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Engineering Geological Characterization and Mapping of Aleta Wondo Town for Urban Development in Southern Ethiopia

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Abstract: Aleta Wondo town, located in the Sidama Regional State of Ethiopia, lacks comprehensive geotechnical information on its ground conditions. The soils and rocks of the area have not been comprehensively characterized, despite the presence of geotechnical and geo-environmental challenges, including settlement, landslides, and groundwater problems. Comprehensive information on the types, characteristics, and distribution of underlying soils and rocks is essential for the safe and economically feasible construction of engineering structures. The primary objective was to characterize the geological and geotechnical properties of the study area through engineering geological investigations of soil and rock and to prepare a detailed multipurpose engineering geological map. Field investigations and laboratory testing were conducted to achieve this objective. Laboratory tests included natural moisture content, Atterberg limits, grain-size distribution, free swell, and shear strength. Seven traverses were conducted across the town to document exposures along road and river cuts, quarry sites, stream channels, and slope cuts. Discontinuity characteristics were measured and recorded, and Schmidt hammer tests were conducted on exposed rock surfaces. The laboratory and field results were used to classify the soils and rocks for engineering purposes. The Unified Soil Classification System (USCS), British Standard System (BSS), Rock Mass Rating (RMR), and unconfined compressive strength were used for classification. According to the USCS, the soils are classified as CL, representing inorganic clays of low to medium plasticity, and MH, representing inorganic and elastic silts. According to the BSS, the soils are classified as compressible silt and medium-plasticity inorganic clay. Based on RMR, unconfined compressive strength, and degree of weathering, the rocks are classified as good basalt with slight weathering and very high strength, good ignimbrite with slight weathering and high strength, and poor ignimbrite with high weathering and very low strength.

Keywords: ***Engineering geological map, Rock Mass Rating (RMR), Residual soil, Ethiopia.***

Introduction

Structural failures involving buildings, roads, dams, bridges, and other infrastructure have resulted in loss of life and significant economic damage. This is partly attributed to the focus on complex structural design without adequate consideration of the geotechnical characteristics of the ground surface and subsurface (Ayalew et al., 2022). The ground beneath complex structures is naturally anisotropic and heterogeneous, making geotechnical investigations essential for assessing the engineering suitability and economic feasibility of construction sites (Berhane, 2010). These investigations consider both surface and subsurface conditions. Foundation design, construction methods, and the mitigation of geotechnical and engineering geological problems depend on understanding the engineering and geological characteristics of soil and rock (Hunde, 2014).

Geotechnical properties control the suitability of soil and rock for engineering structures. These properties include grain-size distribution, plasticity, hydraulic conductivity, consolidation, shear strength, density, and porosity. Ground suitability can be properly assessed when these geotechnical properties are evaluated together with geo-environmental conditions (Bell, 2007).

Inadequate understanding of the geotechnical characteristics of foundation materials can lead to various foundation problems, including differential settlement of subsoil and masonry, horizontal movement caused by low shear strength, shrinkage resulting from moisture loss beneath foundations, and lateral pressure that may cause structural overturning (Ayalew et al., 2022). Engineering geologists use engineering geological maps to identify problematic areas, determine suitable locations for construction, and assess potential risks associated with poor foundation conditions and geohazards (Gure et al., 2013). These maps are specifically prepared for engineering purposes and provide information on lithology, layer thickness, depth below the ground surface, groundwater-table depth, and significant geomorphological features such as karst formations, landslides, active faults, and sources of construction materials (Price, 2008). In larger towns containing heavy engineering structures such as multistory buildings and roads, detailed knowledge of the geological and geotechnical properties of foundation materials and construction materials is essential (Berhane, 2010).

Ethiopia, a rapidly developing country, is experiencing extensive urbanization and infrastructure development, while many areas are affected by seismic and geotechnical hazards. Therefore, engineering geological investigations are essential to support present and future construction activities. The information obtained from such investigations provides an important basis for land-use planning and for the planning, design, construction, and maintenance of civil engineering projects throughout the country.

In Ethiopia, several studies have investigated the engineering properties of soils and rocks in different towns to assess their suitability for engineering applications. Ayele et al. (2022) used multichannel analysis of surface waves (MASW) to estimate shear-wave velocity for the engineering characterization of soils in Hawassa town, southern Ethiopia. Birhane (2010) investigated the engineering geological characteristics of soil and rock in Mekelle town, northern Ethiopia, and identified expansive clay soils that caused physical damage to buildings. Debebe (2011) investigated the engineering characteristics of soils in Adama town and identified silt and clay soils. Chemeda (2020) conducted an engineering geological investigation of Adama town and identified expansive soils and erosion problems.

Several regional-scale studies have also been conducted in and around the study area, particularly on groundwater, hydrogeology, and Lake Hydrology. Yasin (2002) investigated the hydrogeology of the Upper Gidabo River catchment in southern Ethiopia. Mussie (2007) studied groundwater circulation and hydrochemistry along the Upper Gidabo River and Lake Awassa catchments in the Sidama Zone. Wahid (2007) assessed the suitability of ground conditions for foundation and road construction in Awassa town, southern Ethiopia. Hroch and Megerssa (2018) prepared explanatory notes for thematic geoscientific maps of Ethiopia at a scale of 1:50,000, addressing soil and rock characterization, hydrogeological conditions, exogenous and endogenous geohazards, and possible mitigation measures. Ganole (2010) conducted a GIS-based assessment of surface irrigation potential for river-catchment development in Dale Woreda, Sidama Zone.

Despite previous studies, the engineering properties of the ground in Aleta Wondo town remain inadequately investigated. Civil engineering structures, including single- and multistory buildings and roads, are being developed without sufficient geotechnical investigations. The town also lacks detailed engineering geological and geological maps, while potential geotechnical hazards have not been systematically assessed. These knowledge gaps are reflected in existing infrastructure problems, including building damage and road deterioration along the Hawassa–Yirgalem–Aleta Wondo corridor. Furthermore, substantial areas of the town are vulnerable to flooding, highlighting the urgent need for comprehensive engineering geological investigations to support safe and sustainable urban development.

Therefore, this study investigates the geo-environmental and geotechnical conditions of Aleta Wondo town and prepares multipurpose engineering geological and geological maps to support safer construction, improve design practices, and reduce the risk of infrastructure failure. The study is based on the interpretation of secondary data, collection of primary data through field investigations, and laboratory testing of engineering and index properties of soil and rock. A major limitation of the study is the lack of organized secondary data on the soils and engineering geological conditions of the study area, as many engineering projects have been undertaken without adequate site investigation, standardized data collection, and systematic record keeping.

Study area

Location and accessibility of study area

Aleta Wondo is an autonomous town located in the Sidama Regional State of Ethiopia. Its coordinates range between 43578–43798E and 71799–72500N, with a maximum elevation of 2,008 m and a minimum elevation of 1,879 m above mean sea level. The town is located approximately 337 km south of Addis Ababa and 65 km from the regional capital, Hawassa. It is accessible via the Hawassa–Yirgalem–Aleta-Wondo–Negele Borena asphalt road, as shown in Figure 1.

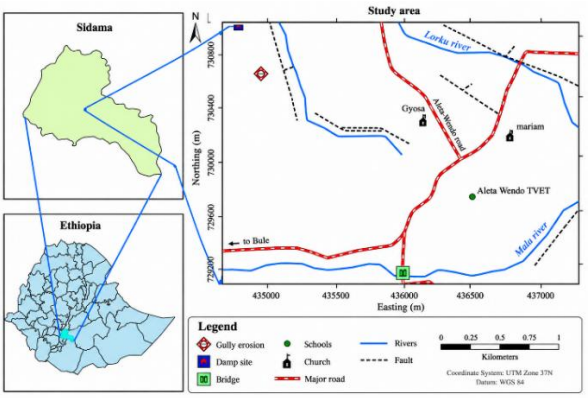


Figure 1, Location map of the study area.

Topography and slope

The topography of the town and its surroundings consists of flat to undulating terrain, deep gorges, river dissections, and steep slopes, resulting from its relatively close proximity to the Rift margin (escarpment), as shown in Figure 2. The larger part of the built-up area is characterized by an average slope ranging from 5% to 15%, while the hilly portions of the town have an average slope greater than 20%. The elevation at the center of the town, near the bus station, is approximately 1,925 m a.s.l. Generally, the elevation increases from the western part of the town toward the east.

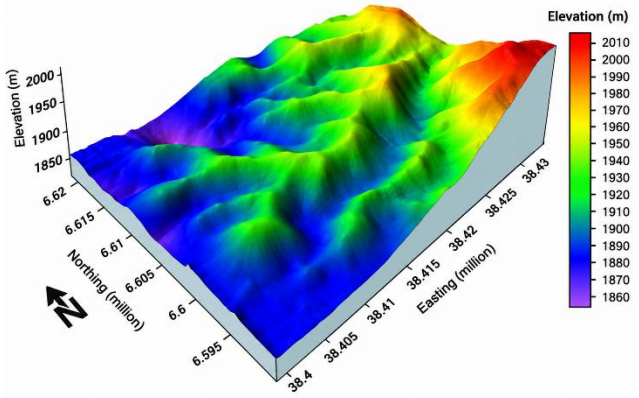


Figure 2, The Physiographic diagram of Alata Wondo Tow.

Drainage

The town is located within the Aleta Chuko watershed, a sub-basin of the Gidabo River Basin. It is bounded by two perennial rivers, the Kola River to the north and the Melebo River to the south. The Melebo River crosses the town, and both rivers ultimately drain into Lake Abaya. The rivers generally follow the major geological structures of the town, with streams flowing from southeast to northwest. The drainage network comprises first-, second-, and third-order streams, labeled 1, 2, and 3, respectively, as shown in Figure 3. The dendritic drainage pattern is strongly controlled by geological structures, indicating that the streams preferentially occupy zones of weakness.

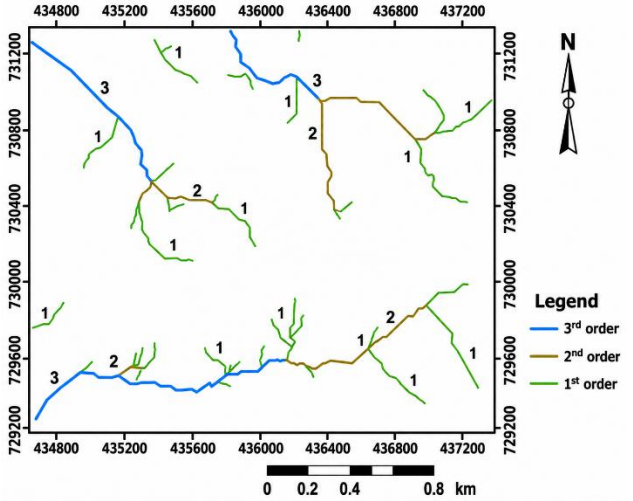


Figure 3, Drainage map of the study area (Aleta Wondo town) the town has third-order Melebo.

