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INTEGRATED GEOPHYSICAL, GEOTECHNICAL AND STREAM SEDIMENT INVESTIGATION FOR A DAM PROJECT ACROSS RIVER AGBARA, SOUTHWESTERN NIGERIA

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ABSTRACT

Proper site selection is crucial for constructing civil engineering projects, such as a dam, that would have a long-term sustainable benefits to mankind. A combined geophysical, geotechnical and sediment analysis were carried out at a site along Agbara River channel in Afin-Akoko southwestern Nigeria, with the aim of determining the conditions, potentials, suitability of the subsurface geology, environmental appraisal and river flow assessment on the site for construction of a sustainable dam. This dam is considered important for addressing the current severe water supply challenge in the area. Geophysical survey, involving Schlumberger vertical electrical sounding (VES), and geotechnical investigation of nine soil samples excavated from different trial pits at the depth of 1.5 - 3 m, were carried out using standard procedures. Five river sediment samples collected from the river were analyzed for environmental appraisal related to concentration of heavy minerals. Topsoil resistivity variation (57 – 1,339 Ωm) and thickness (0.9 – 15.5 m) reflects the degree of soil compaction and anthropogenic activities in the area. Northeastern and southwestern parts of the area characterized by stable zones of competent bedrock with thin overburden are suggested suitable for the proposed dam construction. Results of soil types showed that 77.8 % of the tested soils are good foundation materials (A-2-6 to A-2-7) with maximum dry density above 1,956 kg/m^3 and optimum moisture content (OMC) below 14.5 %. The unconfined compressive strength (UCS) of the soil (230.1 – 320.3 kN/m^2) indicating the soils' very stiff consistency is attributed to its resistance to volume change under load, capable of withstanding embankment weight, thus, protecting the dam from erosion and flood. The soils' resistance to shear failure guarantees firm bond between the projected dam and subsoil foundation to avert washouts and piping. Coefficients of volume compressibility and consolidation of the soils show no tendency of differential settlement. Coefficient of permeability, within 3.96×10^{-6} - 2.40×10^{-5} cm/sec, indicate impervious nature of the subsoil guiding against seepage. Results indicate that River Agbara sediments are mineralogically sub-mature to mature, suggesting mixed acid igneous and high grade metamorphic rock source. The heavy minerals are moderately stable to ultra-stable indicating an oxygen-rich (oxic) depositional environment. Dam foundation design and construction is recommended on properly compacted soil across Agbara River with priority for compacted spillway and rock lining for sustainability. Earth fill dam with consistent maintenance is encouraged for its optimal usage and proposed benefits to the society.

KEYWORDS: Geophysical survey, environmental appraisal, River Agbara, site selection, proposed Afin dam, sustainable dam construction

INTRODUCTION

Dams have played significant role in sustainable water development and management with diverse benefits offered for nation's advancement and enviromental sustainability. Each environment possesses inherent features and undergo diverse climatic conditions which influence chemical and geological processes. Subsoil characteristics and supporting structural foundation determine stability of civil engineering works (Ademila, 2018). Geophysical techniques provide valuable information on subsurface properties, geology and architecture underlying an area (Ademila and Ololade, 2018; Ademila, 2021; Ademila, 2022). Geology and subsoil nature are among several factors guiding the design,

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structural foundation and construction of sustainable dams and other infrastructures. Subsoil foundation investigation for dam construction is essential to guarantee proper design for the required dam weight, competence and ensure stability. Geophysical investigation offers quality information of subsoil profile needed to model the subsurface geological setting to reveal subsurface conditions that could pose threat to stability and integrity of structural foundation (Ademila, 2022). Subsoil geotechnical analysis also presents existing site conditions essential to guide structural design and construction influencing earthworks usage, integrity, safety and stability (Ademila, 2018; Ademila, 2021).

Stream sediment survey is a notable geochemical analysis for recognizing potential sources of concentrations of anomalous elements. Stream sediments are noted by their colour, particle size, textural and compositional variability with decrease in anomalous metal concentration downstream from dilution of non-mineralized materials constituting a dispersion train. The stream sediment characteristics reveal the bedrock geology, geological processes, anthropogenic activities, hydrological and climatic conditions. These factors have significant influence on the geochemistry of an area, water chemistry, vegetation and provide insightful details on provenance, transportation and depositional history of sediments (Grunsky et al., 2009; Singh, 2010). Natural processes and anthropogenic activities are primary sources of elements and heavy metals channeled into aquatic bodies (lakes, rivers, streams and oceans). Chemical composition of sediments particularly presence of heavy minerals indicate sediment provenance, flow pattern and dynamics of diverse sediments (Ali et al., 2014).

Dam construction for water storage and supply for irrigation farming has been encouraged to boost high yield agricultural production other than rainfall harvesting practices to enhance food security. Dam site conditions, subsoil and source of stream sediment along River Agbara would serve as controlling factors influencing the selection of the site for the dam construction. The site for dam construction must have good potentials for water storage, management and regulation for irrigation and flood control. Construcion of dam usually alters river flow pattern with resultant modification in sediment transport processes and deposition (Charoenlerkthawin et al., 2021). Dams retard sediments accumulation and direct river flow downstream to control flood which impacts the environment. Water shortage due to insufficient water supply in dry season, water wastage due to absence of storage facility and resultant flood encountered during rainy season necessitated the proper site selection for dam construction in the study area for water resource development and management to ensure sustainable water, food security and healthy environment. Sustainable water management through dam is beneficial to mankind and environmental friendly. Its negative environmental impacts could be minimized if the dam site is properly planned, selected, designed and constructed for its targeted purposes. Structural development for water resources and management involve indepth knowledge of the subsurface geological setting, sequence and structural disposition of an area (Ademila, 2021, Ademila, 2022).

Geophysical methods are useful tools for generating subsurface profiles in relation to groundwater exploration, groundwater character discrimination, contamination mapping and monitoring. Subsoil competence for sustainable structural works development can only be guaranted from subsoil quality engineering evaluation because soil response differently to diverse conditions and uses (Ademila and Olayinka, 2020). Variability of geophysical responses and engineering characteristics of subsoil influence performance, foundation stability and sustainability of engineering structures (Ademila, 2018; 2021; 2022). Electrical resistivity geophysical methods offer immense information on subsurface architectural setting of the study area. Schlumberger vertical electrical sounding (VES) techniques is a non-invasive geophysical method that probes earth resistivity with depth, suited for shallow subsurface investigation in different geological terrains. It characterizes the geological condition and aquiferous system of the area, revealing the subsurface disposition. The subsoil types, geological sequence and structural bedrock geometry were deduced from the electrical resistivity signatures. Subsurface geology, depth to bedrock, structural disposition and engineering characteristics of soil are vital for suitable site selection in sustainable design of civil engineering works. Knowledge of the area overburden thickness would guide in proper planning, design and construction of the dam. The need for consistent water supply for use of the residents, challenges pose by seasonal flood and low yield agricultural farm products during dry season prompted this study. Futhermore, the site selection based on ascertaining the conditions and competence of subsoil around River Agbara would enhance construction of sustainable dam.

STUDY SITE DESCRIPTION

Location and accessibility

The study site is along the flow channel of River Agbara within Afin-Akoko area of Southwestern Nigeria. It falls within latitudes 7° 35' N and 7° 40' N and longitudes 5° 40' E and 5° 45' E in the northern Senatorial district (Akoko Northwestern part) of Ondo State, Southwestern Nigeria. It is bordered by Ikare, Ikakumo, Oke-Agbe Akoko and Omuo-Ekiti to the west, east, south and north respectively (Fig. 1).

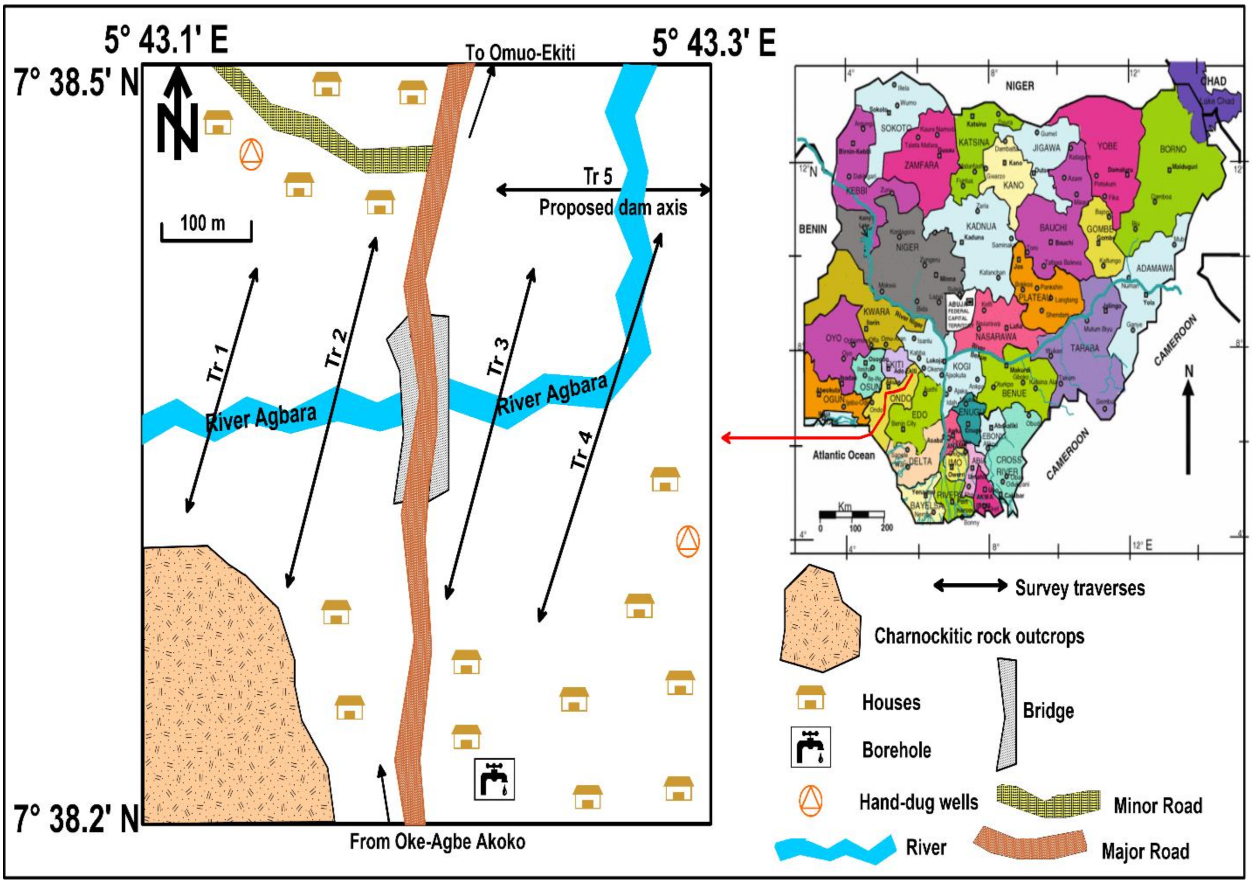

Figure 1: Location of River Agbara, Afin-Akoko.

Climate and vegetation

The area is endowed with favourable climatic conditions with an average rainfall of above 1550 mm per annum and noted with respective mean temperature of 27.5°C and relatively 72% humidity per year. It is characterized by alternating annual rainy and dry seasons of evergreen tropical rainforest with thick vegetation and rich humus soil, fertile for bountiful agricultural practices.

