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Geotechnical Characterization and Foundation Soil Assessment for a Proposed Earth Dam in Shendam, Central Nigeria

Daku, Sunday Sani[1], Inalegwu, Samuel Elaigwu[2], Diyelmak, Victor Bulus[1], Isah, Bunyaminu[1]

[1]Department of Geology, Faculty of Natural Sciences, University of Jos, Nigeria

[2]Ramah Earth Engineering Limited, Kaduna, Nigeria

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ABSTRACT

A comprehensive geotechnical investigation was conducted along the proposed earth dam axis at Ngod'togut, Shendam, Central Nigeria, to evaluate subsurface conditions and the suitability of the soils for the foundation. Four boreholes were drilled to depths ranging from 0 to 6.6 m, and Standard Penetration Tests (SPT) were performed at 1.5 m intervals. Laboratory testing conducted in accordance with BS 1377 (1990) included particle size distribution, Atterberg Limits, specific gravity, natural moisture content, permeability, shear strength, consolidation, and chemical analyses (pH and sulphate). The subsurface profile consists predominantly of sand, silty sand, laterite, and weathered shale. Permeability values of the foundation soil range from 1.88×10^{-6} to 5.10×10^{-6} cm/s, indicating moderate drainage characteristics. Preliminary bearing capacity estimates range from 20 to 1000 kN/m² depending on depth and lithology. The coefficient of consolidation (Cv) ranges from 1.68×10^{-6} to 4.55×10^{-6} m^2/yr, while the coefficient of compressibility (Mv) has a constant value of 3.11×10^{-4} m^2/KN. The bearing conditions are generally adequate at depth. However, seepage control and slope stability analyses are necessary for final design validation. Recommendations include excavation of a cut-off trench to weathered shale, improvement of core material permeability, and detailed seepage and stability modeling.

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Corresponding author. E-mail address: dakus@unijos.edu.ng (Daku S., S *et al*...)

INTRODUCTION

Dams are critical hydraulic structures constructed to impound water for various purposes, including irrigation, water supply, and flood control (Greager & Hinds, 2002; Madhloom *et al*., 2025). However, their performance is significantly compromised when excessive seepage occurs within the embankment or foundation materials (Salem, 2019). Consequently, the selection and evaluation of construction materials require comprehensive geotechnical investigations to determine their engineering suitability across different source locations. The interdependence of soil properties further underscores the need for an integrated assessment, as variations in one property may significantly influence others (Surendra & Sanjeev, 2017). In dam construction, the engineering behavior of foundation and embankment materials is largely governed by critical soil properties such as composition, grain-size distribution, plasticity characteristics, degree of compaction, permeability, and shear strength (Umar *et al.,* 2024; Iliyas *et al*., 2024; Umar *et al.,* 2023). These factors collectively determine how the soil will respond to loading, seepage forces, and environmental conditions over time.

Among the geotechnical parameters, shear strength is particularly important, as it governs the stability of earth structures, including embankments and foundations, and is essential in analyses involving bearing capacity, slope stability, and earth pressure (Karsten *et al*., 2006). Specific gravity is another key parameter that provides insight into soil suitability, influences strength characteristics, and serves as a basis for deriving other indices such as void ratio, porosity, and degree of saturation (Prakash & Jain, 2002). In addition, Roy (2016) observed that an increase in specific gravity is often associated with higher California Bearing Ratio (CBR) values, indicating enhanced load-bearing capacity. These relationships underscore the importance of specific gravity in evaluating soil suitability for dam construction and other civil engineering applications.

Similarly, permeability plays a decisive role in the performance of earth dams, as it controls seepage, drainage behavior, pore-pressure dissipation, and settlement rates in compressible soils (Murthy, 2002). Excessive permeability in dam materials can lead to significant seepage losses and increase the risk of piping and internal erosion. Conversely, low-permeability materials are desirable for the core zones of earth dams, as they help minimize seepage and enhance structural integrity (Omofunmi et al*.*, 2017). According to Iliyas *et al*. (2024), soils with permeability greater than 10^{-8} m/s are often used as dam core materials to minimize seepage. Furthermore, the rate of settlement in compressible soils is closely related to permeability, which governs the rate of pore-water pressure dissipation (Zhang *et al.,* 2021). Soils with low permeability tend to consolidate slowly, leading to long-term settlement, while highly permeable soils may drain rapidly but increase the risk of seepage. The indirect relationship between permeability and shear strength further emphasizes the need for careful evaluation of this parameter in dam design.

Grain size distribution is widely used in soil classification and has practical applications in filter design and in evaluating permeability, capillarity, and frost susceptibility (Apparao & Rao, 1995; Raj, 2012). In addition, compaction significantly improves soil performance by increasing density, shear strength, and bearing capacity, while reducing void ratio, permeability, and settlement (Prakash & Jain, 2002). Properly compacted soils, therefore, enhance the overall stability and durability of earth dams (Murthy, 2002).