Climate

Aleta Wondo town falls within the Woyna-Dega agro-climatic zone, characterized by cool and sub-humid climatic conditions. The town experiences considerable annual and monthly variations in rainfall. The annual rainfall data for Aleta Wondo town over a 22-year period (1987–2008) are presented in Figure 4. During this period, annual rainfall ranged from 1,233 mm to 2,079 mm, with a mean annual rainfall of 1,564 mm.

The seasonal distribution of rainfall in the town indicates a bimodal pattern. The mean monthly rainfall of Aleta Wondo town for the period 1987–2008 is presented in Figure 5. As shown in the figure, low rainfall occurs from November to February, while high rainfall is recorded from April to October.

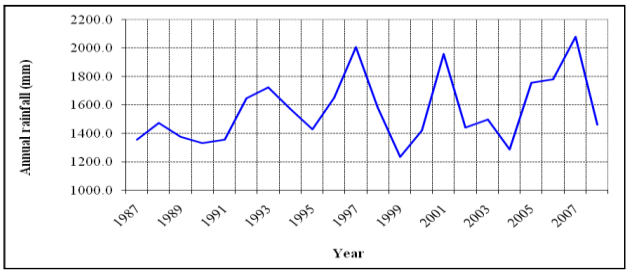


Figure 4, Annual rainfall of Aleta Wondo from 1987-2008 (Data source: Ethiopian Meteorology Agency).

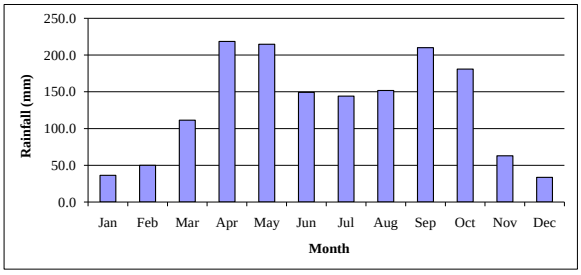


Figure 5, Mean monthly rainfall of Aleta Wondo from 1987-2008 (Data source: Ethiopian Meteorology Agency).

Theoretical concepts

To a civil engineer, soil is any uncemented or weakly cemented accumulation of mineral particles formed through the weathering of rocks, with the void spaces between the particles containing water and/or air.

Because soils and rocks are naturally anisotropic and heterogeneous, geotechnical investigations are essential for assessing the economic feasibility of engineering structures at and around a proposed site (Gure et al., 2013). Geotechnical investigations include both surface and subsurface assessments. Foundation design, construction methods, and the resolution of geotechnical and engineering geological problems begin with determining the engineering and geological characteristics of the soil and rock (Price, 2008). The main objective of geotechnical investigation of soil and rock is to prepare an engineering geological map.

Engineering geological map

Engineering geology is a sub-discipline of applied geology that bridges the professional gap between geology and civil engineering. It is an important field for identifying suitable locations for civil engineering structures (Bell, 2007). Without adequate engineering geological assessment, it may be difficult to identify areas suitable for safe construction and areas affected by poor foundation conditions, geohazards, and unacceptable risks (Gure et al., 2013). These conditions can be evaluated through the preparation of engineering geological maps.

In recent years, considerable attention has been given to the preparation of engineering geological maps. These maps are specifically designed for engineering purposes and provide information on lithology, layer thickness and depth, groundwater-table depth, significant geomorphological features such as karst, landslides and active faults, and the location of construction materials (Price, 2008). An engineering geological map is a type of geological map that provides a general representation of geological environmental conditions relevant to land-use planning, design, construction, and maintenance in civil and mining engineering. The principal factors considered in engineering geological mapping include rock and soil, groundwater, geomorphological conditions, and geodynamic processes. In this context, soil generally refers to materials that can be excavated without explosives or specialized loosening or ripping equipment (Hunde, 2014). According to the survey criteria, areas with soil thickness of less than 1 m are mapped as the underlying bedrock, while soil exceeding 1 m in thickness is considered a separate mapping unit.

The main components of an engineering geological map include the characteristics of rocks and soils, including their description, stratigraphic and structural relationships, genesis, lithology, physical condition, and physical and engineering properties; hydrogeological conditions; geomorphological conditions; and geodynamic phenomena.

Based on purpose, engineering geological maps can be classified into specific-purpose and multipurpose maps. Specific-purpose maps provide information on a particular engineering aspect or purpose, such as dam-site suitability, bearing capacity and settlement, or slope stability. Multipurpose engineering geological maps provide information on multiple aspects of engineering geology for a variety of planning and engineering purposes.

Components of engineering geological maps

Engineering geological maps should include interpretative cross-sections, explanatory text, and a legend. They may also include supporting documentation and data collected during map preparation. At all scales, engineering geological maps should present information in a manner that clearly communicates both the geological conditions and their engineering significance.

A major challenge in multipurpose engineering geological mapping is selecting geological characteristics of rocks and soils that are closely related to important engineering properties such as strength, deformability, durability, and permeability. Determining all these properties quantitatively over large areas, in sufficient detail, and within reasonable time and cost constraints is often difficult. Therefore, geological and index (geotechnical) properties that provide reliable indicators of the physical and engineering geological characteristics are commonly used.

Geotechnical characterization of soil

To assess the suitability of soil for use as a foundation material or construction material, its geotechnical properties must be characterized. Soils are characterized based on their index and engineering (design) properties (Arora, 2008). Index properties are not of primary interest to geotechnical engineers but provide indicators of the engineering properties of soil and are used for classification in engineering practice (Arora, 2008). The index and engineering properties of soil are described in following subsection.

Natural moisture content

The water content of a soil mass is defined as the ratio of the mass of water in the voids to the mass of soil solids. It is usually expressed as a percentage and can range from zero for completely dry soil to several hundred percent for highly saturated soil (Murthy, 2003). Natural moisture content influences soil behavior when used for construction and as a foundation material. It affects settlement and consolidation, shear strength, and the suitability of soil for compaction.

Grain-size analysis

Grain-size analysis determines the particle-size distribution of soil, which influences its engineering properties and is used for soil classification (Arora, 2008). The particle-size distribution curve (gradation curve) represents the distribution of particles of different sizes within a soil mass and indicates the degree of gradation, allowing the soil to be classified as well graded or poorly graded.

Consistency limit

The consistency of soil depends largely on its water content (Arnold, 2001). As the water content of fine-grained soil gradually increases from 0%, the soil passes through different consistency states: brittle solid, semi-solid, plastic, and liquid. The Atterberg limits represent the boundary water contents between these states and include the liquid limit, plastic limit, and shrinkage limit.

Specific gravity

Specific gravity is the ratio of the mass of soil solids to the mass of an equal volume of water at 4°C. It is an important index property of soil and is closely related to its mineralogy and chemical composition (Osuolale et al., 2012). It is also useful for assessing the qualitative behavior of soil (Raj, 2012) and for classifying soil minerals. For example, iron-rich minerals generally have higher specific gravity than silica (Bowles, 1996).

Free swells

The degree of soil swelling depends on clay mineralogy, soil structure and texture, and various physical and

chemical properties. Among clay minerals, montmorillonite has the greatest influence on the swelling magnitude and activity of soils compared with illite and kaolinite (Holtz and Kovacs, 1981). Expansive soils can be identified through mineralogical analysis, indirect index property tests, or direct expansion potential tests (Chen, 1988). The expansivity of soil is primarily governed by the type and proportion of clay minerals present.

Shear strength

The shear strength of soil is its ability to resist sliding along internal surfaces within a soil mass. The stability of cuts, earth dams, foundations, natural slopes, and other structures constructed on soil depends on the shearing resistance of the soil along potential failure surfaces. Cohesion (C) and angle of internal friction (ϕ) are the key parameters of shear strength (Murthy, 2003). The shear resistance of soil results from friction and particle interlocking, as well as possible cementation or bonding at particle contacts.

Permeability and consolidation

Consolidation is the time-dependent settlement of soil resulting from the expulsion of water from its pores. In clay soils, the expulsion of pore water may take considerable time because of their low permeability (Arnold, 2001).

Soil compaction

Soil compaction is a ground improvement technique in which compactive energy is applied to rearrange soil particles into a denser configuration. Compaction increases the shear strength of soil and reduces its compressibility and permeability (Kaniraj, 1988). Compaction is not an index property of soil; rather, it is the densification of soil through the expulsion of air.

Engineering geological classification of soil

From an engineering perspective, soil classification is based on the suitability of soil for use as a foundation or construction material (Arora, 2008). Determining engineering properties in the laboratory can be expensive and time-consuming; therefore, soil classification provides an efficient approach by grouping soils with similar index properties within specified ranges of variation. Soils within these ranges generally exhibit similar engineering qualities for civil engineering applications. A soil classification system should provide an indication of the engineering performance of a soil type and allow rapid identification of soil characteristics (Matula, 1981). Several classification systems are available, each developed for specific applications. For example, the American Association of State Highway and Transportation Officials (AASHTO, 2014) system classifies soils according to their suitability for roads and highways, whereas the Unified Soil Classification System (USCS) and British Standard System were originally developed for airfield construction and later adapted for general engineering applications (Ayalew et al., 2022).

Engineering geological classification and characterization of rock

Rocks exhibit different engineering properties depending on their mode of origin, mineralogical composition, texture, structure, and the presence of primary and secondary structures. Therefore, a qualitative assessment of their engineering properties can often be made based on their genetic type. Rock mass classification provides a quantitative assessment of rock mass quality. Several classification systems are available, among which Rock Quality Designation (RQD) and Rock Mass Rating (RMR) are widely used for engineering characterization.

Geologic setup of the study area

Regional geology

Aleta Wondo town is situated in the southern segment of the Main Ethiopian Rift Valley and represents a transition zone between the Ethiopian Plateau and the Rift Valley, with a poorly defined escarpment. The evolution of the southern segment of the Main Ethiopian Rift has been divided into three stages based on age (Yismaw et al., 2012): pre-rift (32–45 Ma), syn-rift (22–12 Ma), and post-rift (0–5 Ma).

Syn-rift volcanic deposits

Syn-rift volcanic deposits include the Nazareth Formation of Miocene age, consisting of transitional to mildly alkaline and subalkaline basalts and rhyolites, aphyric and porphyritic basalts with lesser vesicular basalt, and minor alkali trachyte flows and tuffs. These deposits cover the areas around Dilla, Wenago, Chinchu, Bedesa, Teferikela, Aleta Wondo, and Kebado. The transitional to mildly alkaline and subalkaline basalt is highly weathered, forms cliffs, and exhibits fractures and joints. It is composed mainly of olivine, pyroxene, and plagioclase and is overlain by rhyolite (Yismaw et al., 2012).

Post-rift volcanic deposits

Post-rift volcanic deposits include pumiceous pyroclastics, ignimbrites, tuffs, water-laid pyroclastics, lacustrine deposits, volcaniclastic sediments, and diatomites. These deposits are exposed in the northern part of the mapped area, covering areas around Midre Genet, Morocho, Yirga Alem, Hawassa, and Chuko.