Geomorphology and drainage pattern

The topography is gently undulating, characterized by rocky highlands and lowlands in form of valleys and plains (Fig. 2). It is mainly drained by seasonal Rivers Oda, Ode-Eye and Agbara in a dendritic drainage pattern. These major rivers and their tributaries form the sources of surface water, while the weathered and fractured rock layers constitute the aquiferous unit hosting groundwater in the area. Volume of River Agbara varies with season, although, the water volume of the river was low during the investigation with the second, third and fourth-order streams dry.

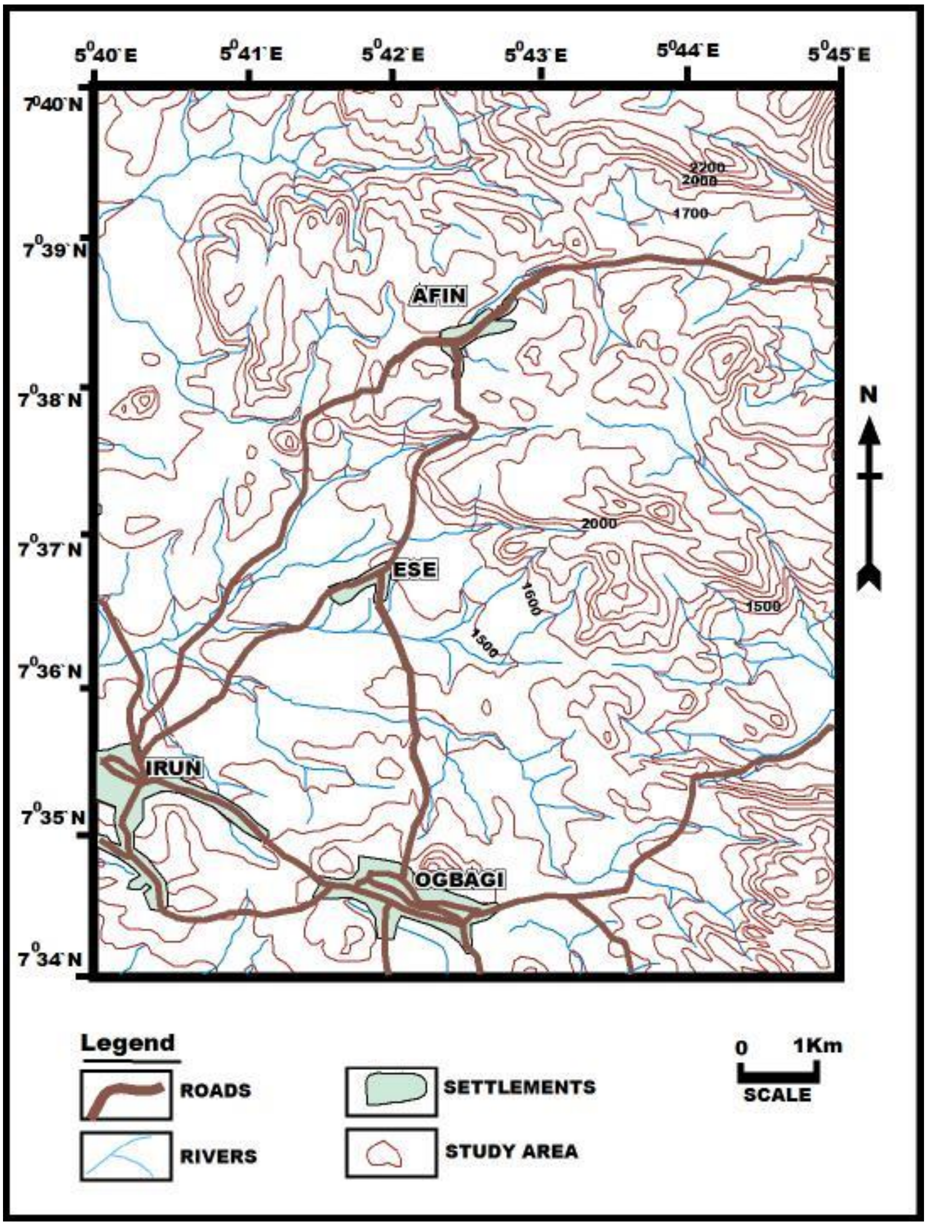

Figure 2: Topographical map of Afin-Akoko (study area)

Geology of the area

Afin-Akoko is recognized with the Precambrian basement rocks of Nigeria and falls within the southwestern migmatite-gneiss-quartzite complex with intrusion of quartzite and schist cross-cutting granitic rocks of the area. The granites are Older granites of Pan-African age (Kroner et al., 2001) with textural varieties ranging from fine-medium-coarse/porphyritic biotite-hornblend granite. Migmatite, grey gneiss and charnockitic rocks dominate the study area (Fig. 3) in form of hills, ridges, outcropping basement and boulders with mica schist, pegmatites intrusion and quartzite patches (Fig. 3). Varying trends of geological structures observed in the rocks during geological field mapping of the area indicated the topographical nature of the area being subjected to geotectonic activities. The structurally deformed bedrock are good sources of groundwater in the area with the weathered, sheared and fractured zones at specific locations to boost the development of substantial groundwater resources throughout the season. The need for potable water supply to the residents during dry season and overflow of River Agbara on excessive rainfall result to devastating flood, which usually submerges the area, have drawn the attention of the government and residents often clamouring for solution to this menace.

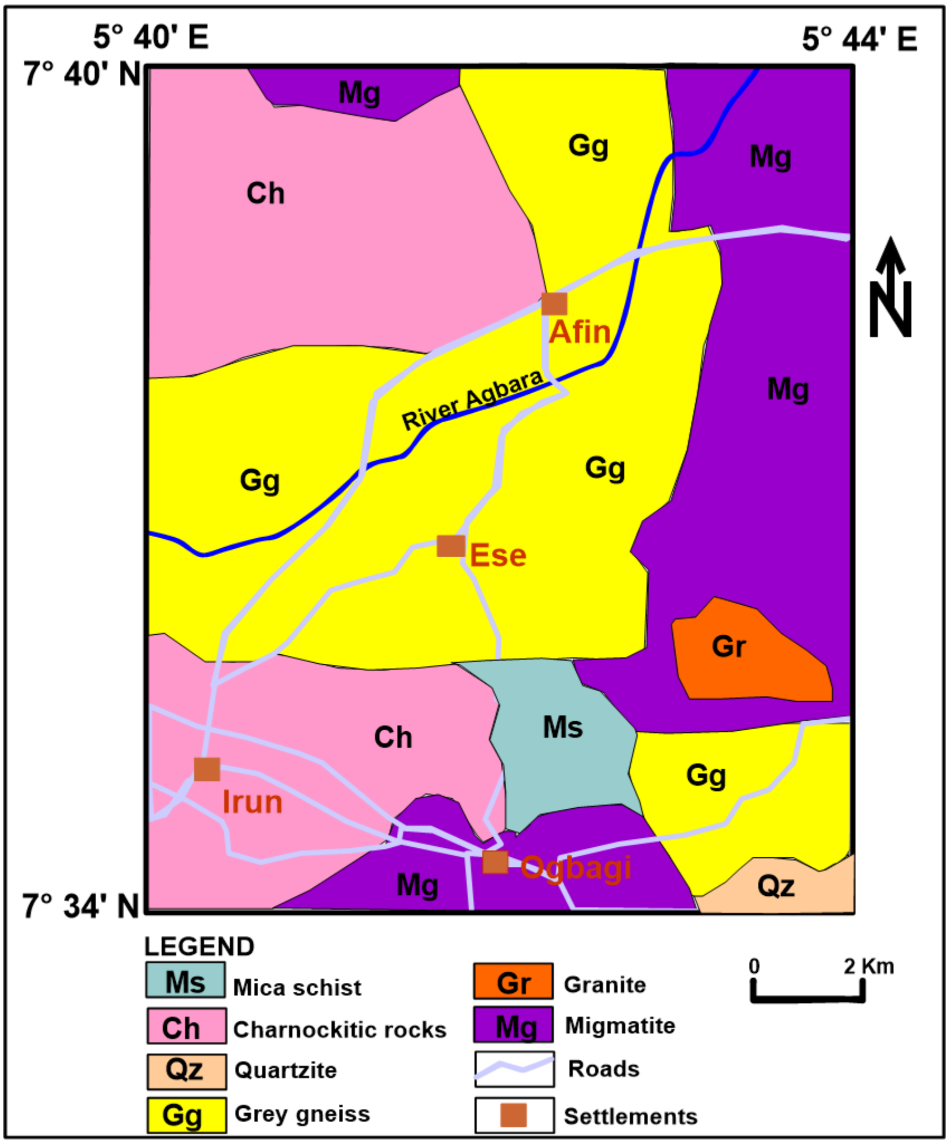

Figure 3: Geological map of Afin-Akoko and its environs.

MATERIALS AND METHODS

Twenty-nine (29) electrical depth sounding measurements were carried out along five established traverses with ABEM Terrameter SAS 1000. This instrument is considered as a result of its relatively high input resistance and potential successive measurements on every electrode. A maximum electrode spread (AB/2) of 150 m was engaged using the Schlumberger vertical electrical sounding technique to determine the vertical changes in the subsurface resistivity distribution. The electrical resistivity responses are related with sequential disposition of geologic materials and existing conditions of the dam site. Processing of the acquired field data involved plotting apparent resistivity against AB/2 on bi-log graph paper resulting to production of VES curves, interpreted quantitatively with the aid of partial curve matching with master curves and its auxiliaries to estimate the electrical resistivity distribution of the subsurface layers. Competence of the subsoil underlying the area was evaluated from the geoelectric parameters derived from computer iteration modeling of the estimated resistivities and thicknesses of the subsurface layers. Information of the subsurface geology and bedrock setting achieved with their thicknesses led to production of different maps characterizing the area for dam foundation design and construction.

The geotechnical assessment of the proposed dam site included field and laboratory tests which comprised determination of natural moisture content, particle size analysis, Atterberg limits, compaction, California bearing ratio, unconfined compression test, triaxial test, permeability, and consolidation tests on soil samples. These samples were collected from nine trial pits at different locations of the area at the depth of 1.5 - 3 m each from upstream, downstream and proposed dam axis around River Agbara.

The soil samples collected were guardedly labeled in different soil sample bags, sealed in polythene sacks to prevent contamination and moisture loss and thereafter taken to the laboratory of the Department of Earth Sciences, Adekunle Ajasin University, Akungba-Akoko, for analysis. In the laboratory, soil natural moisture content was instantly determined after which the soil samples were air dried for two weeks. Lumps in the soils were cautiously disaggregated to retain the original size of each grain with bare minimum pressure. The soil permeability potential was categorized to determine its water transmitting capacity and specify the extent of soil saturation in the area. The geotechnical tests were carried out in line with the British Standard (BS 1377: 1990) and American Society for Testing and Materials (ASTM) standard D1557 (2009) test procedures for civil engineering purposes. Geotechnical laboratory tests of the soil samples collected reveal the strength and suitability of the subsoil for the projected dam construction.