Previous studies have demonstrated that no single borrow source may satisfy all geotechnical requirements for dam construction without improvement. For instance, Ogedengbe and Oke (2010) reported that soils along the Ogun River in Iseyin exhibited varying degrees of suitability and recommended stabilization measures such as lime or cement treatment. Similarly, Ibrahim *et al.* (2020) found that lateritic soils in Minna generally met the requirements for embankment construction, despite variations in gradation and hydraulic conductivity. In contrast, Umaru *et al*. (2018) linked many earth dam failures in northeastern Nigeria to poor gradation, low plasticity, inadequate compaction, and high permeability, emphasizing the importance of rigorous soil testing and appropriate ground improvement techniques. Existing studies have largely focused on embankment materials, with limited integration of foundation stratigraphy, bearing capacity, consolidation characteristics, seepage potential, and the engineering suitability of both foundation and borrow materials within a single framework in a sedimentary terrain of the Middle Benue Trough where there has been difficulty in assessing groundwater in some locations due to the impermeability of the subsurface shaly layers. This study therefore fills an important gap by evaluating these parameters collectively and assessing their implications for earth dam performance in Shendam, Central Nigeria. These were achieved through the following objectives: (i) determine the subsurface stratigraphy and groundwater conditions; (ii) evaluate the engineering properties of the foundation soils; (iii) assess the suitability of borrow materials for core and embankment construction; and (iv) provide preliminary recommendations for foundation design.

Site Description and Geological Setting

The study area is located within a gently undulating terrain that slopes toward a river channel. The surface soil consists primarily of sandy and lateritic materials underlain by weathered shale. Regional geology is dominated by sedimentary formations characterized by intercalations of sandstone, shale, and limestone units typical of the Middle Benue Trough. The joints on the outcrops appear as fractures with no observable displacement, predominantly oriented in NE–SW, NNE–SSW, NNW–SSE, and NW–SE directions. These joints occur within sandstone beds, whereas the indurated limestone exhibits a dense, closely spaced fracture network trending mainly NE–SW. The dominant NE–SW and NW–SE orientations are associated with fracture systems formed during the Pan-African orogeny, which predate the development of the Benue Trough and represent key elements of the tectonic framework of the Nigerian Basement Complex (Kogbe *et al.,* 1983; Ananaba, 1983; Oluyide, 1988). The map of the study area and the geological maps are presented in Figures 1 and 2.