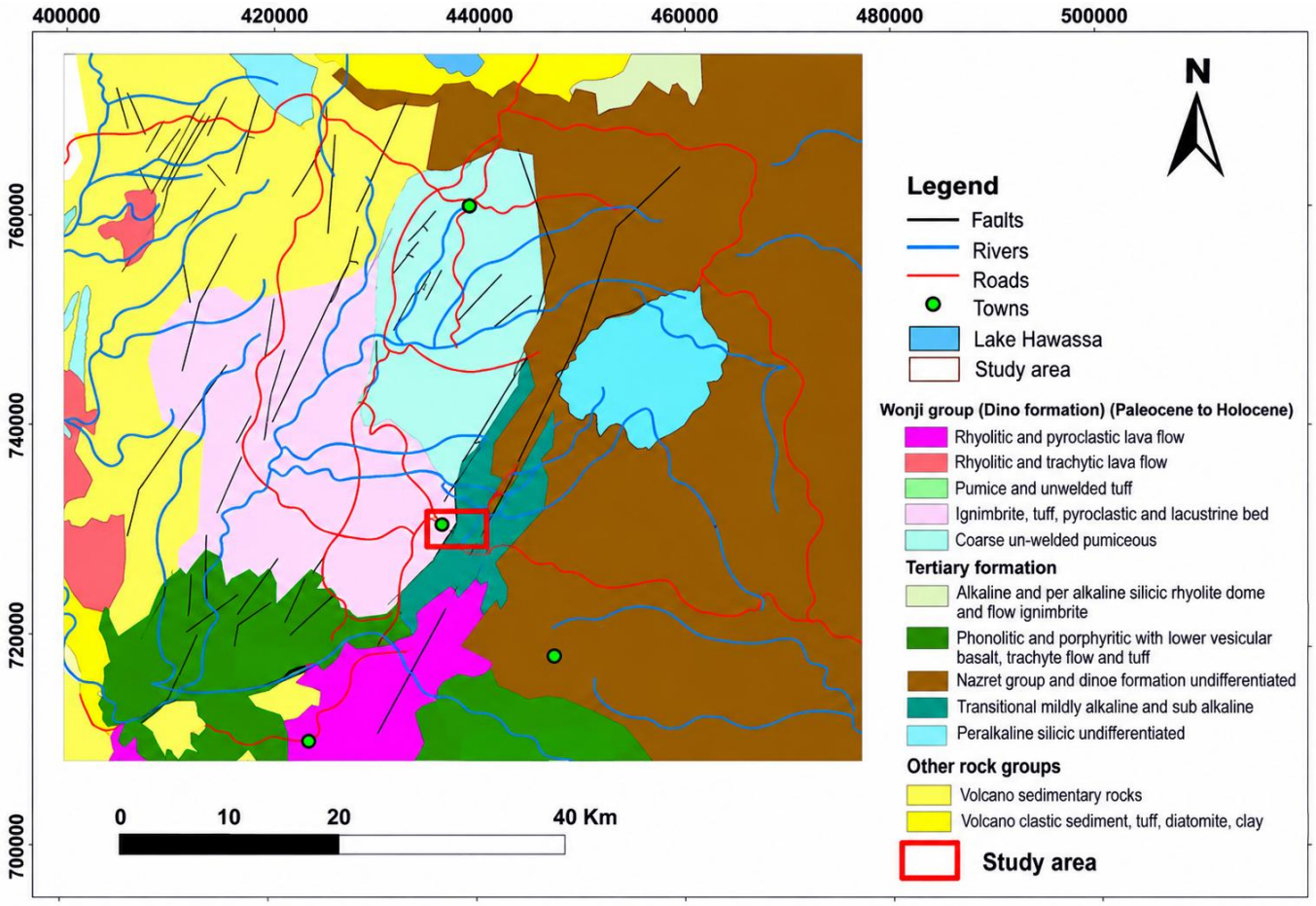


Figure 6, Regional Geologic Map showing location of study area.

Local geology

The geology of the Aleta Wondo area is represented by two volcanic units. The lower unit consists of basaltic lava flows (basalt), which crop out along the river in the eastern to southeastern parts of the town and represent the oldest unit in the area (Figure 11). It consists mainly of sub-horizontal lava flows with thicknesses ranging from a few meters to 20 m. The maximum exposed thickness occurs east of the town along the river. The ignimbrite unit is exposed near Aleta Wondo along the rivers. It overlies the Aleta Wondo basalt and locally covers the products of the composite central volcanoes of Wechecha and Furi. The sequence consists of different flow units, including pale-green to pale-yellow welded and crystal-rich ignimbrites (Figure 7).

Aleta Wondo town is predominantly underlain by thick residual soil. In the southern part of the town, particularly along the slope cuts of the Kibre Mangist Road, thick residual clayey to silty soil deposits ranging in color from white to brown and reddish hues are exposed (Figure 8). The average thickness of the residual soil within the town is approximately 12 m.



Figure 7, Ignimbrite unit deposit along with river "A" and at quarry site "B".

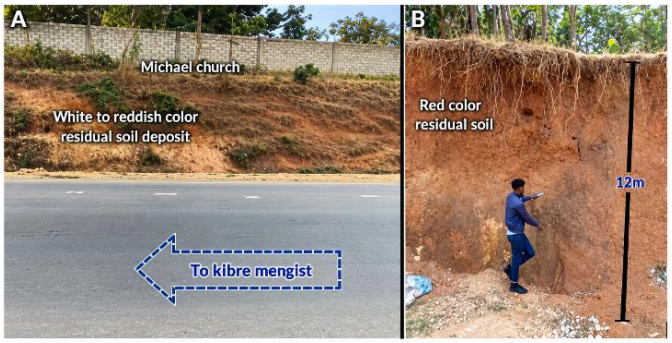


Figure 8, Residual soil deposits.

Geological structures and tectonics

In an engineering context, discontinuities are important factors governing the deformability, strength, and permeability of rock masses. Large and persistent discontinuities can significantly affect the stability of surface and underground excavations. Therefore, understanding the geometric, mechanical, and hydrological properties of discontinuities is essential for rock mechanics and engineering.

The town is located in the southern segment of the Main Ethiopian Rift (MER) system. As shown by the rose net model (Figure 10), the regional fault system and local faults and joints predominantly strike NNW–SSE. However, the southern segment of the MER trends NNE–SSW, indicating that the structural trend of the MER has had limited influence on the structures in the study area. Thus, the strike directions of the MER system and the major fault system in the study area are not similar. The faults in the study area predominantly dip toward the NE and SSW. In the northern part of the town, particularly along stream cuts (Figure 9), minor, persistent joints and two sets of joints dissecting the ignimbrite rock are observed.



Figure 9, Minor local fault and Joints on ignimbrite along to Hawassa route.

Methodology

Climatic, topographic, geomorphological, hydrogeological, geological, and engineering geological data are essential for achieving the objectives of the present study. Based on these data, different methodological stages were designed and implemented in accordance with the intended objectives (Figure 13).

Primary and secondary data obtained from field investigations, previous studies, and laboratory activities were used in this study. The study considers the future expansion of the town boundary as outlined in the current master plan.

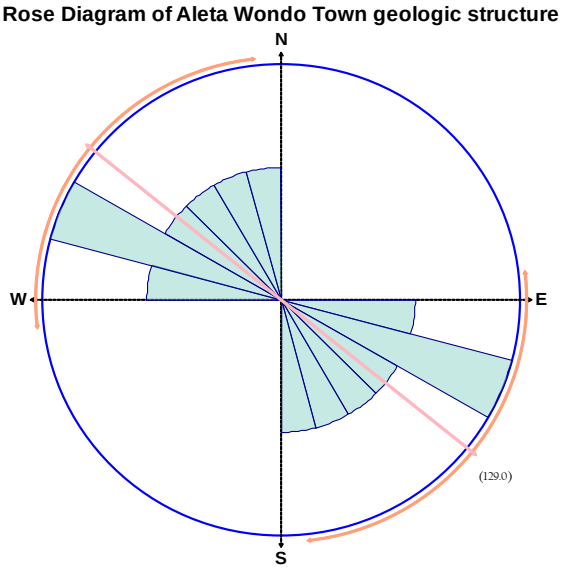


Figure 10, Rose diagram.

Fieldwork included detailed descriptions and observations of exposures along road and river cuts, quarry sites, stream channels, and slope cuts to identify the engineering geological characteristics of the rock. Measurement and recording of discontinuity characteristics were also conducted. Sampling locations and the number of samples were determined based on the geological variations of the soil and bedrock (Figure 12).

Ten test pits were excavated to a maximum depth of 4 m using shovels and other appropriate hand tools. During sampling, vertical variations in the soil profile were carefully observed and recorded. The number of test pits and samples was considered sufficient to characterize the subsurface soil conditions of the study area.

To determine the uniaxial compressive strength (UCS) of the rocks, in-situ tests were conducted on exposed rock surfaces using an N-type Schmidt hammer. The tests were performed on smooth and relatively uniform rock surfaces (Wang et al., 2017). Prior to testing, the rock surfaces were smoothed using the rubbing stone provided with the Schmidt hammer. Rebound values were recorded at each selected test location and converted to unconfined compressive strength (Wang et al., 2017) using the linear relationship presented in Eq. (1).

$$UCS=3.03RN-30.3 \quad (1)$$

The Rock Quality Designation (RQD) was determined using the volumetric joint-count method on exposed rock surfaces. This method estimates RQD based on the number of discontinuities within a defined rock mass volume. The RQD was calculated using the relationship proposed by Deere and Deere (1988).

$$RQD = 115 - 3.3Jv \quad (2)$$

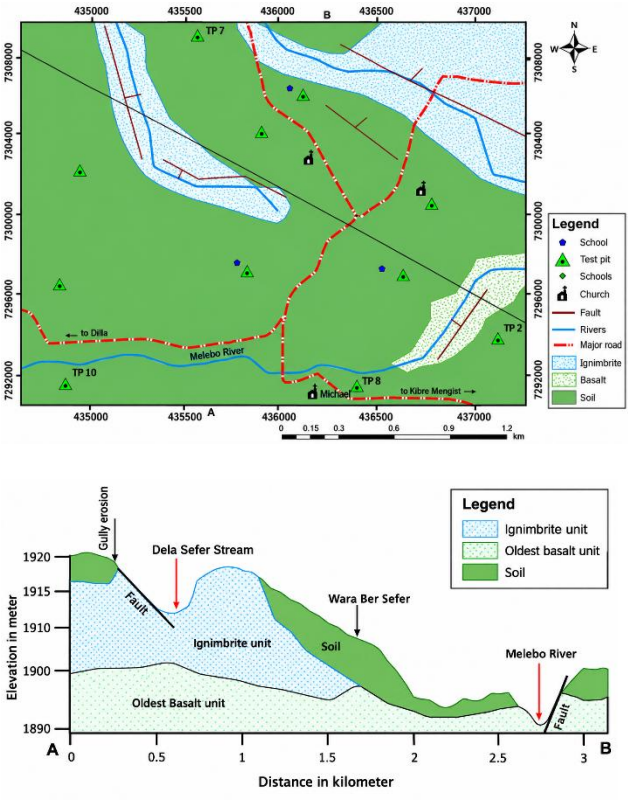


Figure 11, Geologic map and geologic cross section of the study area.

where (Jv) represents the volumetric joint count, defined as the total number of joints per unit length for all joint sets having discontinuity lengths of ≥10 cm. In addition, the condition of the discontinuities and the general groundwater conditions of the exposed rock masses were assessed in the field to evaluate the overall quality of the rock mass.