Agbara River sediment geochemical analysis was carried out for the purpose of determining the source rock, concentration and type of heavy mineral present. Five river sediment samples were collected in labeled sample bags at different locations from River Agbara (Fig. 4) and analyzed for heavy mineral concentration. The analysis of the river sediments for heavy minerals separation followed standard procedures of Mange and Maurer, 1992. About 100 g of each of the river sediment sample was treated with dilute HCl (dilute hydrochloric acid) for almost 2 mins to clean the sample grains and for removal of carbon contents, thereafter washed with distilled water for removal of acidic effects. The samples were poured on filter paper and allowed to dry. The heavy mineral separation involved the gravity settling method of separation. The following reagents; bromoform, acetone, dilute HCl, Canada balsam and materials; filter paper, funnel and slides were used. The samples, after drying were poured into different separating funnels partly filled with bromoform content. The mixture was then stirred and given time to settle. The funnel tap was opened and this allowed separated heavy minerals to be collected in a filter paper attached to a glass funnel placed in a conical flask. Heavy mineral obtained were washed with acetone to remove bromoform and enhance proper cleaning and dryness. Thereafter, the heavy minerals were placed on glass slides using Canada balsam and were examined under petrographic microscope based on their optical characteristics for identification of the type of heavy minerals. The results of the analysis on the minerals (opaque and non-opaque) were obtained with their percentages evaluated. ZTR (Zircon, Tourmaline and Rutile) index was used as an index to quantitatively assess the mineralogical maturity of the river sediment. The empirical formula for the determination of this parameter is give in equation (1);

ZTR index = [(Zircon + Tourmaline + Rutile)/ Total non-opaque minerals] × 100 ………………….. (1)

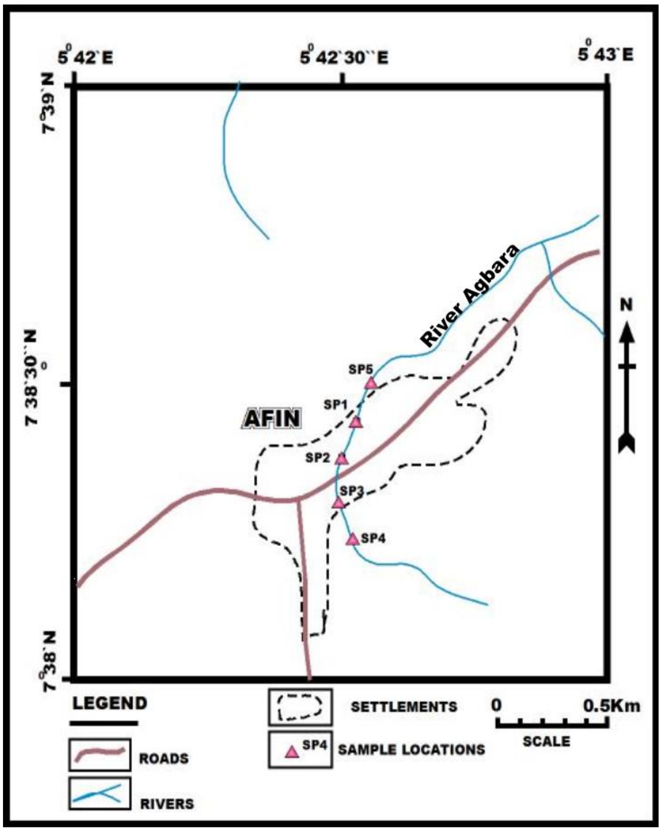

Figure 4: Five sediment samples collected from Agbara River.

RESULTS AND DISCUSSION

Geoelectrical site characterization

Five distinctive curve types were generated in the area as shown in Fig. 5. They are dominated by HA types (55.17%) followed by A types (17.24%), HKH (13.79%), AA (10.34%) and QH type (3.45%).

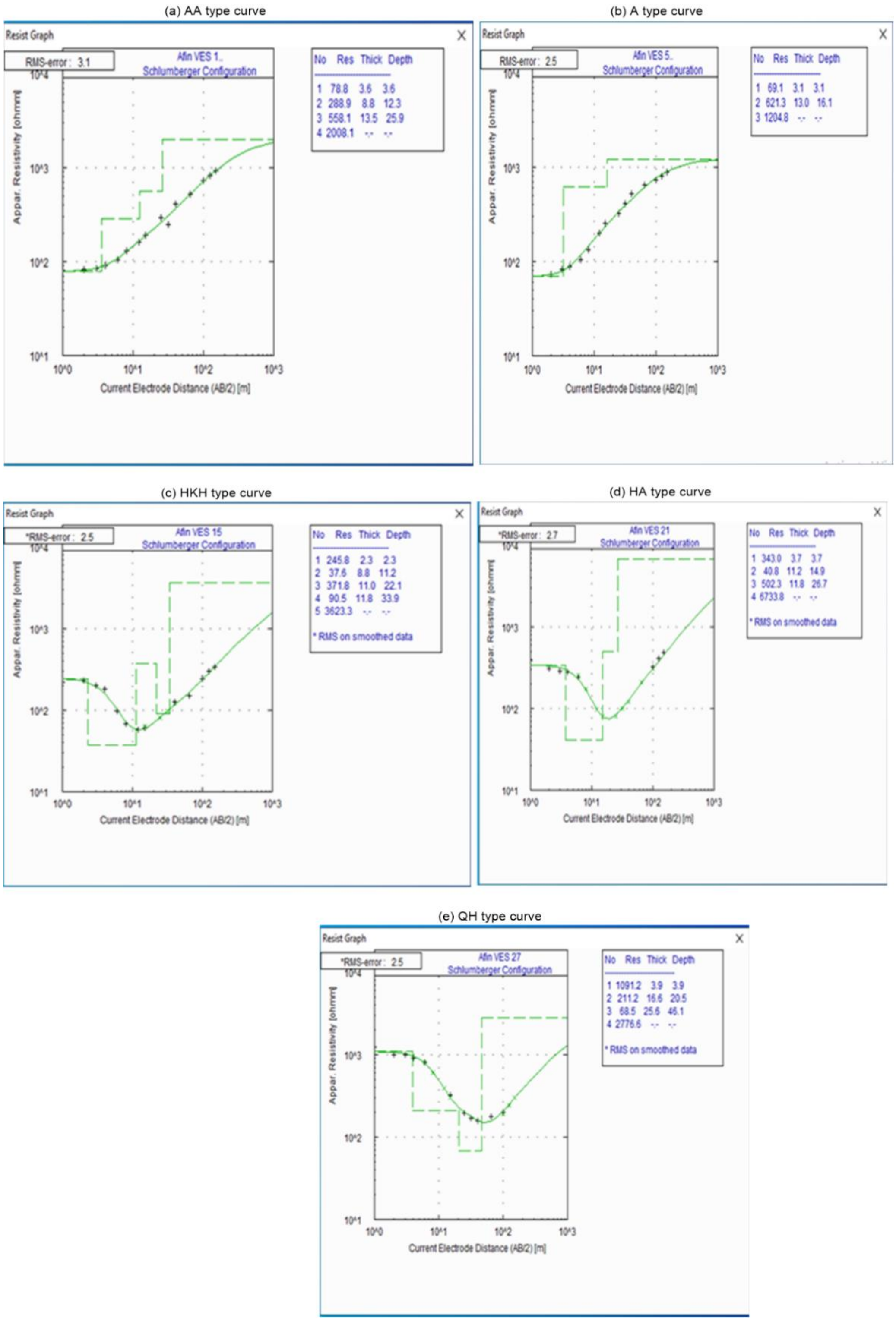

Figure 5: Typical curve types of the proposed Agbara River dam site.

Subsurface layers across Agbara River dam site

Three - four subsurface layers; topsoil, weathered basement, partially weathered/fractured basement and fresh bedrock are identified across Agbara River dam site (Figures 6 - 10). The topsoil having resistivity range 57 – 1339 Ωm and thickness composing of clay, sandy clay, clayey sand, sand and lateritic soil extending from the surface with a thickness in the range 0.9 – 15.5 m. This layer permits flow of water to the saturated subsurface zones. The weathered basement is majorly characterized by clayey materials (resistivity and thickness in the range 38 – 289 Ωm and 3.1 – 21.4 m respectively). The clay content of the weathered layer would impede water flow and protect the groundwater in the area from contamination. Partly weathered/fractured basement host groundwater with resistivity range 211 – 621 Ωm indicating saturated layer of 5.6 – 17.5 m thick. Variation of the layer thickness is due to weathering, erosion and compaction. The sandy composition of the unit is porous and permeable of good aquifer materials for substantial groundwater yield suitable for sustaining dam construction. Thus, groundwater in the area would boost dam functionality. The resistivity of the fresh bedrock is in the range 910 – 6734 Ωm with depth to bedrock of 12.6 – 46.1 m.

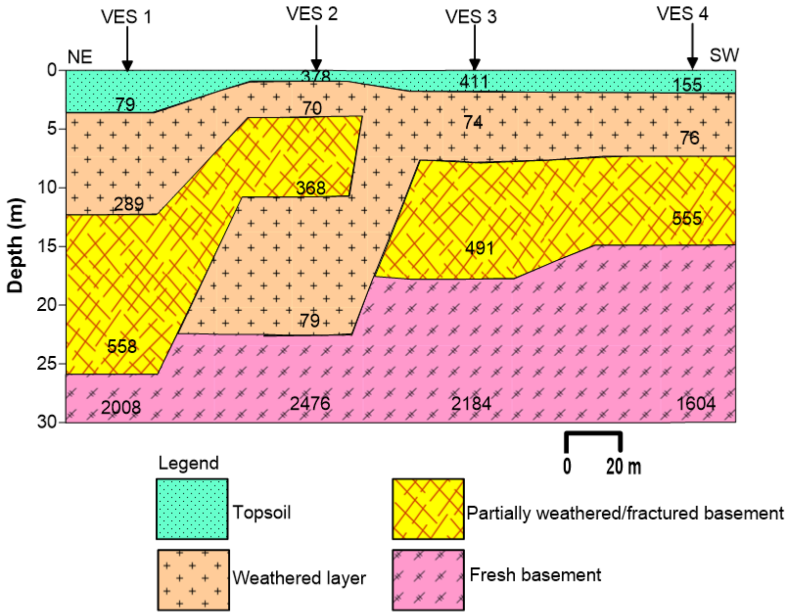

Figure 6: Geoelectrical section across Agbara River dam site (Traverse 1).

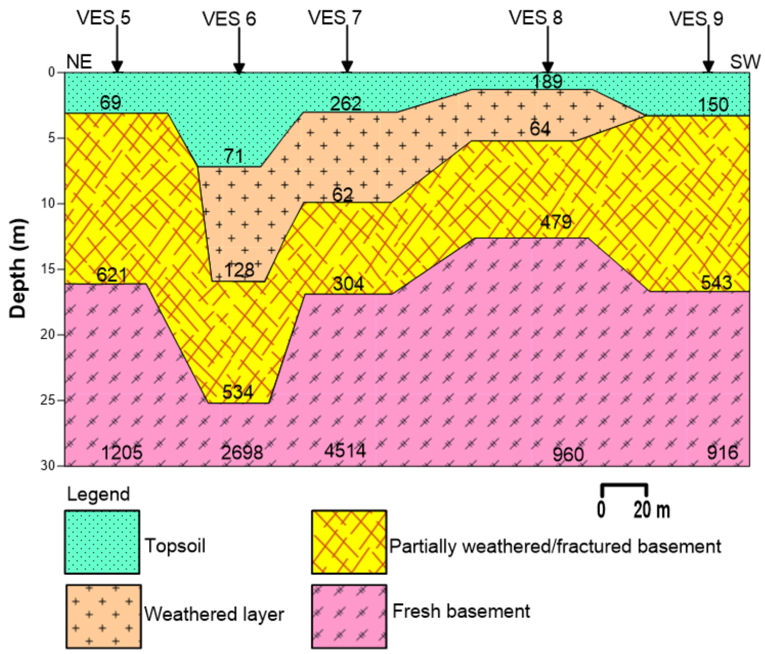

Figure 7: Geoelectrical section across Agbara River dam site (Traverse 2).