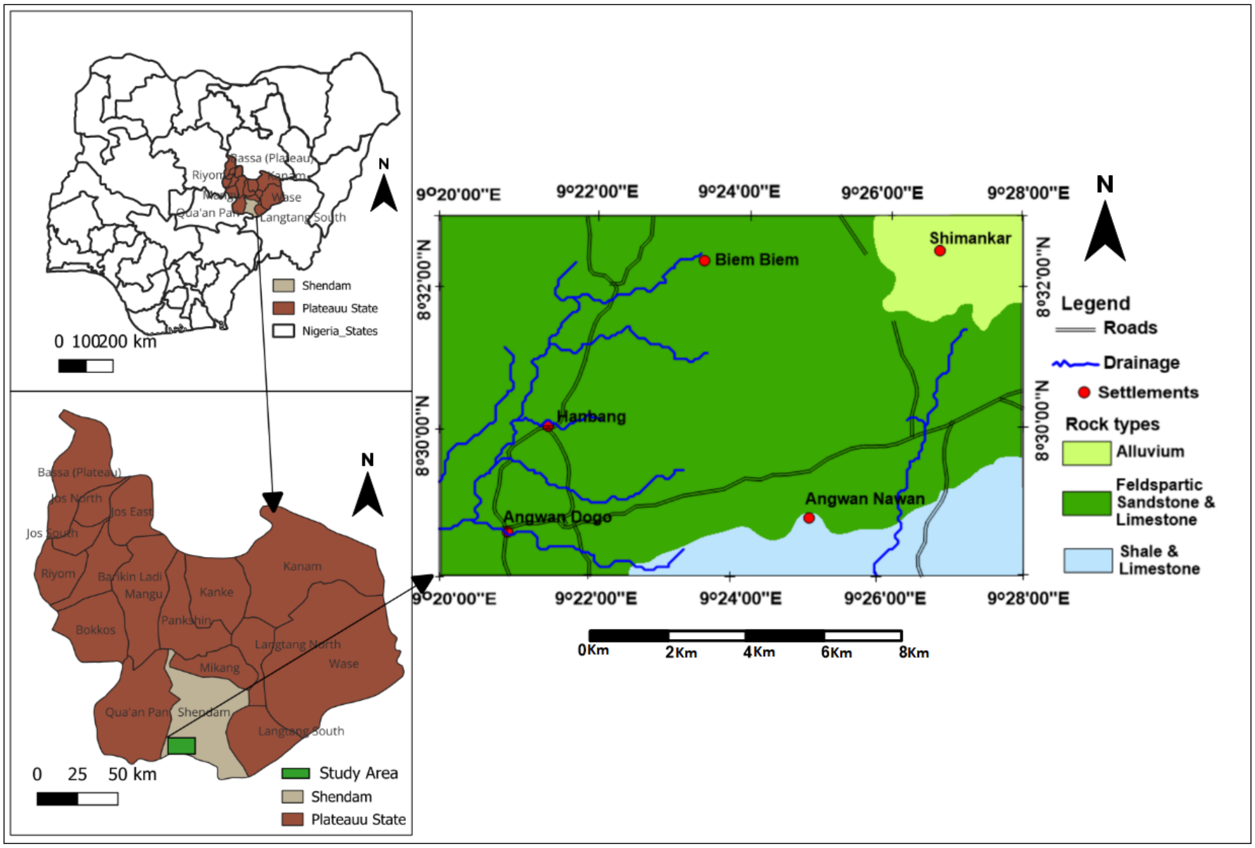

Figure 1: Regional Geologic Map of the Study Area.

MATERIALS AND METHODS

Field Investigation

Standard Penetration Test (SPT) was conducted in accordance with the British Standards Institution BS 1377 (1990). Four boreholes were first drilled to depths of 0-6.6 m or to refusal using the percussion drilling method, and the bases of the boreholes were carefully cleaned to remove loose and disturbed materials. A standard split-spoon sampler of 50mm external diameter was then attached to drill rods and lowered to the bottom of the boreholes.

The sampler was driven into the soil by repeatedly dropping a 65 kg hammer from a height of 760 mm onto the anvil. The sampler was driven to a total penetration of 450 mm, and the number of hammer blows required for each 150mm increment was recorded. The SPT N-value was taken as the sum of the blows required to drive the second and third 150 mm increments (i.e., the last 300 mm of penetration). After driving, the sampler was withdrawn, and the disturbed soil sample was recovered for identification and laboratory testing. The test was typically carried out at depth intervals of 1.0–1.5 m or at any noticeable change in soil strata. The set-up of the SPT is presented in Plate 1.

Plate 1: (a)Process of Standard Penetration Test and (b)Recovered spoon sample at the site

Laboratory Testing

Two trial pits were dug (Plate 2) to a depth of 1.5m to sample disturbed and undisturbed samples for the laboratory determination of particle size distribution, natural moisture content, consistency limits, direct shear strength, permeability, specific gravity, pH, and sulphate concentration. These procedures were carried out in accordance with the British Standards Institution BS 1377 (1990)

Plate 2: Trial pits for sampling of disturbed and undisturbed samples.

Particle Size Distribution

A 250g soil sample obtained from the field was soaked in water for 24 hours and thoroughly washed to remove fines. The washed sample was then oven-dried at 100–105°C for 24 hours and subsequently weighed to determine the percentage of silt and clay (fines). The dried soil was sieved using a mechanical sieve shaker fitted with British Standard sieves (Nos. 10, 14, 18, 25, 36, 52, 72, 100, 150, and 200), after which the mass of soil retained on each sieve was measured and expressed as a percentage of the original sample mass.

Natural Moisture Content

The moisture content determination procedure involves obtaining a representative (preferably undisturbed) soil sample and weighing three empty, labeled moisture cans with their lids. About 45 g of thoroughly mixed soil was placed into each can and weighed while wet. The samples were then oven-dried at a controlled temperature of 105–115°C for 24 hours with lids removed. After drying, the cans were covered, cooled in a desiccator, and reweighed to determine the dry mass of the soil for moisture content calculation using equations 1, 2, and 3.

Weight of moisture = (Weight of can + wet soil) – (Weight of can + Dried soil) (1)

Weight of dry soil = (Weight of can + dried soil) – Weight of empty can (2)

$$\text{Moisture content} = \frac{weight\ of\ moisture}{weight\ of\ dried\ soil} X100 \quad (3)$$

Consistency Limits

For the determination of the liquid limit, about 100 g of soil passing the No. 200 (0.075 mm) sieve was thoroughly mixed with 15–20ml of distilled water, with additional water added incrementally until a uniform paste was obtained. A portion of the paste was placed in the cup of the liquid limit apparatus, leveled to a maximum depth of 12.5 mm, and divided using the standard grooving tool. The cup was then repeatedly raised and dropped at a rate of two revolutions per second until the two sides of the groove came into contact over approximately 12 mm. The corresponding number of blows was recorded.

A representative sample of the paste was taken for water content determination by oven-drying at 100–105°C until a constant mass was reached. This procedure was repeated at varying moisture contents to obtain at least four readings within the range of 10 to 40 blows. A graph of water content versus number of blows was plotted, and the liquid limit was determined as the moisture content corresponding to 25 blows.

For determining the plastic limit, approximately 20 g of the soil paste previously prepared for the liquid limit test was kneaded for about 10 minutes to form a uniform ball. The soil was then rolled on a glass plate by hand until a thread of about 3 mm diameter was formed. When slight surface cracks appeared, the soil was divided into two equal portions, and each portion was alternately rolled between the fingers and the glass plate under steady pressure until the thread crumbled at approximately 3 mm in diameter. The crumbled pieces were collected, oven-dried at 100–105°C to constant mass for water content determination, and the average moisture content of the crumbled samples was taken as the plastic limit.