Finally, the Rock Mass Rating (RMR) was determined using the relevant discontinuity characteristics and RQD as input parameters. The combined assessment of UCS, RQD, discontinuity conditions, groundwater conditions, and RMR provided a basis for evaluating the engineering characteristics and quality of the rock masses in the study area.

Laboratory work included testing the index and engineering properties of soil samples, including natural moisture content (NMC), specific gravity, Atterberg limits (liquid limit and plastic limit), grain-size analysis, pH value, free swell, and shear strength. Laboratory tests were conducted according to ASTM (2018) and AASHTO (2014) standards. The soils of the study area were classified based on their engineering behavior according to the Unified Soil Classification System (USCS) and British Standard System (BSS).

Analysis and interpretation of in-situ and laboratory data were conducted to convert the raw soil and rock data into meaningful information about the study area. Data processing and interpretation were carried out using various software tools, including Microsoft Office for calculation, sorting, and tabulation of raw data; Rose Net projection for geological structural analysis; ArcMap 10.4 and Golden Surfer 9.11 for the preparation and manipulation of maps; and Google Earth Pro for collecting geospatial data.

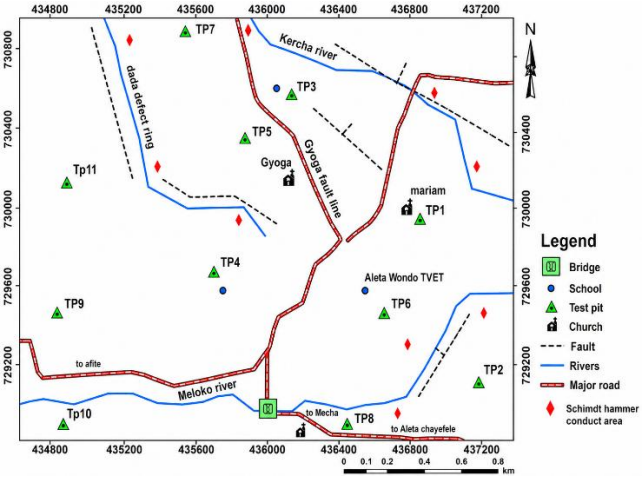


Figure 12, Test-pit and Schmidt hammer test locations.

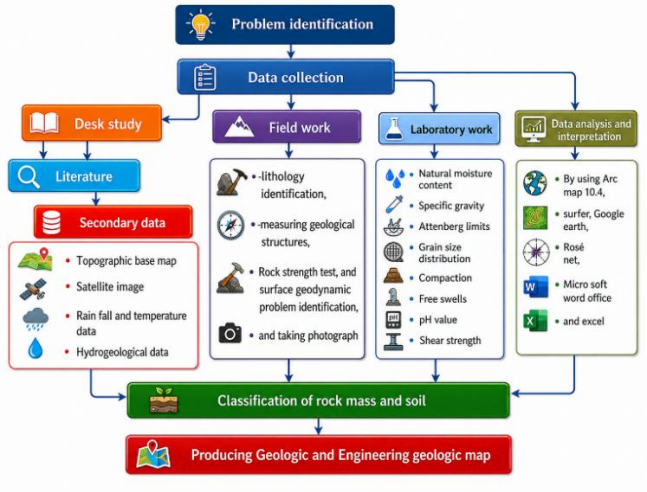


Figure 13, Flow chart of this study.

Results and discussion

Engineering geological characterization and classification of soils

Genetically, the study area is dominated by residual soils formed through in-situ weathering of the parent rock. Characterization of the geotechnical and engineering geological properties of the soils was initiated by describing their genetic, lithological, and textural characteristics, followed by analysis and discussion of the geotechnical laboratory results from the study area.

Index properties

Natural moisture content

For many soils, water content is an important index for establishing the relationship between soil behavior and its properties. The natural moisture content of the soils in the study area ranges from 23.2–48% for silty soil, 39% for clayey silt, and 28.8% for sandy silt. These

results indicate that the soils of the study area generally have medium water-holding capacity, with fine-grained fractions being dominant.

Table 1, Summarized index property test results of study area.

S. No.	Depth (m)	NMC	SG	PD (%)			LL	PL	Soil type		Lithology
				%Sa	%Si	%C			USCS	BSS	
1	10	3	39	2.60	18.7	41.3	40	38.93	CL	CM	Clay
2	7	3	28.8	2.51	47	33.26	13	50.7	SM	SM	Sand
3	1	1.5	31.64	2.47	7.4	61.95	30.65	71.76	MH	MH	Silt
4	1	3	—	2.40	7.61	63.69	28.43	59	MH	MH	Silt
5	2	3	34.9	2.50	10.5	54	36	57	MH	MH	Silt
6	3	3	31.7	2.54	15.65	56.55	27.24	60.8	MH	MH	Silt
7	4	3	27.4	2.52	10	58.8	32	66.7	MH	MH	Silt
8	5	3	23.2	2.48	8.7	63.65	27.64	69.5	MH	MH	Silt
9	6	1.5	30.7	2.55	8.93	73.9	18	62.3	MH	MH	Silt
10	6	3	—	2.50	8.34	70	15	48.3	MH	MH	Silt
11	2	2	48	2.60	22	49.5	28	42.0	CL	MH	Silt
12	8	4	—	2.56	20	42.95	37	58.4	MH	MH	Silt
13	9	3	35	2.52	10.2	64.59	25.21	62.4	MH	MH	Silt

The degree of consolidation of the soil can be estimated by comparing the natural water content (w) with the liquid limit (LL) and plastic limit (PL). If the water content is closer to the liquid limit than to the plastic limit, the soil is likely to be normally consolidated. Conversely, if the water content is closer to the plastic limit than to the liquid limit, the soil is likely to be pre-consolidated (Munsell, 2000). Based on the particle-size analysis, water content, and Atterberg limits, the silt- and sand-dominated soils in most parts of the town have water contents closer to the plastic limit, indicating that they are likely pre-consolidated. However, the southwestern and some parts of the southeastern areas of the town (Figure 14) are dominated by clayey soil, where the natural moisture content is closer to the liquid limit.

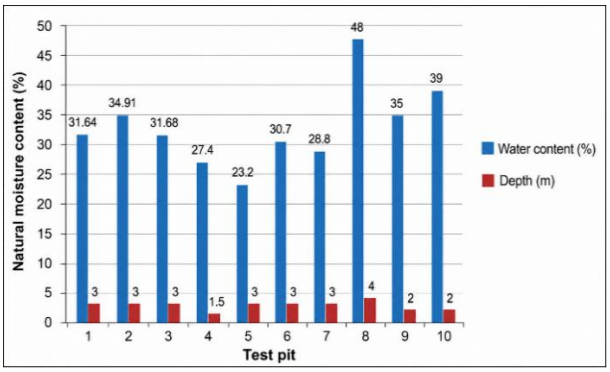


Figure 14, Graph of natural moisture content of soils in the study area.

Specific Gravity (Gs)

The specific gravity of soil is the ratio of the unit weight of soil solids to the unit weight of water. In the laboratory, the specific gravity of soil was determined by placing a known weight of oven-dried soil sample in a pycnometer, which was then partially filled with distilled water. The specific gravity of solids for most natural soils generally ranges from 2.65 to 2.80, with lower values typically observed in coarse-grained soils. Specific gravity is used to determine the void ratio and particle-size characteristics of soils.

The specific gravity laboratory determination followed ASTM D854-23 (ASTM, 2023).

$$Gs = \frac{Unit\ weight\ of\ solid\ soil}{Unit\ weight\ of\ water} \qquad (3)$$

In study area-specific gravity range from 2.47-2.6 for silty soils and 2.61 and 2.55 for clayey and sandy respectively.

Grain size analysis

To determine the index properties of the soils in the study area, thirteen soil samples were collected from ten test pits, as presented in Table 1. Based on grain-size distribution, the soils in the study area were classified into sandy, silty, and clayey types. The sandy soil contains approximately 47% sand, 37.5% silt, and 13% clay. The silty soils contain 37.5%–73.9% silt, 8.7%–15.65% sand, and 18%–30.65% clay. The clayey soil contains approximately 50% clay, 31.6% silt, and 18.4% sand. Overall, the grain-size analysis indicates that the study area is predominantly underlain by silty soils, as illustrated in Figure 15.

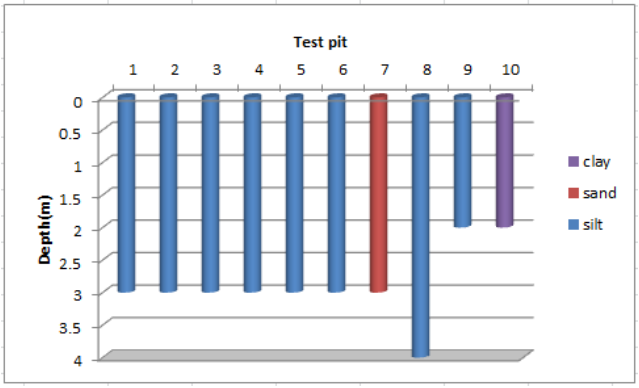


Figure 15, lithological description of grain size distribution.

Atterberg limits and plasticity index

According to Bowles (1996), soils with higher plasticity indices may present greater engineering problems when used as engineering materials, particularly for foundation support and road subgrades. As shown in Table 1, laboratory test results indicate that the clayey soils have liquid limit (LL) and plastic limit (PL) values of 38.93% and 15.8%, respectively. The silty soils have LL values ranging from 57%–71% and PL values from 41%–48.6%, while the sandy soils have LL values ranging from 39.9%–50.7%. The plasticity indices (PI) of the clayey and sandy soils are 23.23% and 10%, respectively, while the PI of the silty soils ranges from 10%–23%.

Soils with higher plasticity indices generally have lower engineering suitability. Soils with PI >35% are classified as very highly plastic, while those with 20% ≤ PI ≤ 35% and 10% ≤ PI < 20% are classified as highly and moderately plastic, respectively. Soils with PI ≤10% are classified as low-plasticity soils (Seed et al., 1962). In the study area, sandy soils have low plasticity, whereas silty and clayey soils have medium to high plasticity. Therefore, special consideration is required during construction, particularly in the southwestern parts of the town, where compressible clay and silt with high plasticity and shallow groundwater conditions are

present. Based on the Casagrande plasticity chart (Figure 16), the soil samples from the study area range from low to high plasticity.