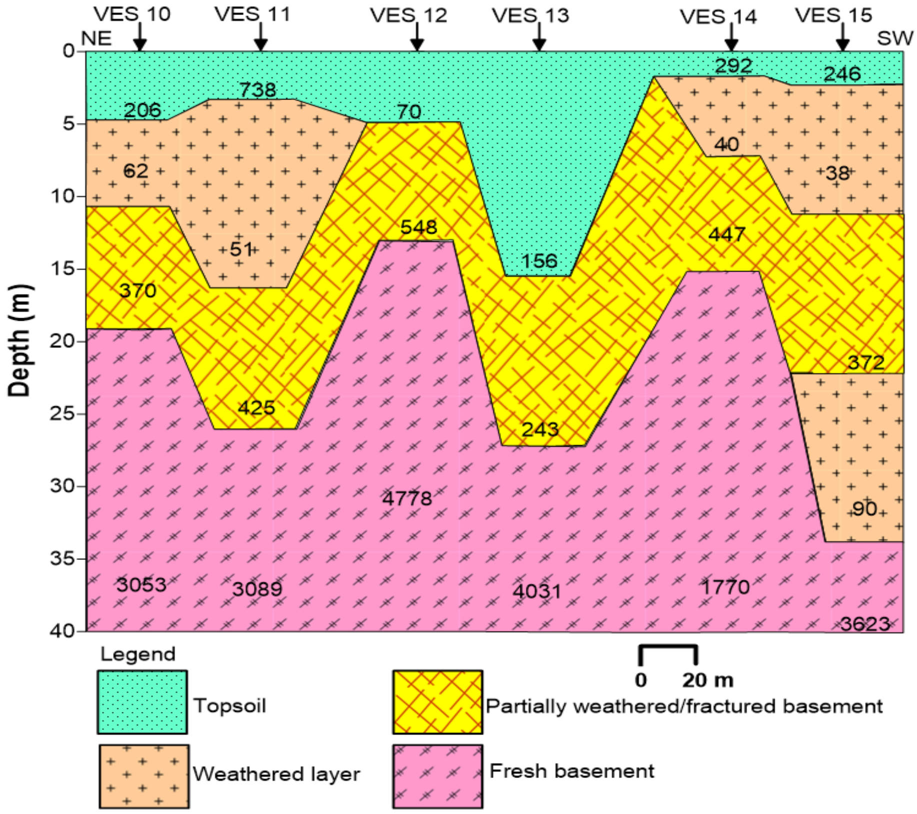

Figure 8: Geoelectrical section across Agbara River dam site (Traverse 3).

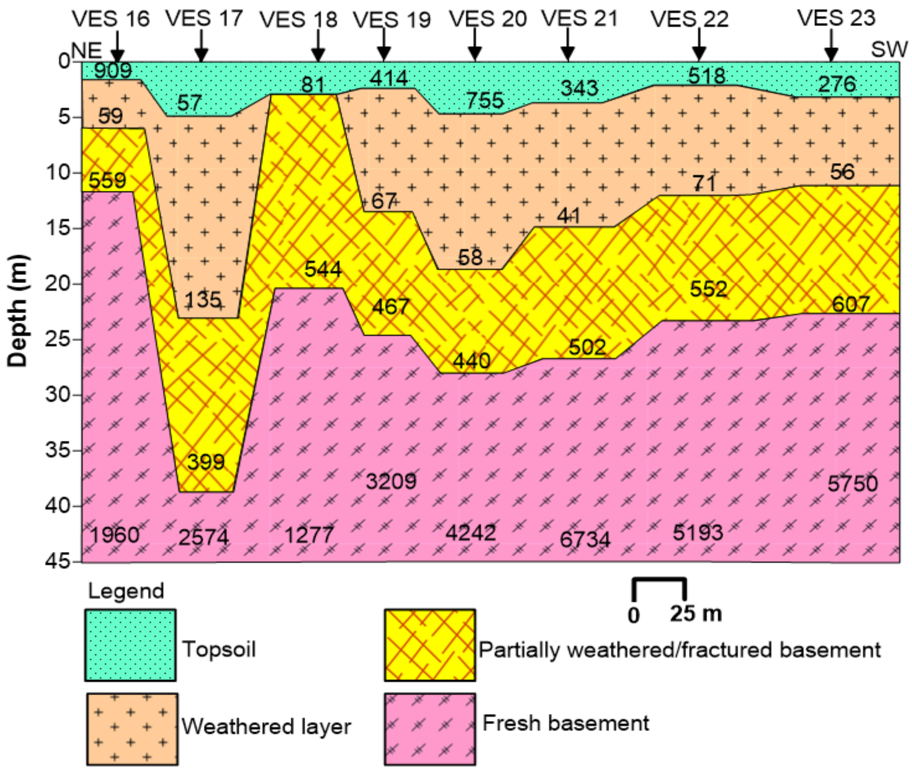

Figure 9: Geoelectrical section across Agbara River dam site (Traverse 4).

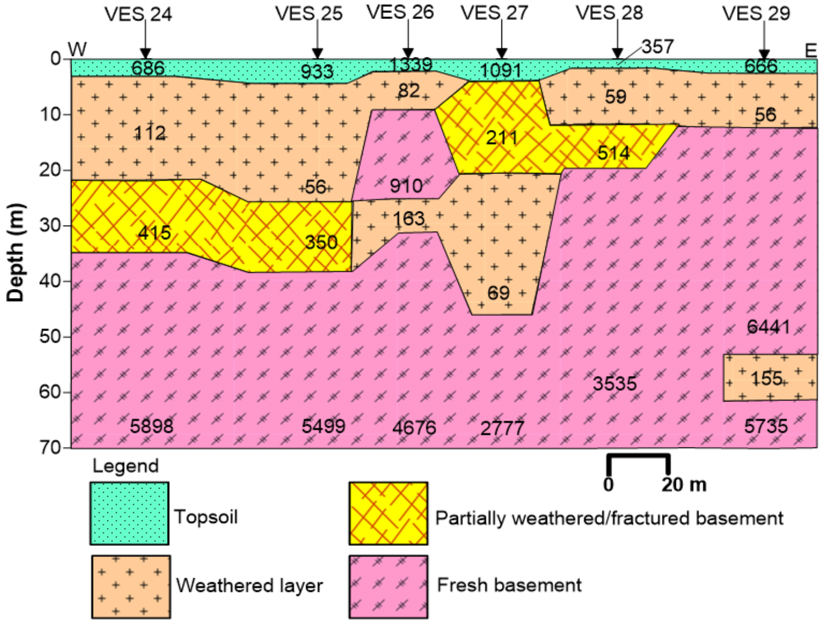

Figure 10: Geoelectrical section across Agbara River dam site (Traverse 5).

Resistivity and thickness of the topsoil

The variation of the topsoil resistivity (57 – 1339 Ωm) (Fig. 11a) and its thickness (0.9 – 15.5 m) (Fig. 11b) reflects the diverse degree of soil compaction and influence of human activities on the area. Northwestern and southwestern parts of the topsoil are characterized by low resistive geomaterials identified as portions with increased clayey subsoil materials unfavourable to civil engineering works. Subsoil resistivity guides the competency and suitability for engineering construction works. Thus, the structural dam foundation should be erected on competent bedrock for sustainability enhancement as clayey topsoil zones is attributed to high moisture content that could facilitate dam failure in the area (Ademila, 2021). The low resistive portions of the topsoil signify increased moisture content, weak and incompetent for civil engineering construction works. Shallow structural dam foundation is not encouraged due to the increased subsoil moisture content encountered in parts of the area to avert the threat of dam failure. The topsoil layer varying in composition from clay, sandy clay, clayey sand and laterite, allows water flow to saturated subsurface from the surface. Clay content of the uppermost layer could serve as potential threat to foundation of the proposed dam

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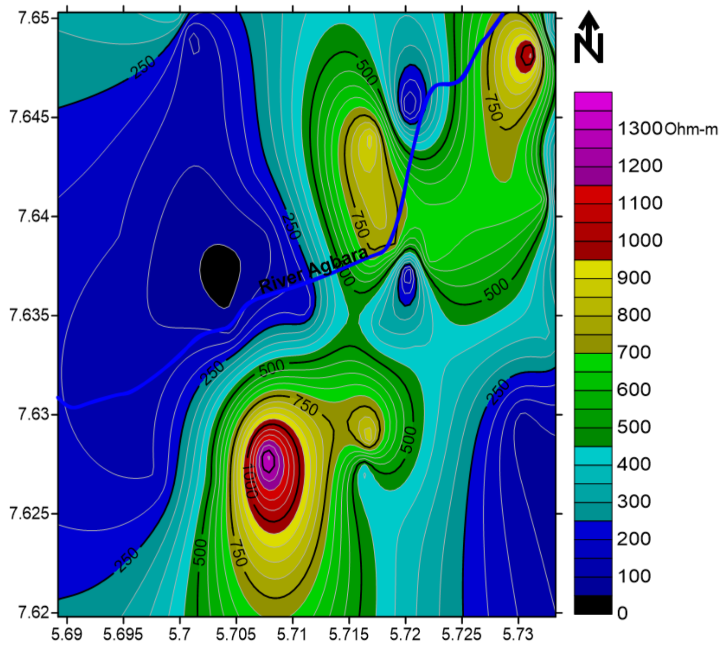

Figure 11a: Topsoil resistivity distribution of the proposed Agbara River dam site.

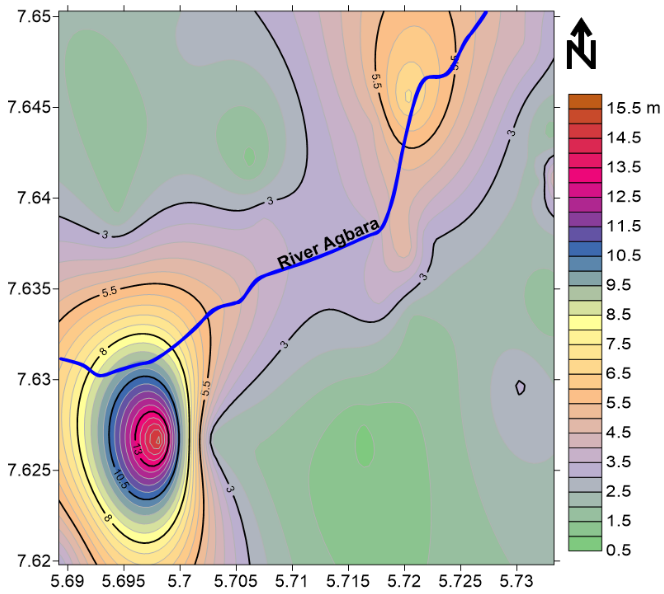

Figure 11b: Topsoil thickness of the proposed Agbara River dam site.