The plasticity index was calculated as the difference between the liquid and plastic limits.

Direct Shear

For the direct shear test, a soil specimen was carefully trimmed to fit the shear box dimensions (60 mm × 60 mm × 25 mm) and placed in the split shear box between properly positioned porous plates. The mould containing the specimen was weighed and assembled within the loading frame, after which the apparatus was aligned and the dial gauge set to zero.

A normal load of 10 kg was applied, and a horizontal shear load was gradually introduced at a constant rate by turning the crank until peak shear resistance was observed, as indicated by the dial gauge reading. The corresponding shear load at failure was recorded. The specimen was then removed after unloading, and the procedure was repeated for two additional specimens under normal loads of 20 kg and 30 kg. The normal stress for each specimen was subsequently calculated from the applied load and cross-sectional area of the rings, as shown in equations 4 and 5.

The normal stress of each specimen was calculated as follows:

$$Normal\ stress = \frac{Normal\ Load \times g \times 10^{-3}}{Cross\text{–}sectional\ Area\ of\ the\ ring} \quad (4)$$

Shear stress for each test was calculated as follows.

Deviator stress =

$$\frac{Load\ at\ failure\ X\ Proving\ ring\ caliberation\ factor}{Cross-sectional\ Area\ of\ specimen} \quad (5)$$

Falling Head Permeability Test

The soil sample was compacted into a permeability mould measuring 100 mm in diameter and 127 mm in height, placed on the base plate, and secured with a circular base plate and a sieve positioned above the specimen. The assembly was tightened to hold the sample firmly in place, and the cover plate was connected to a standpipe through which distilled water was introduced. The sample was allowed to saturate until water discharged steadily from the outlet pipe. Two reference head levels, H_1 and H_2, were marked on the standpipe, and the initial time was set to zero. Water was raised to the H_1 level and allowed to flow through the specimen to the H_2 level. The time taken for the water head to fall from H_1 to H_2 was recorded, along with the corresponding head levels and time readings. The coefficient of permeability (K) was then calculated using the appropriate falling-head permeability equation, as presented in Equation 6.

$$K = \frac{2.3al}{A\,(T2-T1)} \times Log\ H1/H2 \quad (6)$$

Where a = cross-sectional area of the standpipe

l = length of the soil specimen

A = Cross-sectional area of the permeability mould

T_1 = Initial time of water at initial height H_1

T_2 = Final time of water at final height H_2

Specific Gravity

The soil sample was first obtained and dried to ensure it was completely dry. All apparatus were inspected to confirm proper working conditions. The empty 50ml density bottle was weighed (M_1). About 50g of the dried soil was then introduced into the bottle, capped, and weighed (M_2). Distilled water was added halfway using an aspirator, and the mixture was shaken to remove entrapped air. The bottle was then filled to the brim with distilled water, capped, wiped dry externally, and weighed (M_3). The bottle was emptied, washed, and filled with distilled water only, wiped dry, and weighed again (M_4). The procedure was repeated twice with fresh samples, and all recorded measurements were used to compute the soil's specific gravity, as shown in equation 7

$$\text{The specific gravity (Gs)} = \frac{M2-M1}{(M4-M1)-(M3-M2)} \quad (7)$$

Chemical Analysis (pH and sulphate)

Soil pH and sulphate content of the soil were determined as follows:

Soil pH was determined by preparing a 1:2.5 soil–water suspension, calibrating the pH meter with standard buffer solutions, and inserting the electrode into the mixture to obtain a direct pH reading, which is reported as the soil pH.

Sulphate content was determined by mixing the soil with distilled water, filtering the solution, adding barium chloride to develop turbidity, and measuring the sulphate concentration using a spectrophotometer. The concentration obtained from the calibration curve is then converted to mg/kg of soil using equation 8**:**

$$SO_4\ (mg/kg) = \frac{C\ X\ V}{W} \quad (8)$$

Where C is the sulphate concentration in the extract (mg/L), V is the volume of extract (L), and W is the weight of soil (kg).

Consolidation Test

An undisturbed soil sample was first obtained and trimmed to fit the consolidation ring (50 mm diameter, 19 mm height). The specimen was placed in the consolidation cell between porous stones, properly secured, and submerged in distilled water to achieve saturation.

A load was applied incrementally using the loading frame, and dial gauge readings were recorded over time to monitor settlement. When deformation was stabilized under a given load, the load was increased. This process was continued until sufficient data were obtained.

After testing, the load was removed, and the specimen's moisture content and specific gravity were determined. The recorded data were then used to calculate changes in thickness and specimen dimensions.

Finally, a graph of dial reading versus the square root of time was plotted to determine consolidation characteristics, including t_{90} (time for 90% consolidation), using tangent methods.

RESULTS AND DISCUSSION

Subsurface Stratigraphy and Groundwater Conditions.