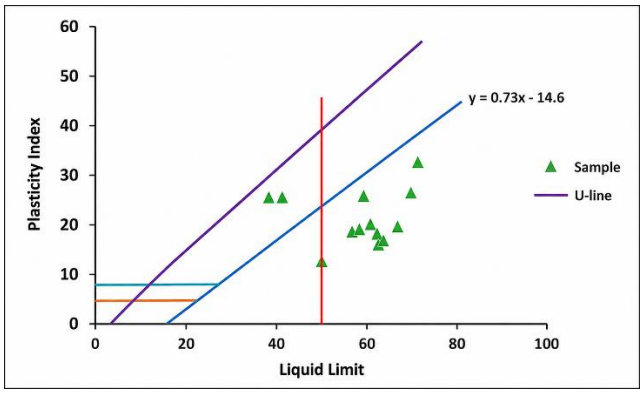


Figure 16, Plots of soils of the study area on Casagrande plasticity chart.

Activity of soils

Activity of soil is as the ratio of the plasticity index and the percentage of clay fraction, i.e. finer than 2μ (Clayton, 1995.)

$$Ac=\frac{PI}{\%\ of\ caly\ fraction} \qquad (4)$$

Eq. 3 illustrates activity and it is a measure of the water-holding capacity of clay soils. The change in volume of clay soil during swelling or shrinkage depends on its activity, which is related to the percentage by weight of soil particles smaller than 2 μm. Based on Table 1, soils with an activity of 0.75 < A < 1.25 are classified as normal clays, A < 0.75 as inactive clays, and A > 1.25 as active clays. Activity is useful for classifying and evaluating the engineering properties of soils, particularly active and inactive clays. It also shows a fair to good correlation with the type of clay mineral.

Laboratory test results indicate that activity, swelling potential, and plasticity index are generally directly related, whereas the percentage of clay fraction does not necessarily have a direct relationship with activity. The swelling potential and activity of clayey soils are strongly influenced by clay mineralogy rather than solely by the percentage of clay fraction. The laboratory data show that the plasticity index has a stronger relationship with soil activity than with the percentage of clay fraction, owing to the influence of clay mineralogy and chemical behavior. Soils containing active minerals such as montmorillonite and smectite generally exhibit higher plasticity and activity, regardless of the clay fraction. In contrast, clay fractions dominated by quartz do not exhibit significant water-absorption behavior because quartz is an inactive mineral. Montmorillonite has an expandable lattice and exhibits a high degree of hydration and cation adsorption. The degree of lattice expansion depends on the nature of the adsorbed cations. Illite is another common clay mineral and exhibits limited expansion due to strong bonding between silica sheets by potassium ions (Holtz and Gibbs, 1956). Therefore, soils with a low clay fraction may have high swelling potential if they contain montmorillonite-group minerals, and vice versa.

Generally, the influence of clay content on soil activity is significant when active clay minerals are present; otherwise, variations in clay fraction may have little effect on activity when the soil is dominated by inactive minerals such as kaolinite. Clay fractions containing kaolinite generally have low activity, whereas those containing montmorillonite have high activity (Rich, 1968). As observed in Table 2 and the activity–soil category plot (Figure 17), the soils of Aleta Wondo town are predominantly classified as inactive to normal. Soil activity in the study area was determined using the plasticity index and grain-size analysis results based on Skempton's classification of soil activity.

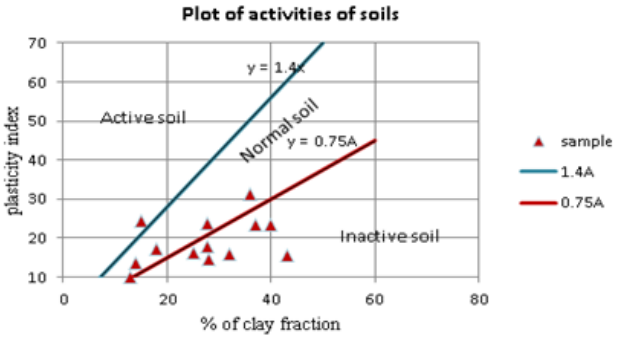


Figure 17, Skempton's chart showing the activity of soils in the study area.

Table 2, Activity of study area soils.

S. No.	Depth (m)	Dominant	PL	LL	PI	Activity	Remark
1	1-2	Clay	15.8	38.93	23.3	0.612	Active
2	1-3	Sand	39.9	50.7	10	0.76	Normal
3	1.5	Silt	41.6	71	31.16	1.016639	Normal
4	3	Silt	35.2	59	23.8	0.837144	Normal
5	1-3	Silt	41	57	16	0.444444	Inactive
6	1-2	Silt	43	60.8	17.8	0.653451	Inactive
7	1-2	Silt	49.5	66.7	17.2	0.5375	Inactive
8	1-3	Silt	45	69.5	24.5	0.886397	Normal
9	1.5	Silt	48.6	62.3	13.7	0.761111	Normal
10	3	Silt	48.3	63	14.7	0.98	Normal
11	2	Silt	19	42	23	0.812143	Normal
12	4	Silt	42.2	58.4	16.2	0.437838	Inactive
13	1-3	Silt	47	62.4	15.4	0.610869	Inactive

Liquidity index (LI), plasticity index and consistency index (CI)

The liquidity index of a soil indicates the proximity of its water content to the liquid limit. At the liquid limit, the liquidity index is 100%, and the soil behaves as a liquid, whereas at the plastic limit, it is zero. Negative liquidity index values indicate a water content below the plastic limit (Arora, 2008). These indices are determined from the natural moisture content, liquid limit, and plastic limit using mathematical formulae (Eq. 5).

$$LI = \frac{w-PL}{PI} \qquad (5)$$

The liquidity index of soils in Aleta Wondo town, determined from ten test pits, ranges from −1.26 to 1.285. As presented in Table 3, most soil samples have

negative liquidity index values, except TP10 and TP8, which have liquidity index values of 1.003 and 1.26, respectively. Similarly, the consistency index of the soils in the study area is presented in Table 4. The consistency index indicates the firmness of soil and its proximity to the plastic limit. Soil with water content equal to the plastic limit has a consistency index of 100%, indicating relatively firm soil.

The consistency index values in the study area range from −0.003 to 1.779. Most soils in the study area are firm, except those at TP10 and TP8. Overall, the liquidity and consistency index results indicate that the majority of the soils in the study area are hard to stiff and firm in consistency.

Table 3, The liquidity, plasticity and consistency index of Aleta Wondo Town.

TP	Depth (m)	Dominant	PL	LL	PI	CI	LI
10	1-2	Clay	15.8	38.93	23.3	-0.003	1.003
7	1-3	Sand	39.9	50.7	10	2.028	-1.028
1	1.5	Silt	41.6	71	31.16	1.339	-0.339
	3		35.2	59	23.8	1.109	-0.109
2	1-3		41	57	16	1.381	-0.381
3	1-2		43	60.8	17.8	1.636	-0.636
4	1-2		49.5	66.7	17.2	2.285	-1.285
5	1-3		45	69.5	24.5	1.890	-0.890
6	1.5		48.6	62.3	13.7	2.307	-1.307
	3		48.3	63	14.7	2.109	-1.109
8	2		19	42	23	-0.26	1.26
	4		42.2	58.4	16.2	0.747	0.253
9	1-3		47	62.4	15.4	1.779	-0.779

Free swell

The free swell test is one of the simplest and essential index tests for fine-grained soils, as it indicates the presence of swelling clay minerals based on soil mineralogy. The swelling potential of soil is related to its activity, which is associated with the plasticity index. Free swelling or expansion of clayey soils can cause failure of engineering structures (Holtz and Gibbs, 1956).

Soils having a free swell value below 50% rarely exhibit extensive volume changes, even under very light loadings (Prakash et al., 2004). However, soils with free swell values of about 100% or higher may cause considerable damage to lightly loaded structures.

The free swell values in the study area range from 15.9% to 60% for silty soils, and from 19.5% to 54% for sandy and clayey soils, respectively (Table 4).

According to the IS soil classification system based on the free swell index, Aleta Wondo is characterized by a low to medium degree of expansion. Therefore, samples with free swell values greater than 50% require consideration during the design of civil structures founded on such soils, as they exhibit significant swelling potential. In particular, TP1, TP10, and TP5 require special consideration.

Table 4, Free swell chart of study area.

TP	Depth (m)	Dominant	PL	LL	PI	FS
10	1-2	Clay	15.8	38.93	23.3	47
7	1-3	Sand	39.9	50.7	10	34.5
1	1.5	Silt	41.6	71	31.16	60
	3		35.2	59	23.8	
2	1-3		41	57	16	13.9
3	1-2		43	60.8	17.8	18
4	1-2		49.5	66.7	17.2	27.5
5	1-3		45	69.5	24.5	50
6	1.5		48.6	62.3	13.7	21.7
	3		48.3	63	14.7	
8	2		42	65.3	23.3	15.9
	4		42.2	58.4	16.2	
9	1-3		47	62.4	15.4	18.2

PH (power of hydrogen)

Soil pH is a measure of its acidity or alkalinity, expressed numerically on a scale of 0–14. The geotechnical properties of soil can be significantly affected by changes in pH; therefore, determining soil aggressiveness is essential for assessing its potential effects on engineering structures. Dissolution reactions are more pronounced under highly acidic and alkaline pH conditions, which can deteriorate or corrode concrete in engineering structures (Yadeta, 2020).

The consistency limits generally decrease with changes in pH. Changes in pH can also induce cation exchange, weakening the electrostatic attraction between soil particles and consequently reducing the strength of lateritic soil (Osuolale et al., 2012). In the study area, the pH values range from 7.11 to 7.31 (Table 5), indicating slightly alkaline conditions. Therefore, the soil is not expected to pose significant adverse effects that could lead to the failure of civil engineering structures.

Table 5, pH value of study area.

TP	Depth (m)	Dominant	PL	LL	PI	FS
10	1-2	Clay	15.8	38.93	23.3	47
7	1-3	Sand	39.9	50.7	10	34.5
1	1-5	Silt	41.6	71	31.16	60
	3		35.2	59	23.8	
2	1-3		41	57	16	13.9
3	1-2		43	60.8	17.8	18
4	1-2		49.5	69.7	17.2	27.5
5	1-3		45	69.5	24.5	50
6	1.5		48.6	62.3	13.7	21.7
	3		48.3	63	14.7	
8	2		42	65.3	23.3	15.9
	4		42.2	58.4	16.2	
9	1-3		47	62.4	15.4	18.2

Compaction

Laboratory measurements of the bulk mass of compacted soil were obtained for each trial, and the corresponding moisture content values were determined. The optimum moisture content and maximum dry density results for the study area are presented in Table 6.

Table 6, Compaction test result of study area.

TP	Depth	ρd (kg/m³)	Wopt%
1	1.5	1.562	32.8
2	3	1.604	28.5
3	3	1.38	33
5	3	1.22	30.5
7	3	1.424	31
8	2	1.487	28.8

Geotechnical engineers assess field soil compaction based on the relative compaction value. According to Arora, the dry density achieved in the field is compared with the maximum dry density obtained in the laboratory. The ratio of field dry density to maximum dry density is known as relative compaction.