Overburden thickness

The overburden thickness of the proposed Agbara River dam site, in the range 11.7 – 61.3 m, is presented in Fig. 12. The variation of overburden thickness displays the action of physical and chemical weathering on the pre-existing parent rocks of the area, giving insight of consolidated and unconsolidated geologic materials above the fresh bedrock of the area. The composition of the overburden is attributed to intense weathering of the crystalline rocks; the weathered overburden is porous and saturated with considerable water content. Thick overburden above 30 m is observed around northern and southern parts of the proposed Agbara River dam site (Fig. 12). The remaining part of the area is characterized by relatively shallow overburden (≤ 20 m). Varying overburden thickness of the area is due to the fractured bedrock, topography, weathering and erosion. Saturated subsoil weakens civil engineering foundation because of its water retention capacity, thus precipitating structural failure as a result of water interaction with the base of the structure and subsequently weakening the subsoil bearing capacity that could sustain the dam structure. Structural disposition of the area is characterized by alternating thin and thick overburden cover. Overburden thickness determines subsurface groundwater storage capacity, recharge and aquifer yield.

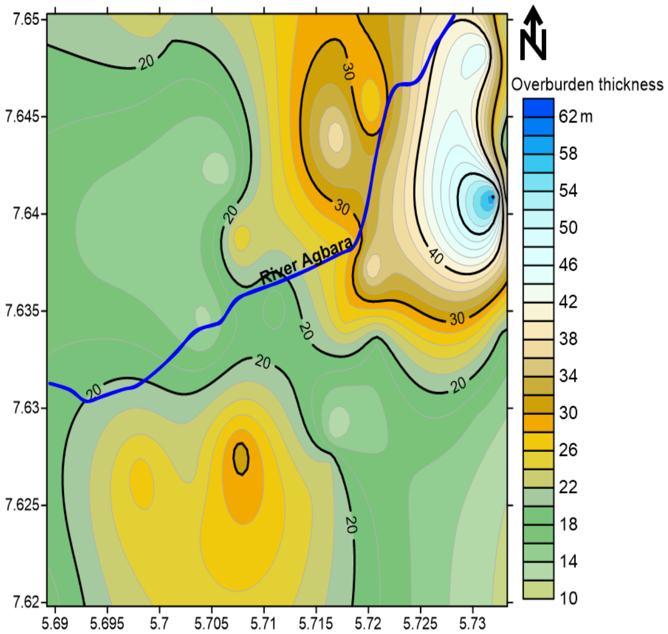

Figure 12: Overburden thickness of the proposed Agbara River dam site.

Bedrock relief

The bedrock relief presents the bedrock elevation underlying the projected dam site, which reveals the bedrock topography and its structural disposition in form of ridges, depression and flat lying terrain (Fig. 13). Bedrock depression observed in the area is trough-like capable of collecting discharge water from the crest and characterized mainly by thick overburden that could accumulate rainwater and permit its flow to water bearing unit (aquifer). Basement depressions are prospective high groundwater zones that could result to water seepage into dam foundation, leading to reduction in subsoil load bearing capacity which results to differential settling that has negative impact on the stability of the proposed structural dam construction. Ridges characterized the northeastern and central parts are as a result of outcropping basement at the surface at the area. The undulating nature of the basement topography of the area (Fig. 13) cannot sustain dam construction except adequate preventive measures are put in place when planning, designing dam foundation and construction to prevent threat of dam failure.

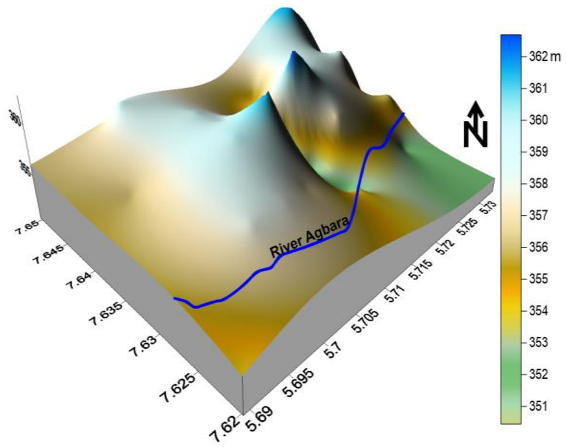

Figure 13: Proposed Agbara River dam site bedrock relief.

Bedrock resistivity of the proposed dam site

The fresh basement resistivity varies from 916 – 6734 Ωm (Fig. 14), The VES result showed that 93.1 % of the bedrock resistivity is above 1,000 Ωm and considered fresh without a sign of weathering and fracturing, which signifies a suitable and competent foundation for structural dam development. The remaining 6.9 % of the basement is fractured and water saturated with resistivity values lower than 1,000 Ωm towards the southeastern and northwestern parts of the area (Fig. 14). The northeastern and southwestern sides of the area are characterized by higher resistivity values with thin overburden cover, invariably relating to the projected dam axis with bedrock ridges. Fresh basement of the area along the northeastern and southwestern parts are stable zones of competent bedrock for the proposed dam construction (Fig. 14). Thus, deep foundation design and construction is recommended for the projected dam for sustainability.

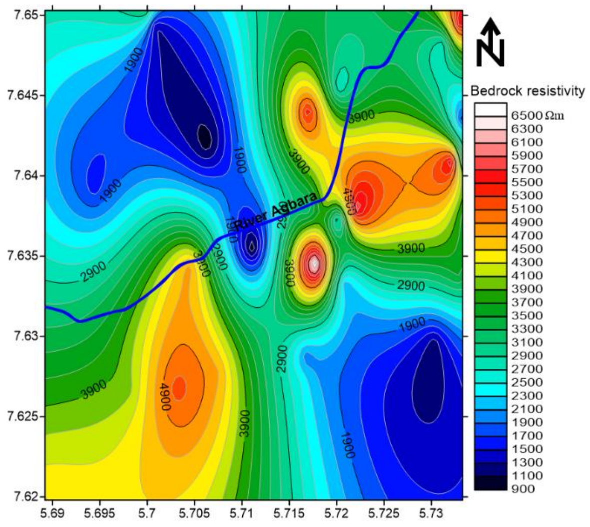

Figure 14: Proposed Agbara River dam site bedrock resistivity.

Geotechnical Characterization of the proposed dam site

Moisture content

Soil natural moisture content (NMC) indicates moisture absorption capacity and groundwater condition of subsoil materials of the area. It expresses the response of soil mass to climate, topography and hydrological condition of the area. The soil moisture content of the tested samples varies from 15.6 – 24.1%, as presented in Table 1., This indicates moderate moisture content of the subsoil in its original state. The moisture content result reveals slight water absorption capacity of the subsoil materials with minimal shrink-swell potential of the soil having insignificant volume change when moisture content changes. This reflects the water level of the area and the soil moderate affinity for water. This moderate water affinity of the soil still make it competent for dam foundation construction to support the engineering structure proposed to be built on it. Increased soil moisture content would lead to reduction and dislocation of subsoil particle interconnectivity with consequent reduction in load bearing capacity.

Specific gravity

The result of the specific gravity (Gs) test is presented in Table 1. The table shows that Gs ranges from 2.49 – 2.62. The variation in Gs of the soil underlying the proposed dam site is as a result of exposure of parent rocks to diverse degree of weathering leading to differences in soil mineralogical composition of the area. This also signifies varied level of laterization and state of saturation of the soil dry surface.

Grain size distribution

The result of the grain size distribution test is presented in Table 1. The percentage of fines in the soil of the proposed dam site range from 6.9 – 39.6% Different particle sizes of the soil signify that the soils are well graded. The clay and silt contents of the soil of some locations may be detrimental to the stability of the proposed dam. The fines in locations L4 and L6 (> 35%) signifies expansion and contraction potential of the soil during alternating dry and rainy season of the area, resulting to dam foundation failure from developed pressures of the expansive soil. The soils are within medium plasticity except soil of L7 rated with high plasticity (Fig. 15). 77.8% of the soil of the area are rated good foundation material with fines content of < 35%, which also fall A-2-6 to A-2-7 AASHTO soil classification (Table 2). The soil classified as SC; clayey sands/sand-clay mixture have low shrink-swell potential with expected unchange soil volume when moisture content changes. Thus, the soil is likely to be suitable as dam foundation material and for other engineering structural constructions. The remaining 22.2% of the soil from locations L4 and L6 with fines > 35% rated A-7-6 (Table 2) are clayey-silty materials indicating poor construction materials that could pose threat to stability of civil engineering construction works due to its high shrink-swell potential at varied climatic conditions.

Gravelly sandy soil predominance in the area would guarantee structural integrity and stability of the proposed dam in the area. All the soils are above the A-line of the plasticity chart (Fig. 15), indicative of inorganic soil composition potentially competent for structural works construction. The medium/high plasticity inorganic soil are rated CL– CH based on the Unified Soil Classification System (USCS), with appreciable sand contents. The medium plasticity (Fig. 15) of the soil indicates its cohesive and non-friable condition suitable as embankment material to confine and prevent water flow in the reservoir.

Table 1: Soil index properties of the area

Location	NMC (%)	Gs	Grain size distribution			Consistency Limits			
			Gravel (%)	Sand (%)	Fines (%)	LL (%)	PL (%)	PI (%)	LS (%)
L1A	20.8	2.55	2.3	90.8	6.9	45.6	23.4	22.2	2.0
L1B	19.6	2.55	2.6	89.4	8.0	46.3	23.1	23.2	3.0
L2	21.1	2.57	2.0	63.0	35.0	48.3	22.2	26.1	3.0
L3	23.5	2.61	2.5	65.1	32.3	44.0	19.5	24.5	1.0
L4	24.1	2.49	2.3	59.8	37.9	46.9	22.8	24.1	2.0
L5	21.0	2.62	2.2	64.8	33.0	39.8	19.2	20.6	3.0
L6	21.6	2.56	3.0	57.4	39.6	48.1	22.3	25.8	2.0
L7	19.2	2.49	2.2	64.6	33.4	51.3	23.2	28.1	3.0
L8	15.6	2.52	2.2	64.4	33.4	44.3	25.2	19.1	1.0

Table 2: Classification of soil of the proposed dam site

Location	Activity of clay (A_c)	AASHTO Classification	USCS Classification	Soil type
L1A	7.93	A-2-7	SC	Silty/clayey gravel and sand
L1B	5.52	A-2-7	SC	Silty/clayey gravel and sand
L2	1.61	A-2-7	SC	Silty/clayey gravel and sand
L3	2.08	A-2-7	SC	Silty/clayey gravel and sand
L4	2.08	A-7-6	CL	Clayey soil
L5	1.39	A-2-6	SC	Silty/clayey gravel and sand
L6	1.18	A-7-6	CL	Clayey soil
L7	46.83	A-2-7	SC	Silty/clayey gravel and sand
L8	1.27	A-2-7	SC	Silty/clayey gravel and sand

SC – clayey sand/sand-clay mixtures
CL– inorganic clay of low to medium plasticity

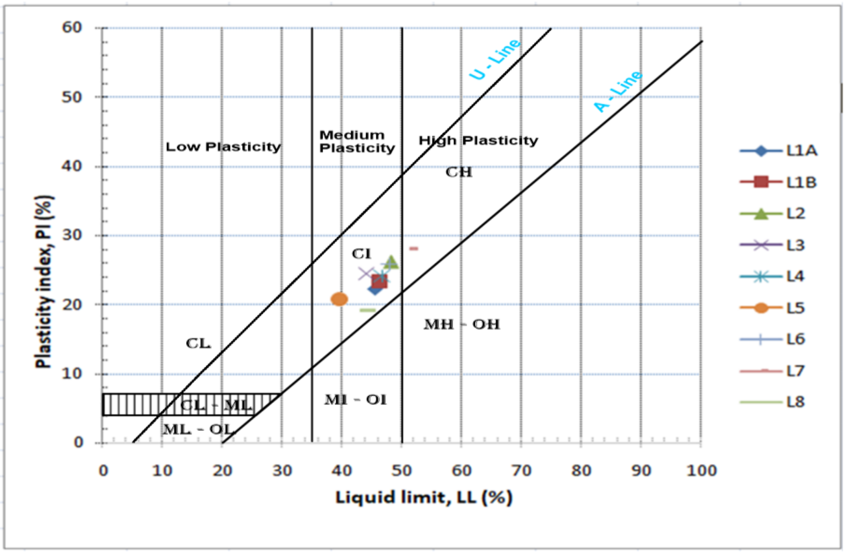

Figure 15: Plasticity chart of the soil of the proposed dam site.

