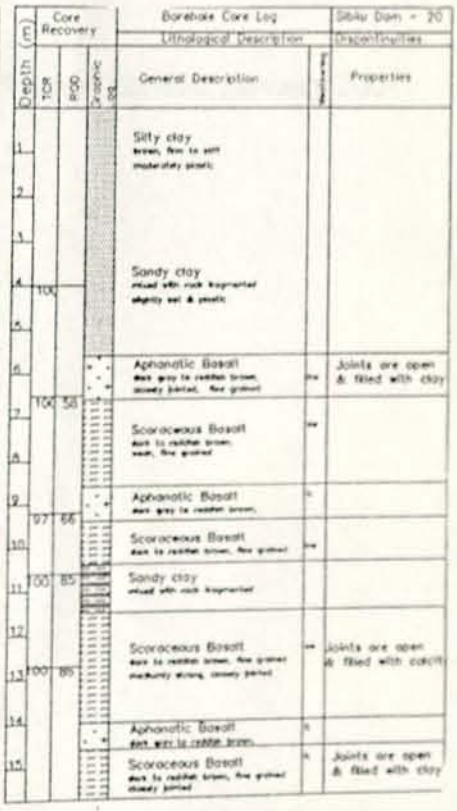

Core Recovery
Borehole Core Log
Lithological Description
Discontinuities
Depth (m)
TCR
RQD
Graphic log
General Description
Weathering
Properties
Gravelly clay
reddish brown, firm clay
gravel content increase with depth
Aphanatic Basalt
dark gray to reddish brown,
closely jointed, fine grained
Joints are open & filled with calcite.
Scoraceous Basalt
dark to reddish brown,
closely spaced joints, fine grained
Joints are open & filled with clay.
Paleosol- reddish clay, fissured & plastic
Scoraceous Basalt
dark to reddish brown,
closely spaced joints, fine grained
Joints are filled with calcite & are planar & angular in shape.
Continious to depth, till 45.5 m


Core Recovery
Borehole Core Log
Lithological Description
Discontinuities
Depth (m)
TCR
RQD
Graphic log
General Description
Weathering
Properties
Trachyte
light grey, fine grained
closely spaced joints
Joints are open & filled with clay
Trachyte
light to yellowish grey
shattered, fine grained
Fragments are shattered & intermingled with clay.
Paleosol- reddish clay & plastic
Aphanatic Basalt
dark gray to reddish brown,
massive, fine grained
Scoraceous Basalt
dark to reddish brown, fine grained
Continuous to depth, till 35.5 m


Depth
TCR
RQD
Graphic log
General Description
Weathering
Properties
Silty clay
Clay
Gravelly clay
Scoraceous Basalt
reddish brown , Hgly fractured.
Fractures partially filled with calcite. They are parallel & closely spaced to define some sort of shear activity.
Aphanatic basalt
reddish brown , Hgly fractured and its intensity decrease with depth
Fractues are tight, but are irregular and sheared.
Scoraceous Basalt
reddish brown , Hgly fractured.
Scoraceous Basalt
reddish brown , Hgly fractured.
Continious to depth, till 50m


Depth
TCR
RQD
Graphic log
General Description
Weathering
Properties
Clay
Basaltic fragments
Scoraceous basalt
reddish brown to dark brown
Jointed are sealed with secondary minerals.
Aphanatic basalt
dark gray closely jointed and fine grained
Joints are tight, but are irregular and angular.
Continious to depth, till 42.5 m


Depth (m)
Core Recovery
TCR
RQD
Graphic log
Borehole Core Log
Lithological Description
Sibilu Dam - 19
Discontinuities
General Description
Weathering
Properties
Clay
reddish brown, firm clay
Scoraceous Basalt
dark to reddish brown,
closely spaced joints, fine grained
Joints are open & filled with clay .
Aphanatic basalt- jointed
Joints filled with calcite
Scoraceous Basalt
dark to reddish brown,
closely spaced joints, fine grained
Joints are filled with calcite & are planner & angular in shape.
Aphanatic Basalt
dark gray to reddish brown,
massive, fine grained
Continious to depth, till 32.5 m


Depth (m)
Core Recovery
TCR
RQD
Graphic log
Borehole Core Log
Lithological Description
Sibilu Dam - 20
Discontinuities
General Description
Weathering
Properties
Silty clay
Sandy clay
Aphanatic Basalt
dark gray to reddish brown,
closely jointed, fine grained
Joints are open & filled with clay
Scoraceous Basalt
dark to reddish brown,
weak, fine grained
Aphanatic Basalt
dark gray to reddish brown,
Scoraceous Basalt
dark to reddish brown, fine grained
Sandy clay
mixed with rock fragmented
Scoraceous Basalt
dark to reddish brown, fine grained
medium strong, closely jointed
Joints are open & filled with calcite
Aphanatic Basalt
dark gray to reddish brown,
Scoraceous Basalt
dark to reddish brown, fine grained
closely jointed
Joints are open & filled with clay

DECLARATION

I, the undersigned, declare that this thesis is my original work and has not been presented for a degree on any other university. All sources of material used for the thesis have duly acknowledged.

Name: Trufat Hailemariam

Signature:

Place and Date of Submission: School of Gradate Studies, January 2001.