According to Arora, cohesive soils should attain at least 95% relative compaction to minimize geotechnical problems. Since the study area is dominated by cohesive silty clay soil, the field compaction value of Aleta Wondo soil should be greater than 95% when compared with the laboratory results.

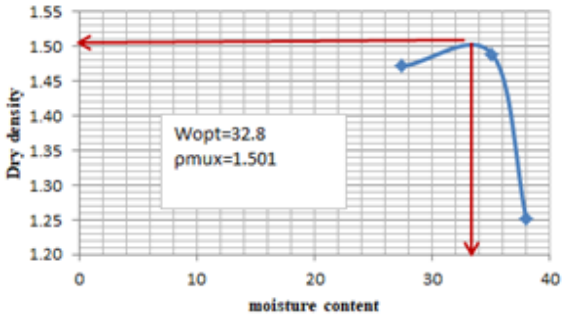


Figure 18, Compaction test result of TP1.

Direct shear test

In this study, six representative samples from different engineering soil classes were selected. The engineering properties and shear strength parameters of the selected samples are presented in Table 7. The results indicate that the cohesion of compressible silt varies from 22.86 to 49.37 kPa, while the angle of shearing resistance ranges from 19° to 22.88°. For low-plasticity clay with silt, the cohesion and angle of internal friction are 54 kPa and 18°, respectively.

Soil classification

Based on the Unified Soil Classification (USCS), Aleta Wondo town is characterized by compressible silt and low- to medium-plasticity clay. According to the British Standard Soil Classification System, the study area soils are classified as compressible silt and medium-plasticity inorganic clay.

Table 7, Shear strength test result of study area.

TP	Lithology	Engineering class (USCS)	Depth	Shear strength	
				Cohesion (kPa)	Internal friction angle
1	Silty	Compressible Silt with clay	1 m	21	22.88
2	Silty	Compressible Silt with clay	3 m	38.4	22.5
6	Silty	Compressible Silt with clay	1.5 m	49.73	20.56
7	Sandy	Compressible Silt with clay	3 m	21.16	22.88
8	Silty	Compressible Silt with clay	4 m	36	19
10	Clayey	Low plasticity Clay with silt	3 m	54	18
11	Sandy	Compressible Silt with clay	3 m	22.12	22.99

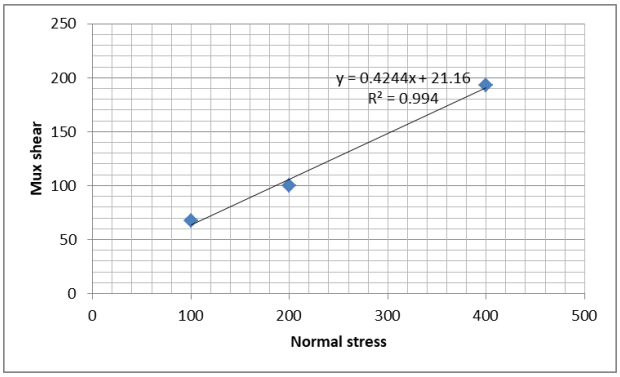


Figure 19, Shear strength test result of TP7.

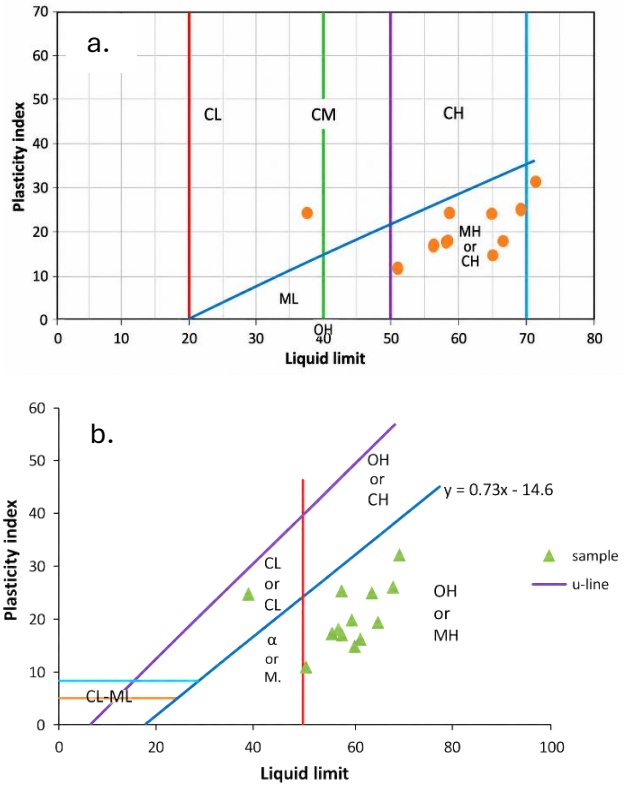


Figure 20, Soil classification according to (a) British Soil Classification System (BSCS) and (b) Unified Soil Classification System (USCS).

Engineering geological characterization and classification of rocks

In the study area, nine testing locations were identified to determine the Schmidt rebound value of the rock, and an average of ten readings was taken at each location. Schmidt hammer rebound values were recorded for each rock type at different locations to classify rock quality. The Schmidt rebound values were converted to unconfined compressive strength using the formula Unconfined Compressive Strength (UCS) = 3.03RN – 30.3 (Wang et al., 2017).

Rock Quality Designation was determined using the volumetric count method, while weathering conditions and discontinuity characteristics were assessed through visual observations. Finally, the rock mass quality in the study area was calculated by summing the ratings of the five basic parameters (Bieniawski, 1989).



Figure 21, Conducting Schmidt hammer test on ignimbrite, the northern part of town at the quarry site.

Table 8, Uniaxial Compressive Strength of rocks of the study area.

No	Northing	Easting	Rock genesis	Rebound value	UCS (MPa)	Description
1	729619	437136	Basalt	45.6	107.868	High Strength
2	729306	436795		42.9	99.687	High Strength
3	729823	437267		42.4	98.172	High Strength
4	729107	436596		40.5	92.415	High Strength
5	730932	435868	Ignimbrite	42.1	97.21	High Strength
6	730312	435323		25	45.45	Medium Strength
7	730568	435965		22	36.36	Medium Strength
8	730312	437125		10	12.12	Medium Strength
9	730919	436008		6	3.03	Very Low Strength

RQD determination by volumetric count method

RQD related to drill core is determined from the summation of discontinuities having lengths greater than 10 cm divided by the total core run. However, where drill core data are unavailable, Rock Quality Designation (RQD) can be determined using the joint volumetric count method. The volumetric count method is more advantageous than the drill-core method because it reduces directional dependence (Palmström, 1982). Therefore, since no rock core drilling data were available for the study area, Rock Quality Designation (RQD) was estimated using the joint volumetric count method (Eq. 6).

$$RQD=115-3.3Jv \quad (6)$$

Where Jv is the total number of discontinuities more than 10 cm long in 1 m x 1 m exposed rock face (volumetric count).

A joint trace exposed on ignimbrite rock at UTM coordinates (X = 436087, Y = 730949) is shown in Figure 22. The total number of discontinuities with lengths greater than 10 cm is 12; therefore, Jv = 12. The average joint spacing is 33 cm, and the joint condition is slightly rough and slightly weathered, with a separation of less than 1 mm. The groundwater condition is completely dry. Therefore, RQD = 115 – 3.3 × 12 = 75.4%.

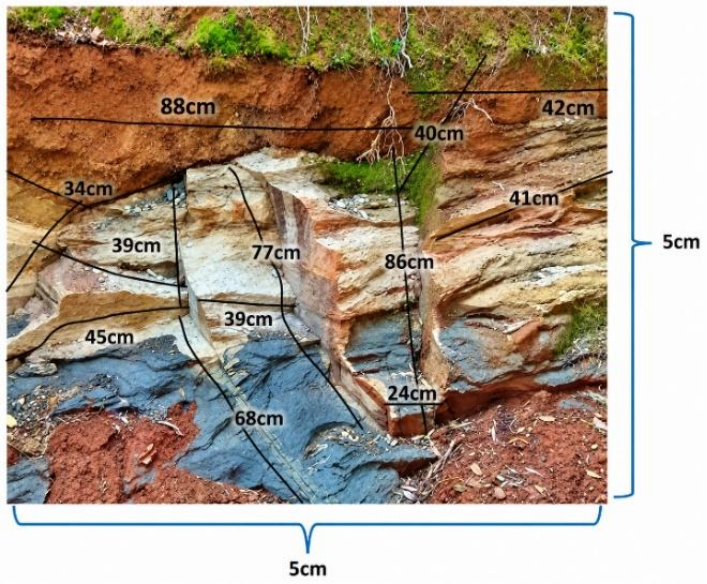


Figure 22, Joint trace exposed in study area.

The remaining seven UTM locations are determined in similar way and presented on the following Table 9.

Meaning and description of RMR

Based on the above-mentioned chart, Aleta Wondo Town is characterized by rock mass classes “B” and “C”. The rock mass quality in the study area for engineering purposes ranges from Good to Fair, as described by Bieniawski (1989).

Relationship of RQD and UCS with RMR

The RMR system provides a numerical value ranging from 0 to 100. Determining the RMR value of the rock mass in the study area is important because RMR provides a more comprehensive representation of actual ground conditions than RQD and UCS alone.

Table 9, RQD and RMR of rocks of the study area. (SW=slightly weathered, HW=highly weathered, SR=slightly rough, CCS=continuous slickenside, R=rating, JSc=joint space, GWC=ground water condition, CD=condition of discontinuity, RQD= rock quality designation, RMR=rock mass rating, D= description, Dr=dripping).

No	Northing	Easting	Rock genesis	USC	R	RQD	R	JS (cm)	R	CD	R	GWC	R	RMR	D
1	730070	435767	Basalt	107.868	12	69	13	35	10	SR and SW	25	Dry	10	70	Good
2	730366	435298		99.687	7	66	13	39	10	SR and SW	25	Dry	15	70	Good
3	730870	435065		98.172	7	71.3	13	38	10	SR and SW	25	Dry	10	65	Good
4	729107	436596	Ignimbrite	92.415	7	65.4	13	33	10	SR and SW	25	Dry	15	70	Good
5	730932	435868		97.263	7	74	13	24	10	SR and SW	25	Dry	10	65	Good
6	730312	435323		45.45	4	66	13	18	8	CSS	10	Wet	7	42	Fair
7	730568	436965		36.36	4	48	8	19	8	SR and HW	20	Wet	7	47	Fair
8	730312	437125		12.12	4	58	13	17	8	SR and HW	20	Dry	10	55	Fair
9	730919	436008		3.03	2	42	8	13	8	SR and HW	20	Dr	4	42	Poor

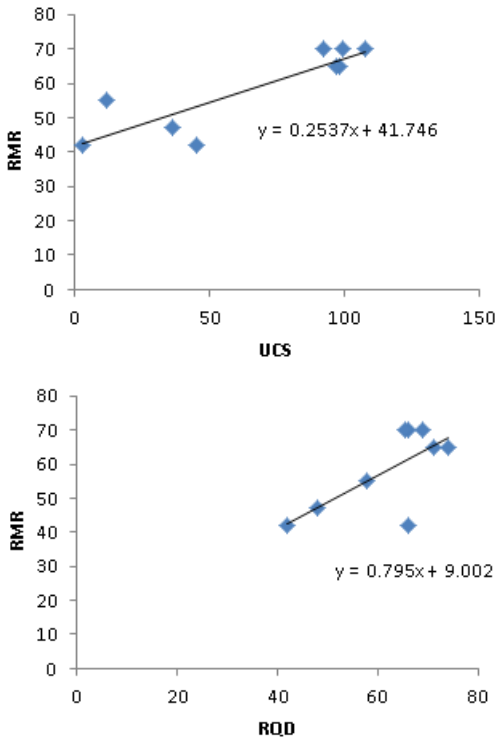


Figure 23, Relationships between RMR, RQD and UCS.