Consistency Limits of the soil

The consistency limits of the soils as presented in Table 1, gives the volumetric change condition of the soil when its moisture content changes. This is required for consideration of soil suitability for civil engineering construction works. The liquid limit, plastic limit and plasticity index of the soils are in the range 39.8 – 51.3 %, 19.2 – 25.2 %, and 19.4 – 29.1 %, respectively. This range is an indication of moderate plasticity condition of the subsoil in its original state (Ademila, 2017). Plasticity index is a function of available clay mineral in the soil that determines the swelling potential of soils. Thus, the swelling potential of the soils of the proposed dam site is classified as medium. The higher the plasticity index, the more plastic and compressibility of the soil. All the soils of the study area are within the medium plasticity with the exception of soil within Location 7 (L7) reflecting high plasticity (Fig. 15). The soils are characterized as semi-impervious to impervious, thus, suitable for dam construction. The variability degree of the soil plasticity is an indication of the response and performance of the soil to its intended dam construction in a seasonal high water level, which is attributed to the soil void spaces, mineralogical composition, topography and climatic condition of the area. The linear shrinkage of the soils varies from 1.0 – 3.0 %, with the implication that the soil would be inactive, inexpansive, competent structural foundation material since the linear shrinkage is below 8 % (Brink et al., 1992). Presence of granular and sand materials in the soil of the area would enhance embankment performance of the area hence, the soil would pose no threat to the proposed dam stability. This very low linear shrinkage values of the soils support the soil inability to shrinkage and deformation under an embankment weight/load.

Soil activity is an index property that measures the swelling and water retention capacity of clayey soil due to clay mineral present in the soil. Soil activity of the proposed dam site is in the range 1.18 – 2.08, except soils of L1A, L1B and L7 with exceptional values (Table 2). This exceptional high activity of the soils of these locations may be due to the presence of slight clayey materials in the soil.

The soil activity values classify the soil clay as normal and active soil (Ademila and Olayinka, 2020). The activity chart shows that the soils are within medium expansion category (Fig. 16) with the exception of soils of L1A, L1B and L7 outside the range. The rating shows that the soils possess medium expansion characteristics and possibility to retain water, which is still suitable for dam siting.

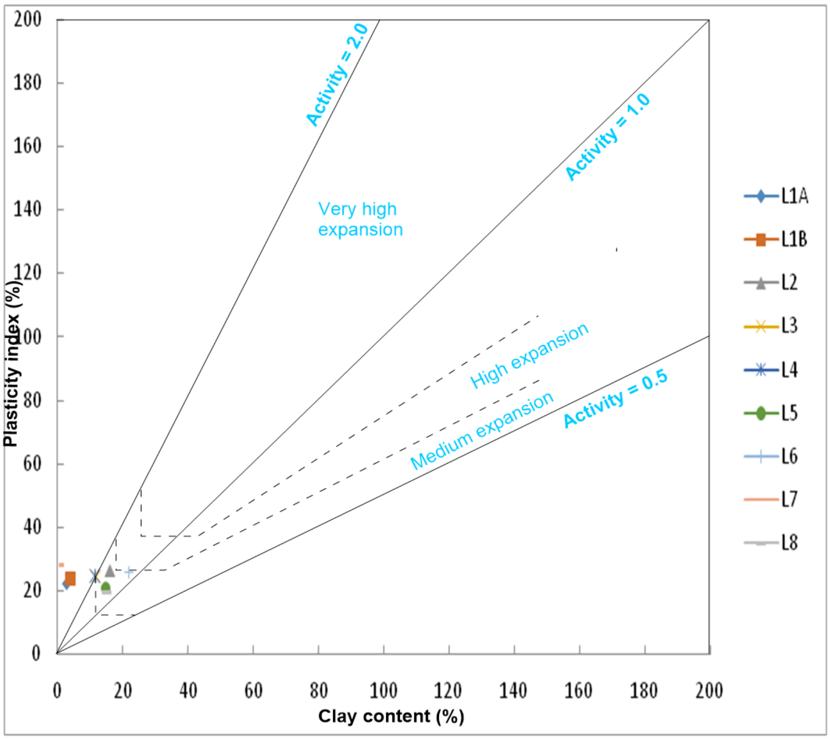

Figure 16: Activity chart of the soil of the projected dam site.

Engineering properties of the soil of the projected dam site

Engineering soil properties influence the soil resistance to stress and deformation under structural load which thereafter determine its structural performance. Determination of the engineering behaviour and characteristics of soil is paramount in establishing the soil load bearing capacity with emphasis on soil workability to guarantee eengineering structural stability and sustainability. The results of the engineering properties of the soil of the proposed Afin dam is presented in Table 3. The engineering properties of the subsoil which revealed its load bearing capacity would determine the design of the thickness and foundation type of the structural dam

Table 3: Engineering properties of the soil of the proposed dam site

Location	Compaction		California Bearing Ratio (CBR)		Unconfined compressive strength (kN/m^2)	Triaxial Compression	
	OMC (%)	MDD (kg/m^3)	Unsoaked CBR (%)	Soaked CBR (%)		Cohesion (kN/m^2)	Angle of internal friction (°)
L1A	17.2	1861	26	13	320.3	73.8	14.4
L1B	20.1	1760	28	13	300.5	76.6	17.4
L2	27.0	1522	27	9	246.7	66.3	14.4
L3	14.6	1953	25	9	237.5	64.3	16.5
L4	18.0	1833	28	13	301.7	78.7	11.5
L5	17.8	1840	26	10	267.1	68.6	13.5
L6	27.2	1515	34	12	230.1	64.6	11.8
L7	14.5	1956	24	6	290.7	81.5	15.8
L8	22.0	1532	32	12	277.7	66.3	13.1

Soil compaction characteristics

Well compacted subsoil underlying engineering structures reduces the detrimental impact of moisture, as exposure of low compacted soil to excessive moisture results in reduction of its load bearing capacity. High compacted density soil having higher maximum dry density (MDD) at low optimum moisture content (OMC) is suitable for quality dam foundation and expected embankment performance for optimum usage. The soil maximum dry density of the proposed dam site (MDD) is in the range 1515 – 1956 kg/m^3 at optimum moisture content (OMC) ranges 14.5 – 27.2 % (Table 3). It was observed under field condition that dry density influences soil response to stress as the soil of L6 with lowest MDD (1,515 kg/m^3) has the highest OMC (27.2 %) and soil of L7 with highest MDD (1,956 kg/m^3) has the lowest OMC (14.5 %) (Table 3). These values reveal the gradual response of the soil to compaction because compaction is crucial in improving the required load bearing capacity and reduce considerably the soil water absorption tendency that could result to differential settling that threatens civil engineering construction works. Also, from the soil compaction properties, the soil of the dam site is not liable to erosion. Acquiring maximum load bearing strength for sustainable dam construction, the foundation soil must be compacted beyond 1956 kg/m^3 (MDD) and below 14.5 % (OMC) to transmit the weight uniformly into the subsoil, prevent moisture influx into the dam foundation to avert future challenges and failure. Figure 17 displays typical compaction curve of the soil of the proposed dam site. The soil is suitable for the dam design having good water retention and impoundment potential. Thus, proper and adequate compaction of the soil on its OMC would offer a sustainable earth dam in the study area.

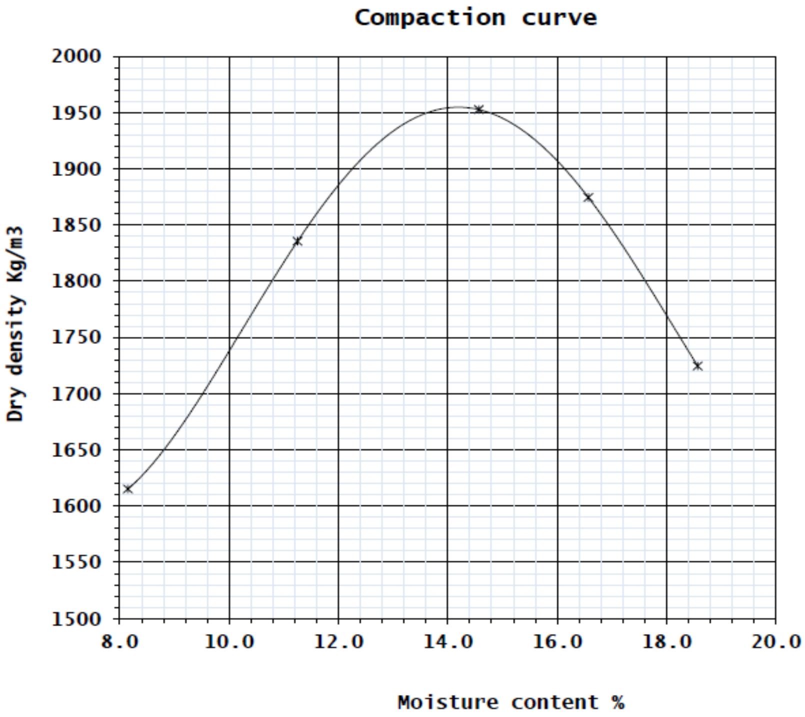

Figure 17: Compaction curve of soil of Location 3 (L3) of the proposed dam site.

Soil strength characteristics

California Bearing Ratio

The soil unsoaked and soaked **California Bearing Ratio (**CBR) values in the range 24 – 34% and 6 – 13%, respectively (Table 3) shows the resistance of the soil to stress and the soaked CBR reveals the soil condition on exposure to excessive water. Although the CBR values possess by the soils make them unsuitable engineering construction materials but good for earth-fill dam embankment. Low CBR soil values denote its relatively incompetent nature for civil engineering construction works. CBR curve of the soil of the proposed dam site is represented in Figure 18. The soaked CBR values indicate reduction in load bearing capacity of the soil on exposure to water, which makes it liable to volume changes thus, unable to support and sustain dam embankment weight. Volume change of soil on wetness could be as a result of presence of impervious clayey soil which would also serve as suitable and competent material for the dam core to avert seepage. 77.8 % of the soil of the area is characterized as good foundation materials with fines content <35 % and suitable for earth-fill dam due its compositional materials and favourable compaction properties, posing no threat to the proposed dam foundation stability and integrity.