The subsurface stratigraphy, as interpreted from the standard penetration test logs executed at the study area, indicates a laterally continuous and relatively uniform lithological sequence with comparable geotechnical and strength characteristics. The soil and/or rock units encountered display consistent material properties from the ground surface to the terminal depths of the boreholes. Accordingly, a generalized stratigraphic profile representative of the subsurface conditions at the study area is presented in Figure 3. The foundation soils exhibit variable strength characteristics, with shallow sandy layers presenting lower bearing resistance and deeper weathered shale providing competent support. The bearing capacity from the N-values of the standard penetration test ranges from 20 to 1000 kN/m^2. Although preliminary ultimate bearing capacity values are adequate, earth dam performance is governed more critically by seepage control and slope stability than by ultimate bearing capacity alone (Fell et al., 2015). However, these values are important because they provide critical insight into the ability of the subsurface materials to carry an imposed load.

The subsurface conditions indicate a laterally continuous and uniform aquifer system. Groundwater is primarily hosted in shallow sandy layers, which are permeable and allow active flow and seasonal recharge. The underlying weathered shale acts as a semi-confining layer, restricting downward seepage.

Overall, the site exhibits moderate to high seepage potential, particularly in the sandy zones, while deeper shaly layers provide some natural control. Groundwater conditions are therefore favorable for storage and movement, but seepage control measures such as cutoff trenches, grout curtains, or impermeable cores may be necessary for safe earth dam performance.

Engineering and Index Properties of Foundation Soils

Table 1 presents key geotechnical parameters for four boreholes (BH1–BH4) drilled to assess the site's suitability for earth dam construction. Interpreting these values together gives a clear picture of the soil behavior and strength characteristics**.** The Cohesion (C) ranges from 5–8 kN/m² while the angle of internal friction (ϕ) ranges between 14°–21°. These values indicate slightly cohesive soils (mostly sandy to silty materials) with low to moderate shear strength (Umaru *et al*, 2018). Low cohesion reduces resistance to slope failure, especially when the soil is saturated. However, a moderate friction angle of 21° in BH4 provides some stability, but overall, the slopes must be designed flatter to ensure stability.

Ultimate bearing capacities were estimated in situ from standard penetration test (SPT) N values, and the allowable bearing capacity was calculated using a factor of safety of 2.5. The results are presented in Tables 2 and 3. These values show that the ultimate and allowable pressures increase with depth. The coefficient of consolidation (Cv) ranges from 1.68x10^{-6} to 4.55x10-6 m2/yr, while the coefficient of compressibility (Mv) has a constant value of 3.11x10^{-4} m^2/KN throughout BH1-BH4. The low coefficient of consolidation, along with the uniform coefficient of compressibility, suggests a slow consolidation rate. This implies that the design of the dam must take into consideration issues relating to settlement and proper compaction of the materials. This is because gradual settlement over time is envisaged, but not rapid failure. The permeability of the foundation soils ranged from 1.88×10^{-6} to 5.10×10^{-6} cm/s. These values indicate that the soils have moderate permeability (Ibrahim et al., 2020). BH2 has the highest permeability, 5.10×10−6 cm/s, which may serve as a potential seepage path leading to internal erosion (piping) and loss of reservoir water. The natural moisture content (NMC) of the soils falls between 9.75% and 12.47%, signifying low moisture content, unsaturated to slightly moist soils that require moisture conditioning to reach optimum moisture content during compaction. This will increase soil density and decrease its permeability (Murthy, 2002).

The non-plastic nature of the soil indicates that it is sand- and silt-dominated, with poor water retention, low cohesion, and high permeability. This property, however, makes it not suitable for use as an impervious core unless otherwise stabilized (Ogedengbe & Oke, 2010). The specific gravity and bulk density ranges of the soils are respectively 2.47 – 2.54 and 17.05– 17.34 kN/m³. These values represent soils that are compact, quartz-rich but not dense, whose strength will need to be improved to reduce permeability. The particle size distribution of the soils, as shown in Figure 4, indicates that they are poorly graded. These soils can present several challenges, including high permeability, which increases seepage and the risk of piping or internal erosion, potentially leading to dam failure. Owing to poor particle interlocking, they may also exhibit low shear strength, thereby reducing slope stability. Additionally, they are difficult to compact effectively, leading to lower density and diminished durability.

Based on the engineering and index properties of the subsurface soils, they are adequate for use in the shell of a zoned earth dam, provided that proper seepage control, compaction, and slope stabilization measures are implemented.