Rock-mass classification based on RMR is therefore a reliable approach for assessing the engineering quality of the rock mass. Where RMR classification is not available, rock quality may be assessed using RQD and UCS. To evaluate the relative reliability of these parameters, a comparison between RMR–RQD and RMR–UCS was conducted. The analysis shows that RQD has a stronger positive correlation with RMR, with a correlation coefficient of 0.795 (Figure 23). UCS also exhibits a positive correlation with RMR, although it is weaker than that of RQD. Overall, rock-mass quality classification based on RMR and RQD appears to better represent actual ground conditions. The authors recommend further analysis using a larger dataset to validate these findings.

Assessment of hydrogeological, geomorphological, and geodynamic hazards

Hazard-related earth processes are broadly classified as geohazards. A geohazard is a geological condition or process that may result in loss of life, damage to property, and disruption of socioeconomic activities. Geohazards may involve short- or long-term geological and environmental processes. They can range from relatively small features to large-scale phenomena, such as submarine or terrestrial landslides, and can significantly affect local and regional socioeconomic conditions. Other major geohazards include earthquakes, volcanic eruptions, avalanches, and floods (Derbyshire et al., 2001). Aleta Wondo town is located in the southwestern part of the Main Ethiopian Rift, within the transitional zone between the Main Ethiopian Rift System and the Ethiopian Plateau. Consequently, significant volcanic and earthquake hazards are not prominent in the town. Landslides, gully erosion, and shallow groundwater are the most commonly observed geodynamic and hydrogeological processes responsible for damage to engineering structures and modification of the surficial features of the study area.

Landslide

A landslide, also called a landslip, the downslope movement of a rock mass, debris, earth, or soil (soil being a mixture of earth and debris). Landslides occur when gravitational and other types of shear stress within a slope exceed the shear strength (resistance to shearing) of the materials that form the slope. Shear stresses can be built up within a slope by some processes. These include over steepening of the base of the slope, by natural erosion or excavation, and loading of the slope, such as by an inflow of water, a rise in the groundwater table, or the accumulation of debris on the slope's surface. Landslides are generally classified by type of movement (slides, flows, spread, topple, or fall) and type of material (rock, debris, or earth). Sometimes more than one type of movement occurs within a single landslide. At study area, small and medium scale soil slide observed specially along slop cut of north eastern and southern part of town (Figure 24). This process damages the asphalt road of town. Landslide phenomena in the study area were documented on the engineering geological map by extracting polygonal landslide features from Google Earth Pro.

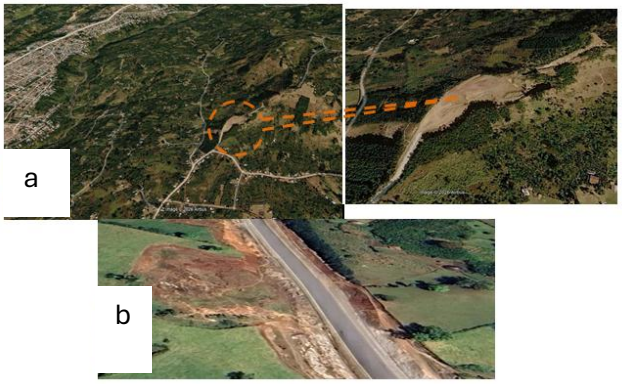


Figure 24, (a) Landslides of study area north eastern part of town and (b) damages of road due to small scale landslide southern parts of town. Source: Google Earth Pro.

Erosion and weathering

The northwestern part of the town experiences gully erosion due to steep topographic slopes. Consequently, roads and residential houses are frequently affected by flooding. In the study area, topography, parent materials, and the degree of weathering govern the type and development of soils. In humid regions, temperature and moisture content control the degree and rate of weathering.

Residual soil dominates the study area, indicating that in situ chemical weathering is more prevalent than mechanical weathering. Highly to slightly weathered ignimbrite rock (Figure 25) is also observed along the river cut in the northern part of the town.

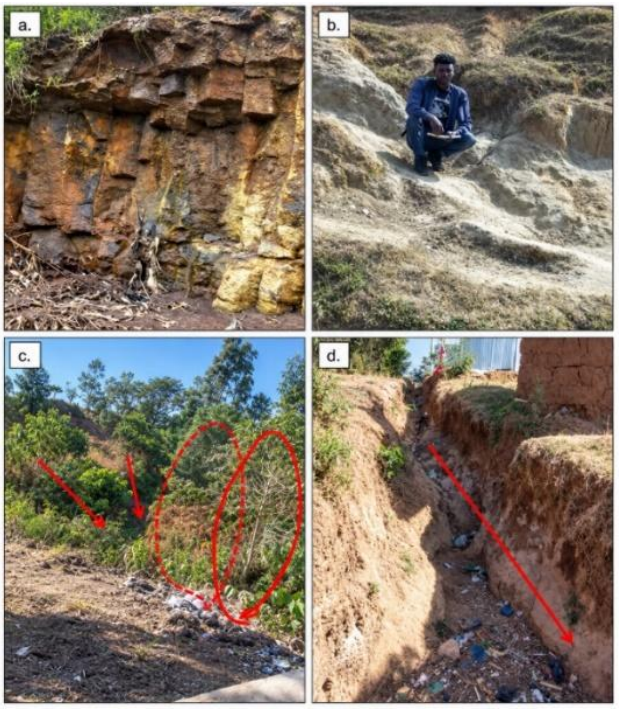


Figure 25, Weathered ignimbrite rock units: (a) erosion of white clay soil, (b) gully erosion in an area covered by trees and grasses (c), lateral erosion (d).

Groundwater

The flow of groundwater below the ground surface is a fundamental factor controlling the strength and compressibility of soil, thereby affecting its ability to support structural loads. When soil becomes saturated, it develops specific physical characteristics due to the relative incompressibility of water. These characteristics are particularly significant below the groundwater table.

Common groundwater issues during construction include unstable subgrades, unstable excavations, water seepage, construction delays, and cost overruns. Common groundwater problems after construction include water leakage, wet basements, mold growth, cracked and uneven floors, cracked and uneven walls, and instability of slopes and retaining walls.

Aleta Wondo town is characterized by shallow groundwater, particularly in the southwestern and south-central parts of the town. Field surveys indicate that the groundwater depth is less than 4 m in the southeastern part of the town, allowing residents to easily access groundwater through boreholes (Figure 26).

The groundwater depth increases to approximately 12 m toward the northern part of the town. Borehole data indicate that the groundwater level gradually increases from south to north. The regional groundwater level of Aleta Wondo Town was estimated using data collected from nine boreholes (Table 10). Groundwater-level contours indicate a general groundwater flow direction from north to south (Figure 27).



Figure 26, Groundwater image captured from Southeastern part of town.

Table 10, Static water level and groundwater level in the study area.

Northing	Easting	Elevation (m)	GWL (m)	SWL (m)
435411	729454	1905	1901.5	3.5
435489	729374	1901	1896.2	4.8
435463	729336	1902	1899	3
436141	729445	1908	1905.5	2.5
436182	729440	1906	1904.3	1.7
436359	729446	1906	1903.8	2.2
436722	729781	1927	1916.8	10.2
435561	720495	1991	1979	12
436892	720022	1920	1905	15

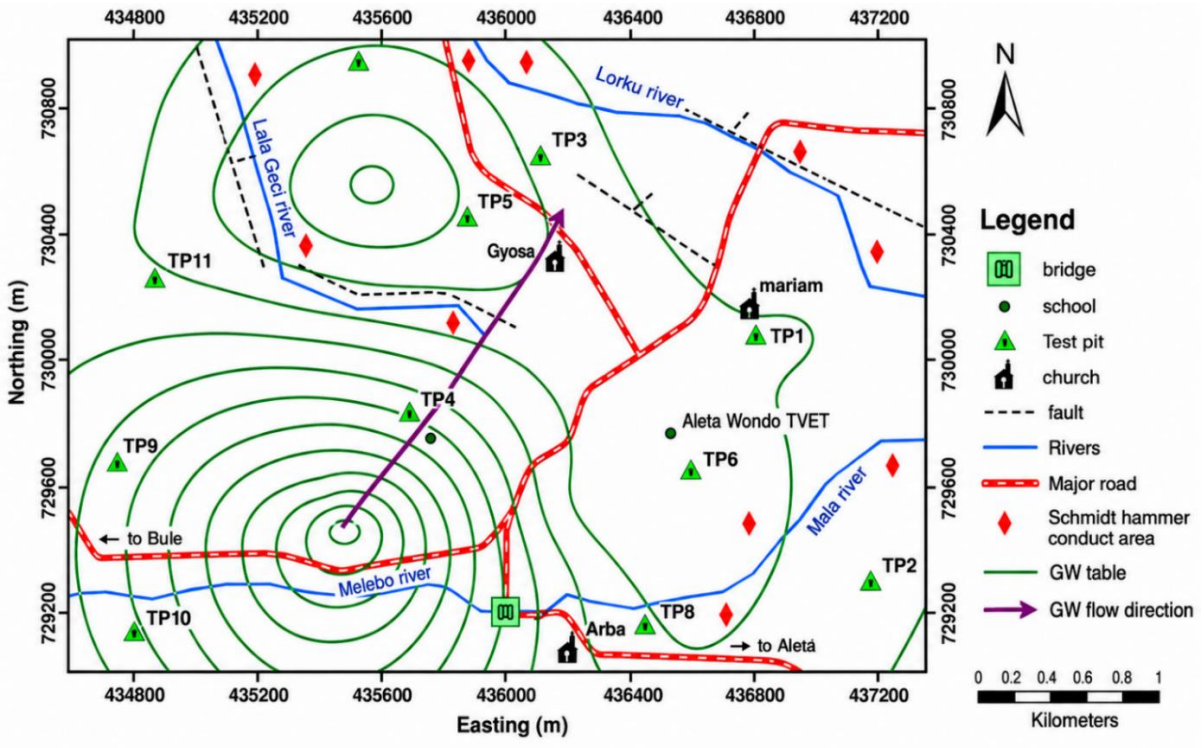


Figure 27, Groundwater level and flow direction in Aleta Wondo Town.