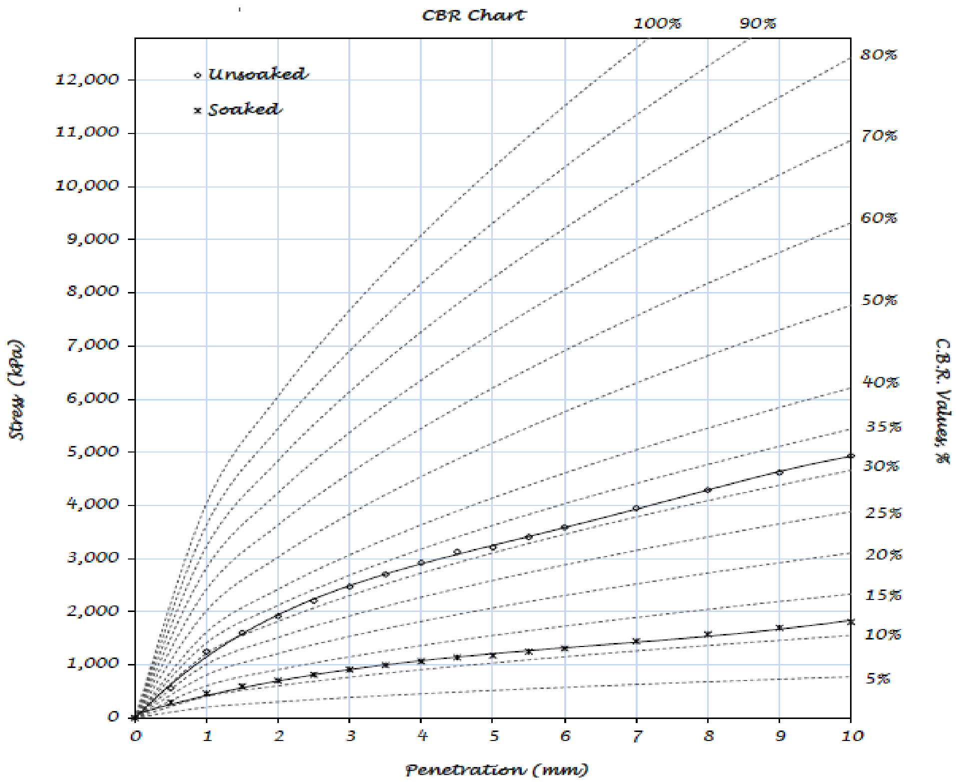

Figure 18: CBR representative curve of soil of Location 8 (L8) of the proposed dam site.

Unconfined Compressive Strength

The unconfined compression (UCS) test is a form of shear strength test that determines soil strength from the resistance of the soil to failure on applied load. Knowledge of soil compressive behaviour is also important in engineering geology to model the soil in-situ stress-strain response for its intended use (Liu et al., 2013). It expresses the soil strength consistency and gives the level of the soil suitability as construction material. The unconfined compressive strength (UCS) of the soil ranges from 230.1 – 320.3 kN/m^2 (Table 3) indicating very stiff soil good as construction material (Das, 2009). The soil very stiff consistency indicates resistance to volume change of the soil under load, capable to withstand the embankment weight and protect the dam from erosion. This level of soil consistency would help the dam to impound water from River Agbara, slow down its flow rate and prevent flood especially during heavy downpour. The soil UCS range confirmed adequate strength of the soil to resist shear failure. This compressive geotechnical behaviour of the soil would also guide the site performance for sustainable dam construction.

Triaxial soil strength

The triaxial compression test is a form of shear strength test, more adaptable and finds applications to a wide range of soil types to suit different engineering problems than the unconfined compression test. In the triaxial compression test, the stress conditions at failure of compacted soil on increased axial stress are evaluated by Mohr circles (Fig. 19) from which the cohesion and its corresponding resistance angle to shear failure are determined. The test assesses the soil resistance to shear failure on applied load which determines its shear strength depending on the angle of shearing resistance (ϕ) of the soil. The test determines the soil cohesion (c) and angle of shearing resistance (ϕ) of soil. The soil cohesion and angle of friction of the proposed dam site range from 64.3 – 81.5 kN/m^2 and 11.5 – 17.4°, respectively (see Table 3), with a typical triaxial curve displayed in Figure 19. The soil cohesion signifies moderate shearing strength with the angle of friction showing the soil resistance to shear failure on dam construction. The varying angle of friction is attributed to different composition of the soil with different grain sizes. The shear strength properties of the soil of the proposed dam site will provide ample bond between the dam foundation and abutment to avert washouts and piping.

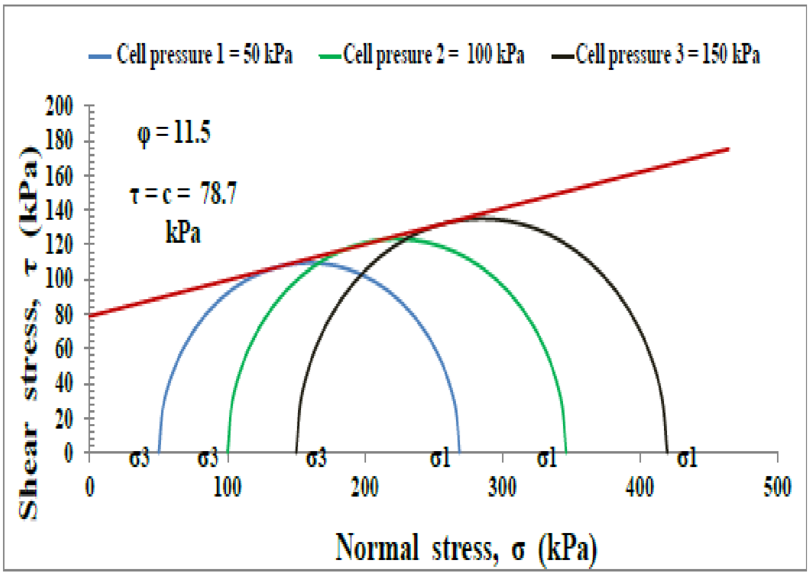

Figure 19: Mohr circles of stress of soil of Location 4 (L4) of the proposed dam site.

Settlement and permeability characteristics of the soil

The soil response to imposed load determines its displacement with respect to space and time. It estimates the settlement rate when the soil is subjected to pressures. The higher the soil dry density, the higher its load bearing capacity (structural strength) and the lower its water retention capacity and the greater its resistance to settlement. Proper and sufficient soil compaction on its OMC will experience low compression when subjected to load, which is a necessary requirement for a sustainable earth-fill dam. From the one-dimensional consolidation test carried out on the soil samples of the proposed dam site, coefficient of volume compressibility (M_v) specifies the volume change characteristics of the soil and the coefficient of consolidation (C_v) evaluates the settlement rate of full scale structure. The M_v varies 0.04782 – 0.05211 kN/m^2 (Table 4) as acquired from the semi-log plot of void-ratio against pressure (Fig. 10) signifying that the soils possess no possible engineering threat (Ademila and Olayinka, 2020) hence, competent for the proposed dam construction. The C_v of the soils is in the range 0.00394 – 0.00398 m^2/yr (Table 4) with a distinctive pressure-void ratio curve shown in Figure 20. This range of C_v of the soils indicate that the soils will not settle instantaneously, which could be attributed to the mineralogical composition of the soil devoid of active and expansive clay minerals. The integrity and stability of the proposed dam foundation would be intact since there is no tendency of differential settlement in any part of the proposed dam and other proposed civil engineering structures at the site.

Table 4: Consolidation and permeability of the soils of the proposed dam site

Location	Consolidation		κ (cm/s)
	M_v (kN/m^2)	C_v (m^2/year)	
L1A	0.05211	0.00394	3.96×10^{-6}
L1B	0.05032	0.00396	4.32×10^{-6}
L2	0.04925	0.00397	1.64×10^{-5}
L3	0.04782	0.00398	1.86×10^{-5}
L4	0.05140	0.00395	4.72×10^{-6}
L5	0.05000	0.00396	6.23×10^{-6}
L6	0.05071	0.00396	2.40×10^{-5}
L7	0.05175	0.00395	5.67×10^{-6}
L8	0.04954	0.00397	6.86×10^{-6}

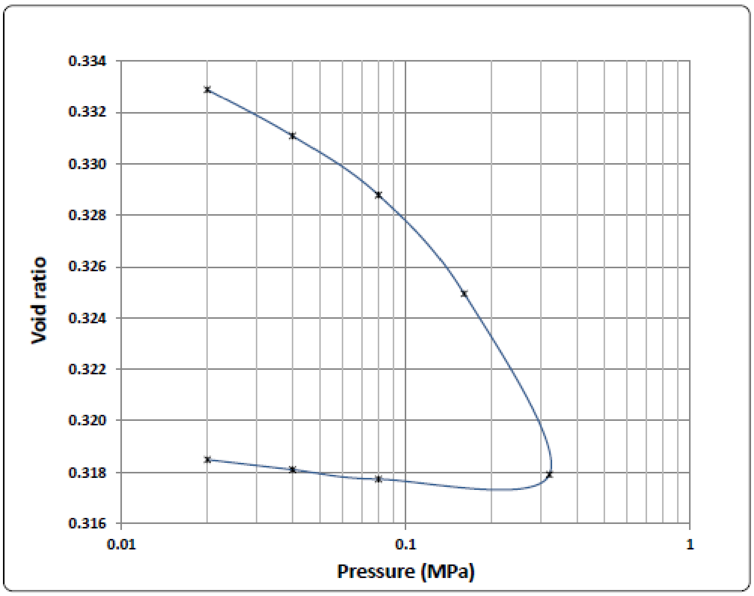

Figure 20: Distinctive pressure-voids ratio curve of the soil of Location 6 (L6) of the proposed dam site.

Soil permeability is an important engineering geological parameter that determines the ease at which water flow through soil and controls water flow through and around civil engineering structures (Ademila and Olayinka, 2020). Determination of soil permeability potential is important and it has a significant impact on structural foundation stability. It also has effects on clayey foundation consolidation under imposed load, water seepage in dam embankments, flow rate of water wells, pavement drainage, open cuts excavation in aquiferous unit and many others (Murthy, 2009; Ademila and Olayinka, 2020). The coefficient of permeability of the subsoil of the proposed dam site is within 3.96×10^{-6} - 2.40×10^{-5} cm/sec (Table 4), which is an indication of very low permeability of impervious/impermeable soil within the area. This range of coefficient of permeability of the soil indicate its water saturation relating to slowly nature of water draining through the soil in the area. The degree of the soil variability is conspicuous with the clayey soil being impervious and serve as suitable material for dam core necessary to protect the proposed dam from water seepage. Presence of fines (clay and silt) in the soils > 32% except in soils of Locations 1A and 1B (L1A and L1B) are impervious soils having very low permeability with very low transmitting potential due to their water retention capacity. This weakens the soils as observed from the soaked CBR resulting to significant strength reduction/lower load bearing capacity with excessive water influx, making it incompetent for civil engineering construction works. However, soils with these properties are suitable for dam siting because of their poor drainage characteristics. The impervious and poor drainage characteristics of the soils would prevent excessive water loss from the dam through seepage. Thus, the resistance of the soil to shear failure and its impervious nature to prevent excessive water loss through seepage make the soil suitable for construction of earth-fill or embankment dam.

Heavy mineral analysis of the river sediments

The analysis of sediments from River Agbara was carried out for environmental evaluation to determine the impact of heavy metals and their distribution in the area. Dams have impact on river hydro-sedimentary functioning system and sediment continuity which in-turn influences the dam safety, volume of exploitable water and flood risk. This study provides vital information on sustainable dam exploitation and sediments management. The result of the heavy mineral analysis of the river sediments is presented in Table 4. It was observed from the heavy mineral analysis that the river sediments are abundantly rich in opaque minerals compared to the non-opaque minerals (Table 5 and Figs. 21 - 25). The ZTR index minerals are wide spread in different rock types, river, stream and beach sediments due to their resistance to weathering and high specific gravity. They also serve as estimation scale for modification of heavy mineral suites. The ZTR mineral index is rated as: < 75% indicates mineralogical immature to sub-mature sediments and > 75% represents mineralogical matured sediments.