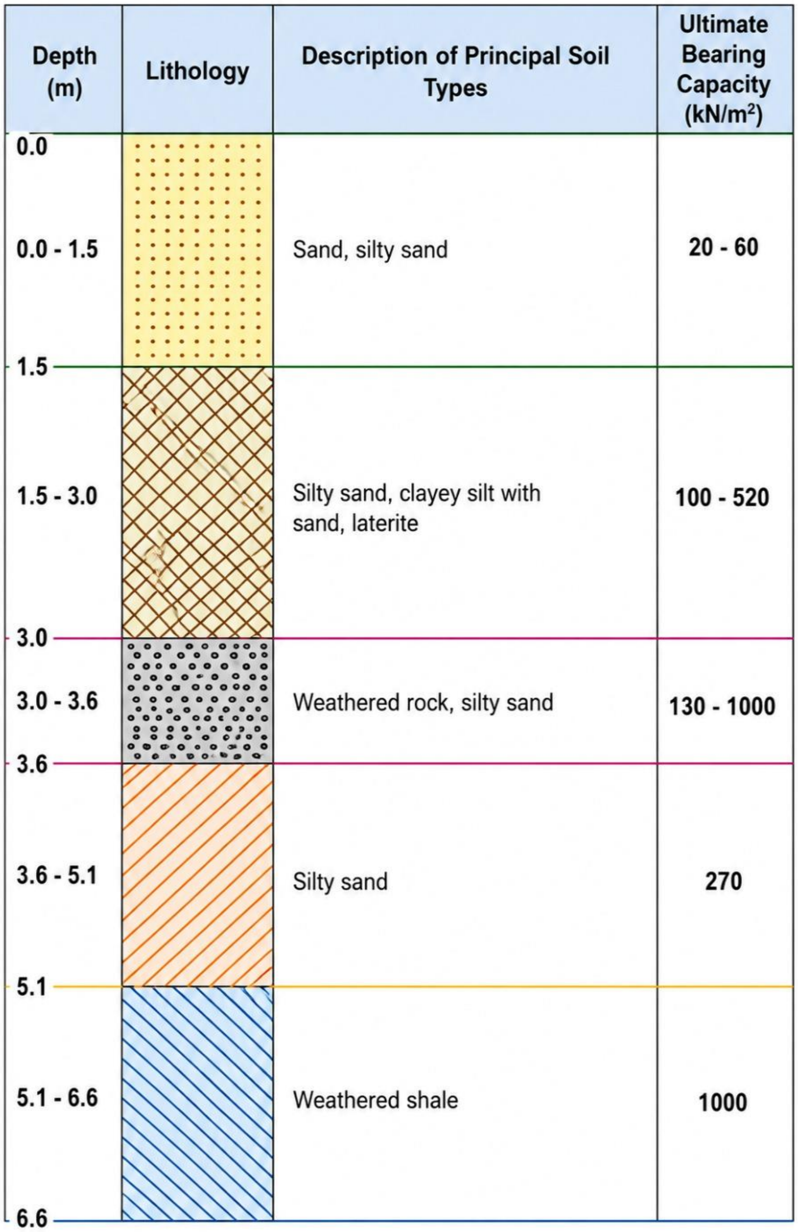

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Figure 3: Generalized Stratigraphy and Ultimate Bearing Capacity of foundation soils of the study area

Table 1: Summary of Engineering and index properties of foundation Soils in the study area

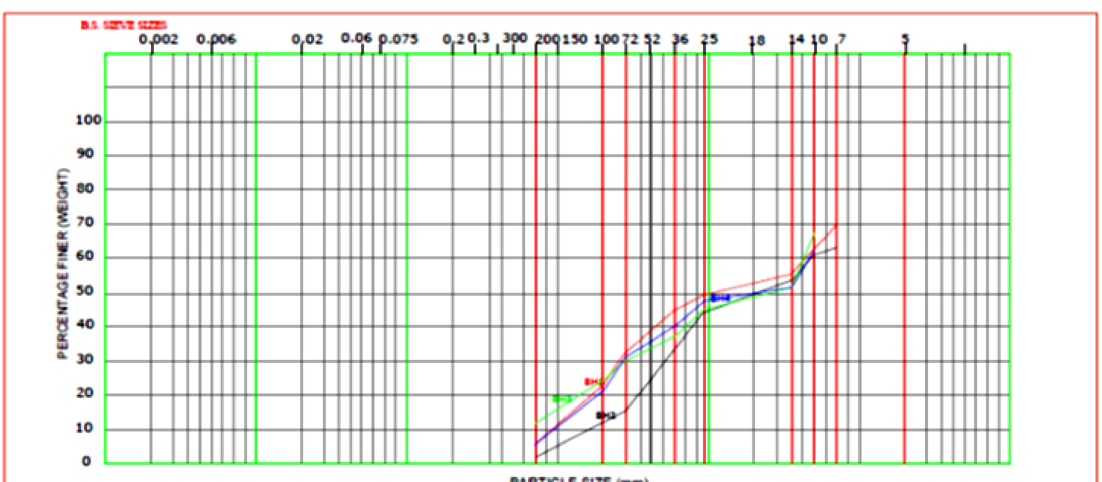
SAMPLE ID	DIRECT SHEAR		CONSOLIDATION		PERMEABILITY	NMC (%)	CONSISTENCY LIMIT	SPECIFIC GRAVITY	BULK DENSITY
	C(KN/m^2)	Φ	Cv (m^2/yr)	Mv (m^2/KN)					
BH 1	5	14	2.16X10^{-6}	3.11X10^{-4}	2.42X10^{-6}	11.5	NON-PLASTIC	2.48	17.05
BH 2	8	17	4.55X10^{-6}	3.11X10^{-4}	5.10X10^{-6}	10.8	NON-PLASTIC	2.51	17.18
BH 3	5	18	1.68X10^{-6}	3.11X10^{-4}	1.88X10^{-6}	12.47	NON-PLASTIC	2.54	17.34
BH 4	6	21	2.07X10^{-6}	3.11X10^{-4}	2.32X10^{-6}	9.75	NON-PLASTIC	2.47	17.09