Preparation of multipurpose engineering geologic map

For the current study, a multipurpose engineering geological map (EGM) was prepared using the engineering properties of soils and rocks, including strength (unconfined compressive strength) and degree of weathering. To map rock units on the engineering geological map, seven Schmidt hammer test areas were used (Figure 12). These areas exhibit similar RMR and UCS values, indicating consistent engineering properties, and their contacts were identified based on these parameters. Geological units with similar RMR and UCS values were grouped and mapped as single engineering geological units.

Similarly, soil units were mapped based on laboratory test results from test pits, and their contacts were delineated by interpolating the results using ArcGIS software. Therefore, similar lithological units were mapped as different engineering geological units based on their engineering properties. In addition, geodynamic phenomena, including gully erosion and flood risk, as well as groundwater conditions, were documented on the engineering geological map (Figure 28).

Engineering geological map units

The engineering geological map contains different engineering soil and rock units. Similar geological units are mapped as different engineering unit based on their engineering properties and quality.

High strength ignimbrite unit

The rock unit in this category is exposed along the small stream in the central part of the town and northeast of the quarry site. The intact rock strength of this rock mass

ranges from approximately 92.415 to 97.21 MPa. The Schmidt hammer rebound values generally range from 41.0 to 42.1, indicating very strong rock that cannot be easily broken with a geological hammer. The intact rock strength class of this unit is highly strong, and the rock is slightly weathered. The discontinuities are closely to widely spaced and have very narrow apertures.

Very high to high strength basaltic rock unit

This unit represents the geologically oldest basement rock and occurs at considerable depth below the ground surface. Consequently, it is not well exposed in the study area. A few outcrops are observed along the Melebo River in the southeastern part of the town, where the rock is slightly weathered, groundwater conditions are dry, and the discontinuities are free of infilling materials. The intact rock strength of this unit ranges from approximately 98.172 to 107.868 MPa. The Schmidt hammer rebound values generally range from 42.4 to 45.6. The intact rock strength class of this unit is highly strong.

Medium strength ignimbrite rock unit

This unit is exposed in the northwestern corner of the study area and has less favorable engineering properties compared with the other exposed rock units. The Schmidt hammer rebound values generally range from 10 to 25, indicating medium-strength rock. The groundwater conditions range from wet to dry, and the joint spacing is 13 to 19 mm. The discontinuity surfaces range from slickensided to highly weathered. This rock unit is moderately to highly weathered.

Low strength to very low strength

This category of rock is exposed north of the town near the Hawassa route and is highly weathered, with wet groundwater conditions. Extensive discoloration of the rock is observed due to weathering. The intact rock strength of this rock mass is less than 10 MPa. The Schmidt hammer rebound value is approximately 3 MPa, and the rock can be easily broken with a geological hammer. The intact rock strength class of this unit is very weak, highly weathered, and characterized by discontinuities with wide apertures.

Compressible silt with clay (MH)

Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, and elastic silts. This unit covers a large part of the town. The general engineering characteristics of this soil category are semi-pervious to pervious, highly compressible, and fair to poor for engineering works.

Lean clay with silt (CL)

Inorganic clays of very low to medium plasticity, gravelly clays, sandy clays, silty clays, and lean clays. This unit is exposed in the southwestern part of the town. According to the USCS classification, this soil is impervious, has medium compressibility, and is considered fair for engineering works.

Significance of engineering geologic map at study area

An engineering geological map is a predictive document that answers the question: Is the ground suitable for construction?

The primary use of an engineering geological map in the study area is to support urban land-use planning and development. It identifies zones of relative suitability for construction, ranging from low-risk areas to areas that are unsuitable without major remediation. For instance, the southern parts of the town are relatively unsuitable for large masonry buildings due to shallow groundwater. Similarly, the southern and northeastern parts of the town are prone to geological hazards such as landslides and erosion. These areas are considered inappropriate for urban expansion because infrastructure, such as pipelines routed through active debris-flow channels, may be damaged, resulting in ruptures, spills, and significant economic and environmental losses.

Conclusions and recommendations

Conclusion

The main objective of this study was to characterize the geological and engineering geological conditions of Aleta Wondo town and to prepare an engineering geological map for identifying geotechnically problematic areas and guiding the selection of suitable sites for engineering construction. Based on detailed field investigations, laboratory testing, and engineering geological assessment, geological and engineering geological maps of the town were prepared at a scale of 1:20,000.

The study identified two major lithological units, namely ignimbrite and basalt, along with residual soils. The rock units were further subdivided into engineering geological units according to their engineering properties, weathering conditions, and rock strength. The identified rock engineering units include good-quality, slightly weathered, very high-strength basalt; good-quality, slightly weathered, high-strength ignimbrite; and poor-quality, highly weathered, very low-strength ignimbrite. These variations demonstrate that lithologically similar rocks may exhibit substantially different engineering behavior depending on their degree of weathering and mechanical properties.

The groundwater table is generally shallow in the study area, particularly in the southern parts of the town, and therefore represents an important constraint for construction and urban development. The major geological structures consist of faults and small-scale joints, predominantly striking NNW-SSE, with dip directions toward the NE and SSW. These structural features may influence groundwater movement, rock mass stability, and engineering performance.

Laboratory investigations indicate that the soil moisture content ranges from 23.27% to 48%. Grain-size analysis shows that the soils are predominantly fine-grained. The soils exhibit low to medium swelling potential. The optimum moisture content ranges from 28% to 32.8%, while the maximum dry density ranges from 1.21 to 1.60 kg/m^3. Shear-strength testing indicates cohesion values of 38.4 to 49.37 kPa and friction angles of 19° to 22.99° for compressible silt (silty clay), while sandy silt exhibits cohesion of 22.73 to 25.86 kPa and friction angles of 22.88° to 22.99°. Clayey silt has a cohesion of approximately 54 kPa and a friction angle of 18°.

Based on the Unified Soil Classification System (USCS), the clayey soils are classified as CL, representing inorganic clays of low to medium plasticity, whereas the silt and sandy silt soils are classified as MH, representing inorganic and elastic silts. The field-based lithological descriptions and soil classifications are generally consistent with the laboratory test results, supporting the reliability of the engineering geological characterization.

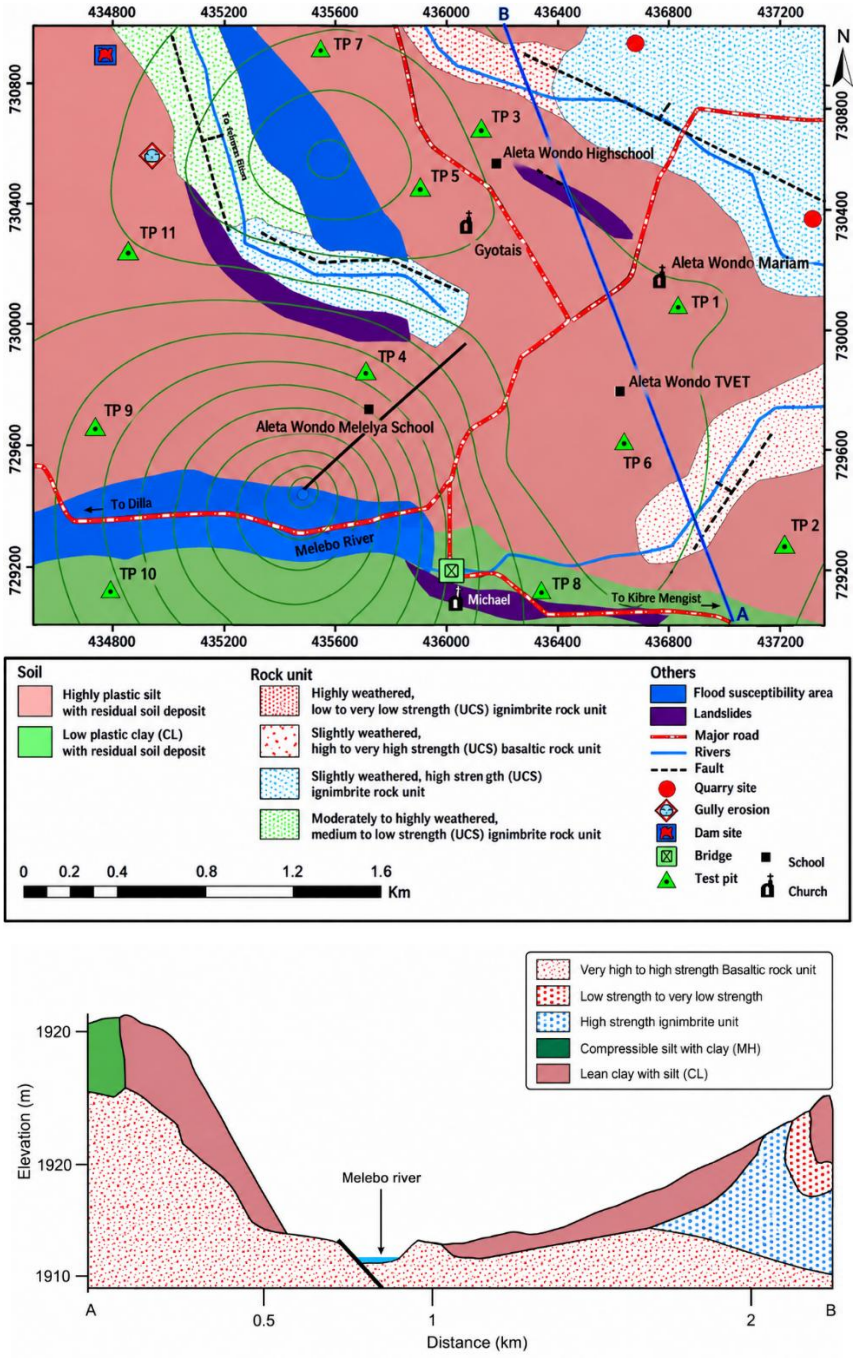


Figure 28, Engineering geologic map and cross section

Overall, the engineering geological conditions of Aleta Wondo town are highly variable and are controlled by lithology, weathering, soil properties, geological structures, groundwater conditions, and geodynamic processes. The resulting engineering geological map provides a practical basis for identifying relatively

suitable and problematic areas for construction and urban expansion. Areas affected by shallow groundwater, highly weathered and weak rock, erosion, and other geohazards require detailed site-specific investigation and appropriate engineering measures before development. Thus, the engineering geological map serves as an essential planning tool for safer and more sustainable urban development in Aleta Wondo town.

Recommendations

The following recommendations are provided for the study area:

- The study area is dominated by compressible silt, which is unfavorable for civil engineering works. Therefore, special design considerations and detailed site investigations are required before construction.
- Potentially medium-expansive soils were identified in the southwestern part of the town. Therefore, appropriate precautions should be taken when constructing civil engineering structures on these soils.
- Detailed subsurface investigations using geophysical methods are recommended to better understand subsurface conditions, including overburden thickness.
- Further research should be conducted by increasing the number of test pits within the study area and extending investigations to additional areas not covered by the present study.

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Availability of data and materials

The datasets supporting the findings of this study are available from the corresponding author upon reasonable request via email.

Competing interests

The authors declare that they have no conflict of interest regarding the publication of this paper.

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