Table 5: Heavy mineral analysis of River Agbara sediments

Sample No.	Z	T	R	G	St	Ep	Ap	Sill	K	Op	Non-Op	ZTR index (%)
SP1	20	12	10	3	4	1	2	-	3	77	55	76.36
SP2	15	3	5	-	5	3	1	1	2	61	35	65.71
SP3	11	4	5	-	2	1	2	-	1	66	26	76.92
SP4	17	5	2	1	2	-	1	2	1	59	31	77.45
SP5	8	6	4	2	3	1	2	1	2	52	29	62.06

Z = zircon, T = tourmaline, R = rutile, G = garnet, St = staurolite, Ep = epidote, Ap = apatite, Sill = sillimanite, K = kyanite, Op = opaque minerals, Non-Op = non-opaque minerals.

The classification of the heavy minerals into opaque (magnetite, haematites and limonite) and non-opaque minerals (zircon, rutile, tourmaline, staurolite, epidote, sillimanite, garnet and apatite) from petrographic study are displayed in the photomicrographs of the river sediments (Figs. 21 – 25). Occurrence of zircon, tourmaline, rutile, staurolite, epidote, sillimanite and garnet in the river sediments are attributed to mixed origin of acid igneous and high grade metamorphic rock source of the river sediments. The ZTR (zircon, tourmaline and rutile) index are quality index reflecting the mineralogical maturity of the river sediments. The ZTR index of the river sediments in the range 62.06 – 77.45% signifies mineralogically sub-mature to mature sediments of long transport history from the source of the river sediments. These results revealed that the origin of River Agbara sediments is from regional basement complex rocks. Zircon occurs as the most dominant non-opaque heavy minerals in the sediments. Zircon, tourmaline and rutile present in all the samples are evidence of ultrastable heavy minerals that resist persistent abrasion and withstand consistent reworkings (Aderogbin and Isibor, 2020). The identified heavy minerals in the sediments are rated as moderately stable to ultra-stable heavy mineral suites. Abundance of opaque heavy minerals in the sediments above the concentration of non-opaque heavy minerals signifies an oxygen-rich (oxic) condition of depositional environment of the sediments. Also, presence of more rutile and staurolite in all the samples compared to epidote, apatite and sillimanite suggest dynamo thermal metamorphic rock source of the sediments (Ojo and Olatunji, 2017).

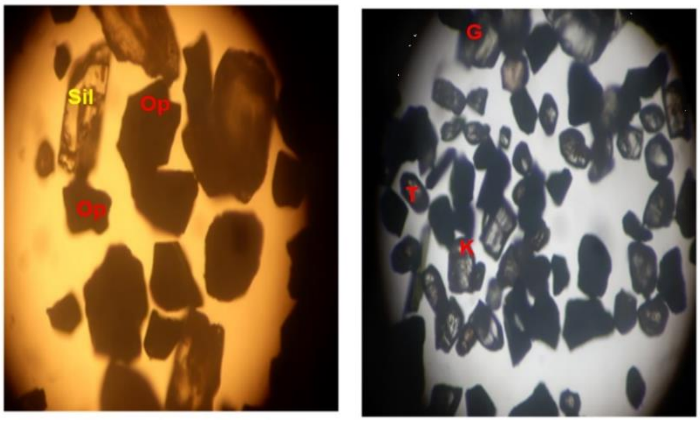

Figure 21: Photomicrograph of River Agbara sediment sample 1

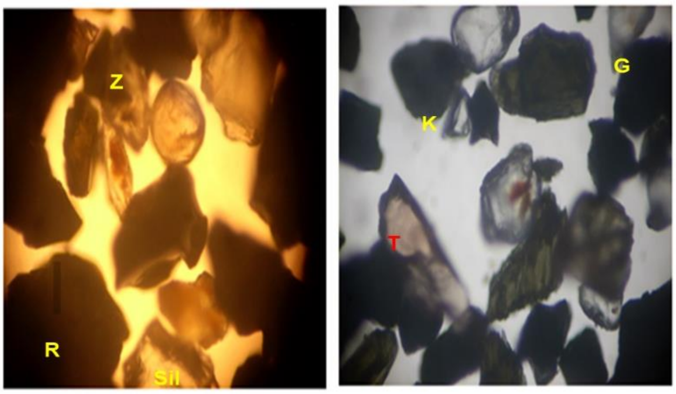

Figure 22: Photomicrograph of River Agbara sediment sample 2

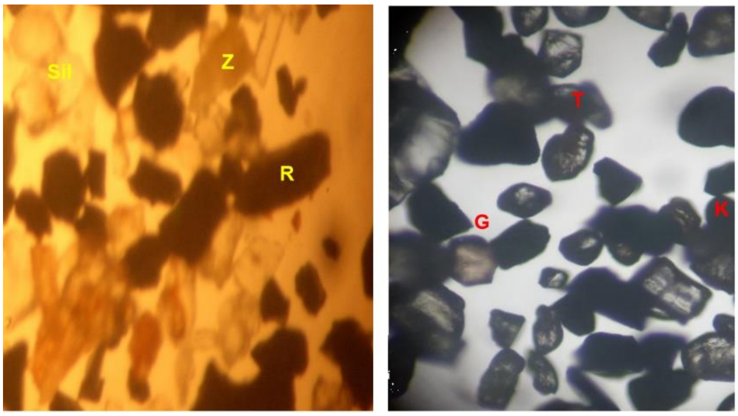

Figure 23: Photomicrograph of River Agbara sediment sample 3

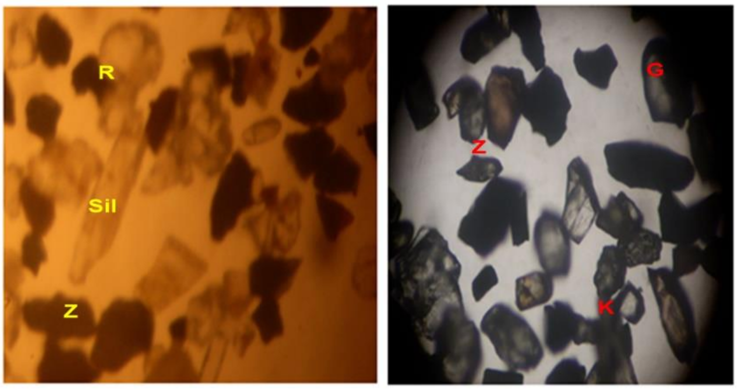

Figure 24: Photomicrograph of River Agbara sediment sample 4

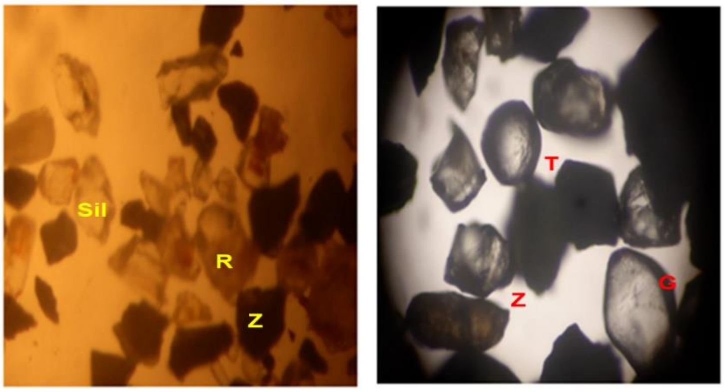

Figure 25: Photomicrograph of River Agbara sediment sample 5

CONCLUSION

Negative economic, environmental impacts and life threat of insufficient water in dry season and flood from excessive rainfall as a result of unavailable storage facility in the study area necessitated the study in the area for appropriate site selection for construction of well planned and designed dam in Afin Akoko across Agbara River to sustain water resource development, boost agricultural products, ensure food security and healthy environment. The variation of the topsoil resistivity (57 – 1339 Ωm) and its thickness (0.9 – 15.5 m) reflects the degree of soil compaction and influence of human activities in the area.

The low resistive portion of northwestern parts of the topsoil signify increased moisture content, incompetent for civil engineering construction works. Shallow structural dam foundation is not encouraged due to increased subsoil moisture content encountered in parts of the area to avert threat of dam failure.

Varying overburden thickness of the area is due to the fractured bedrock, topography, weathering and erosion. Basement depressions and saturated subsoil observed around northern and southern parts of the proposed Agbara River dam site is unsuitable for dam construction because of its water retention capacity, thus precipitating structural failure as a result of water interaction with the base of the structure. Northeastern and southwestern sides of the area are characterized by higher resistivity values with thin overburden cover, invariably relating to the proposed dam axis with bedrock ridges. Fresh basement of the area along the northeastern and southwestern parts are stable zones of competent bedrock for the proposed dam construction.

The soils of the area are semi-impervious to impervious, suitable for dam construction with low linear shrinkage. The soil is expected to be inactive, inexpansive, competent foundation material for dam embankment. High compacted density soil having higher maximum dry density (MDD) at low optimum moisture content (OMC) is suitable for quality dam foundation and expected embankment performance for optimum usage. Acquiring maximum load bearing strength for sustainable dam construction, the foundation soil must be compacted beyond 1956 kg/m^3 (MDD) and below 14.5% (OMC) to transmit the weight uniformly into the subsoil to prevent moisture influx into the dam foundation, avert future challenges and failure.

Low CBR soil values denote its relatively incompetent nature for civil engineering construction works. The soil stiff consistency indicates decrease in the volume change of the soil under load to withstand the embankment weight and protect the dam from erosion. The soil unconfined compressive strength **(**UCS) and cohesion with the angle of friction confirmed strength of the soil to resist shear failure. The coefficient of volume compressibility, M_v and coefficient of consolidation (C_v) of the soils signify that the soils possess no possible engineering threat, hence competent for the proposed dam construction. The integrity and stability of the proposed dam foundation would be intact since there is no tendency of differential settlement in the proposed dam site. The soil resistance to shear failure guarantees firm bond between the projected dam and subsoil foundation. Coefficient of permeability of the soil within 3.96×10^{-6} - 2.40×10^{-5} cm/sec signify impervious nature of the subsoil.

Heavy mineral analysis of sediments of Agbara River revealed that the sediments are mineralogically sub-mature to mature sediments from regional basement complex rocks. Zircon, tourmaline and rutile present in all the samples are ultrastable heavy minerals that resist persistent abrasion and withstand reworkings. Identified heavy minerals in the river sediments are moderately stable to ultra-stable heavy mineral suites. Abundance of opaque heavy minerals in the sediments above the concentration of non-opaque heavy minerals signify an oxygen-rich (oxic) condition of depositional environment of the sediments. Also, presence of more rutile and staurolite in all the samples compared to epidote, apatite and sillimanite suggest dynamo thermal metamorphic rock source of the sediments.

The dam foundation is recommended to be constructed on properly compacted soil across Agbara River with quality priority for compacted spillway to ensure integrity and stability of the dam. Thus, deep foundation design and construction is recommended for the projected dam for sustainability. At the upstream of the dam, rock lining is necessary for its protection from erosion.

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