Table 2: Ultimate Bearing Pressure (kN/m^2) of the subsurface soils

Depth (m)	BH1	BH2	BH3	BH4
0.0 - 0.6	40	60	20	30
0.6 - 2.1	80	100	220	520
2.1 - 3.6	1000	1000	130	1000
3.6- 5.1			270	
5.1 - 6.6			1000	

Table 3: Allowable Bearing Pressure (kN/m^2) of the subsurface soils

Depth (m)	BH1	BH2	BH3	BH4
0.0 - 0.6	16	24	8	12
2.1 – 3.6	32	40	88	209
3.6 – 4.5	400	400	52	400
4.5- 5.1			108	
5.1 -6.6			400	



Specimen Identification	Field Description of sample	Sample Depth (m)		No. 5	No. 7	No. 10	No. 14	No. 18	No. 25	No. 36	No. 52	No. 72	No.100	No.150	No.200	
BH1	[illegible]	0.6		-	70.4	63.3	57.7		50.40	44.30		32.40	23.20		7.60	
BH2		0.6			74.3	62.6	54.9		43.90	33.80		24.80	14.30		4.30	
BH3		0.6				67.9	52.6		45.80	38.70		30.80	25.70		12.90	
BH4		0.6				64.8	54.3		48.30	40.40		32.40	22.80		7.80	

Figure 4: Particle size distribution curve for the soil samples

Evaluation of Borrow Materials for Core and Embankment Construction

Borrow materials are soils or rocks obtained from designated sources and used to construct different zones of a dam, particularly the impermeable core and the supporting embankment shells. Therefore, a thorough assessment involves determining key engineering and index properties such as grain-size distribution, Atterberg limits, compaction characteristics, permeability, and shear strength (Khana et al., 2023). For core materials, low permeability and adequate plasticity are essential to minimize seepage, while embankment materials require sufficient strength, stability, and compaction characteristics to withstand loading and environmental conditions.

The borrow pit was manually excavated near the proposed dam site to a depth of 1.5m. The materials encountered consist predominantly of reddish lateritic soil interbedded with sandy clay.

Laboratory results indicate a natural moisture content of 11.62%, suggesting a relatively dry condition that may require moisture conditioning to achieve optimum compaction. The soil exhibits a liquid limit of 30.8% and a plastic limit of 19.9%, yielding a plasticity index of 10.9%. These values classify the soil as having low to medium plasticity. This range of plasticity is generally associated with moderate cohesion, good workability, and limited shrink-swell potential, making the material suitable for embankment construction, though less ideal for highly impervious core zones (Loupasakis *et al*, 2009).

The coefficient of permeability of 1.27×10^{-6} cm/s indicates low permeability and fair drainage characteristics, suggesting moderate resistance to seepage. However, this value is slightly higher than what is typically required for impervious core materials, which may necessitate additional treatment or compaction control.

Shear strength parameters show a cohesion of 12 kN/m² and an angle of internal friction of 29°. These values indicate moderate strength, adequate for slope stability in earth dam embankments. Chemically, the soil exhibits sulphate concentrations ranging from 288.55 to 306.85 mg/kg and pH values between 6.69 and 6.82, indicating a near-neutral environment with sulphate levels well below harmful limits. This suggests minimal risk of chemical deterioration from sulphate attack on associated structures, in line with the specifications of the Federal Ministry of Works and Housing (1997). Overall, the combined plasticity and permeability characteristics, together with the favorable shear strength, chemical composition, and moisture conditions, indicate that the borrow material is suitable for use in earth-dam embankments and transition zones. The material generally satisfies the requirements of the International Commission on Large Dams (ICOLD), the United States Bureau of Reclamation (USBR), and Nigerian dam design standards for plasticity, seepage control, and stability. Nevertheless, the final suitability assessment should also consider compaction characteristics, grain-size distribution, dispersivity, consolidation behavior, and long-term settlement performance. Therefore, while the material is considered suitable for general embankment construction, its application as a primary impervious core would benefit from enhanced compaction or blending with more plastic, lower-permeability soils to meet the more stringent seepage-control requirements associated with core zones of earth dams.

Statistical Evaluation of the Variability and Consistency of Geotechnical Properties and Their Implications on Foundation Soils

The statistical analysis of the geotechnical properties provides valuable insight into the spatial variability and engineering behavior of the foundation soils across the investigated boreholes. Cohesion (C) has a mean of 6.0 kN/m², a standard deviation of 1.41 kN/m², and a coefficient of variation (CV) of 23.57%, indicating moderate variability and relatively consistent shear strength characteristics throughout the site. The angle of internal friction (ϕ) records a mean value of 17.5°, a standard deviation of 2.89°, and a CV of 16.50%, suggesting a generally uniform frictional resistance within the foundation materials. According to Nawaz et al 2024, $C<5KN/m^2$, $5\leq C<1OKN/m^2$, $C\geq 10KN/m^2$ implies low, medium and high cohesion respectively while Das and Sohban, 2018 classified angle of internal friction (ϕ) of $\phi<10^0$, $10^0\leq \phi<15^0$, $15^0 \leq\phi<20^0$ and $\phi \geq 20^0$ as soils having low, medium, high and very high angle of internal friction respectively. Therefore, using the mean values of cohesion (C) and angle of internal friction (ϕ) implies that the soils possess both medium cohesion and an angle of internal friction and can be described as inorganic clays. Furthermore, the moderate consistency of these parameters therefore suggests that the soils possess reasonably predictable strength characteristics that are favorable for foundation support and slope stability assessments.

The hydraulic and consolidation properties exhibit a different trend. The coefficient of consolidation (Cv) has a mean value of 2.62×10^{-6} m²/yr and a standard deviation of 1.31×10^{-6} m²/yr, while permeability (k) shows a mean value of 2.93×10^{-6} cm/s and a standard deviation of 1.47×10^{-6} cm/s. Both parameters exhibit high coefficients of variation (approximately 50%), indicating considerable spatial heterogeneity in drainage and consolidation behavior across the site. Umar et al. (2024) noted that heterogeneity, especially in permeability, can pose a serious challenge to dam stability. Such variability is common in natural soils because differences in grain-size distribution, soil structure, and pore connectivity significantly influence seepage and settlement characteristics (Das and Sobhan, 2018). The coefficient of volume compressibility (Mv) is constant at 3.11×10^{-4} m²/kN, with no observable variation among the boreholes, suggesting relatively uniform compressibility characteristics within the tested strata. The relatively high variability of Cv and permeability highlights the need for detailed seepage analyses and appropriate drainage control measures in the design of the proposed earth dam.

The natural moisture content (NMC) has a mean of 11.13%, a standard deviation of 1.15%, and a CV of 10.30%, indicating relatively uniform moisture conditions across the study area. Similarly, specific gravity (Gs) has a mean of 2.50, a standard deviation of 0.03, and a CV of 1.26%. At the same time, bulk density records a mean value of 17.17 kN/m³, a standard deviation of 0.13 kN/m³, and a CV of 0.75%. The very low variability observed in these parameters demonstrates a high degree of uniformity in mineralogical composition, weathering characteristics, and compaction state of the foundation soils. Therefore, the low variability recorded for moisture content, specific gravity, and bulk density suggests that the foundation soils were derived from similar parent materials and have undergone comparable geological and weathering processes.

Overall, the statistical results indicate that the foundation soils possess relatively uniform physical and strength characteristics, as evidenced by the low to moderate coefficients of variation for cohesion, friction angle, moisture content, specific gravity, and bulk density. However, the substantial variability in permeability and consolidation parameters suggests localized differences in hydraulic behavior that may influence seepage rates and settlement patterns beneath the proposed earth dam. Consequently, careful consideration should be given to seepage control measures, foundation treatment, and long-term settlement monitoring during the design and construction phases to ensure the structure's safety and performance.

Recommendations

The suitability of the lateritic sandy clay for dam construction can be improved through proper moisture conditioning, compaction, and material modification. Adjusting the moisture content to near optimum and applying adequate compaction will increase density and reduce permeability, thereby enhancing strength and seepage resistance. Blending the soil with more clayey materials or introducing clay liners can further improve its impermeability, making it more suitable for core applications.

Where required, limited chemical stabilization using lime or cement may be adopted to enhance strength and durability. Additionally, incorporating seepage control features such as filters and drains will help prevent internal erosion and improve overall dam stability.

CONCLUSIONS

The integrated assessment of the subsurface conditions and borrow material properties indicates that the site is generally suitable for earth dam construction, provided that appropriate design and material improvement measures are implemented.

The foundation profile, consisting of sandy overburden underlain by weathered shale, suggests a relatively competent subgrade. The sandy layer may permit some seepage, but the underlying weathered shale is expected to provide adequate support and reduced permeability at depth. This is consistent with the observed bearing capacity, which is sufficient to sustain embankment loads without risk of shear failure.

However, the engineering performance of the borrow material presents a key design consideration. Although the lateritic sandy clay exhibits moderate strength and workability, its permeability is only marginally suitable for use as an impervious core. This implies that, without improvement, there is a potential risk of increased seepage through the dam body. Therefore, material enhancement such as improved compaction, blending with more clayey soils, or the introduction of an engineered core or liner is necessary to meet design standards.

Overall, the site conditions and available materials are adequate for dam construction. However, the success of the project will depend on careful design, particularly regarding seepage control, material improvement, and stability verification.

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