ZIBELINE INTERNATIONAL™ PUBLISHING

ISSN: 2521-0920 (Print)
ISSN: 2521-0602 (Online)
CODEN: MJGAAN

Malaysian Journal of Geosciences (MJG)

DOI: http://doi.org/10.26480/mjg.01.2024.17.25



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RESEARCH ARTICLE

GEOTECHNICAL INVESTIGATION FOR SUBSOIL HAZARD DURING EARTH FILL DAM CONSTRUCTION

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ARTICLE DETAILS

Article History:

Received 20 December 2023
Revised 18 January 2024
Accepted 26 February 2024
Available online 28 February 2024

ABSTRACT

The purpose of this investigation was to assess the suitability of the underlying soils for constructing an earth fill dam for irrigation purposes. Eight soil samples were collected from four trial pits and four borrow pits, and were subjected to physical, mechanical and strength performance tests which are natural moisture content, specific gravity, Atterberg limits, grain size analysis, compaction, consolidation, permeability, and triaxial shear strength. The liquid limit, plastic limit, and plasticity index (Atterberg limits) of the soil samples ranged from 33-46%, 22-32.5%, and 6.5-22.2%, respectively. The percentage of fines and coarse contents from the grain size analysis ranged from 7.1% to 52.4% and 44.4% to 91.4%, respectively. The maximum dry density (MDD) values of the soils ranged from 1630 to 2015 Kg/m^3, while the optimum moisture content ranged from 9.9% to 27%. The coefficient of permeability (K) ranged from 1.452× 10^{-6} to 2.196950× 10^{-3} cm/s. The coefficient of volume compressibility (Cv) and consolidation (Mv) ranged from 0.00020 to 0.88 mm/yr and 0.18 to 144 MPa^{-1}, respectively, and the angle of internal friction ranged from 24.30 to 35.40°. The results indicate that the underlying soils contain a significant amount of moisture due to climatic conditions. They are well-graded soils with low to intermediate plasticity. Clay minerals, specifically Kaolinite, are present and contribute to the low to medium swelling potential of the soils. The low hydraulic conductivity makes the soils suitable for the construction of an earth fill dam, and they exhibit good strength with low settlement potential for the engineering structure.

KEYWORDS

Earth fill Dam. Granular soils. Geotechnical Investigation. Permeability

1. INTRODUCTION

A dam is a civil engineering structure built for water storage, irrigation, hydropower electricity generation, and flood prevention. Dams have had a significant impact on human population growth and technological advancement. They have also contributed to economic development in many developing and rural communities (Okosun and Amadasu, 2016). Dams can vary in size and complexity, ranging from small and simple structures in small streams to large and complex structures in large rivers (Attalah 2002; Sissakian et al., 2017). The type and design of each dam depend on factors such as water availability, topography, geology, and the local materials available for construction (Leulalem et al., 2016). Dams are typically categorized as earth or concrete dams, depending on the materials used for construction. They can be used for water supply, irrigation, hydropower, and other purposes. Dam failure is a catastrophic type of failure characterized by the sudden, rapid, and uncontrolled release of impounded water into the environment (Water Supply Regulator, 2010). Such failures can have economic consequences and cause environmental destruction and loss of life (Talukdar and Dey, 2019). Populations living downstream of major dams are always at risk. Previous cases of dam construction have shown that many dams have had defects related to geological and geotechnical problems (Hiller et al., 2011; Al-Ansari et al., 2015). To mitigate or eliminate the threat of dam failure, geological and geotechnical investigations of dam sites are necessary to identify and address these problems (Oyekanmi and Mbossoh, 2018; Adwubi et al., 2012; Bayewu et al., 2012; Umoren et al., 2016; Diego et al., 2017; Timothy and Jennifer, 2017; Timothy et al., 2017). Novak stated that geological, hydrological, and geotechnical investigations of a dam site selected for detailed evaluation focus on determining geological structures, stratigraphy, faulting, foliation, and groundwater conditions at the dam foundation and reservoir area (Novak, 2009). This information helps reveal the characteristics of the underlying soils and groundwater conditions at the dam site. It can be deduced that foundational defects are primarily responsible for the failure and collapse of dam structures. The study area is considered suitable for the construction of an earth dam. The certainty and design of the dam therefore depend on the competence of the foundation materials. The investigation will involve a thorough assessment of the site's geological and geotechnical conditions, as well as the environmental impact of the soils underlying the Takete Ide Area.

Quick Response Code	Access this article online	
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Cite The Article: Olabode Olabanji Olofinyo, Olabode Oluwaseun Franklin, Fatoyinbo Imoleayo Oluwatoyin, Oluremi Success Odebod, Damilola Tope Ogundele (2024). Geotechnical Investigation for Subsoil Hazard furing Earth Fill Dam Construction. *Malaysian Journal of Geosciences, 8(1): 17-25.*

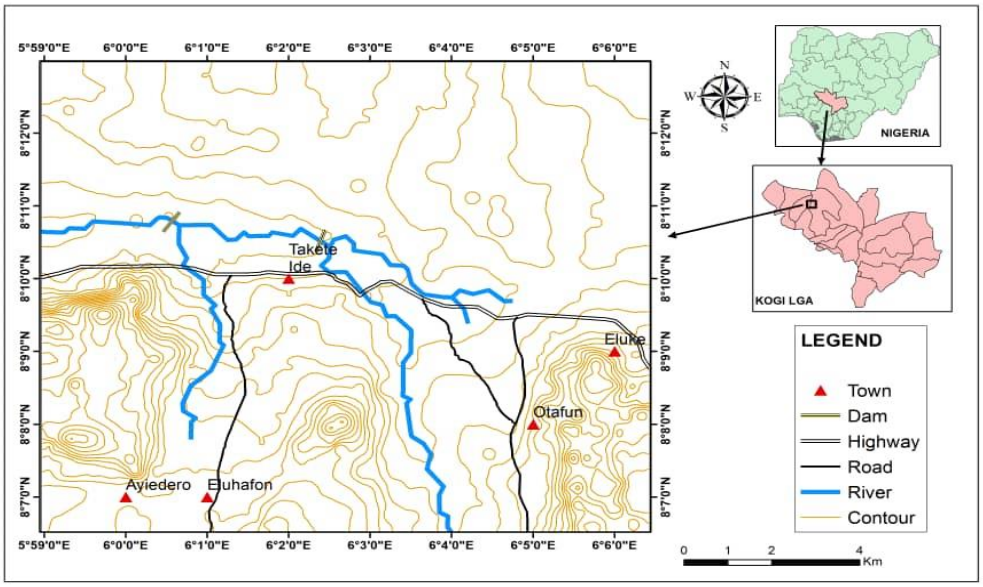
2. THE STUDY AREA

The study area is within Latitude 8°7'0"and 8°12'0" North of the Equator and Longitude 5°59'0"and 6°6'0" East of the Greenwich Meridian. The area formed part of Yagba East Local Government Area of Kogi State (Figure 1a). The State is composed of rocky and undulating landscape. The vegetation consists of rain forest in the western parts and wooded savannah and grasslands in other parts of the area. The notable trees are baobab, akeer-apple, shea-butter, obeche, iroko and mahogany. The two main seasons experienced in the area are the wet and dry seasons. The wet (rain) season starts by March and ends in October; while the dry season commences by November and lasts till February. November- February is also very cold due to harmattan wind (Asiwaju-Bello et al., 2013).

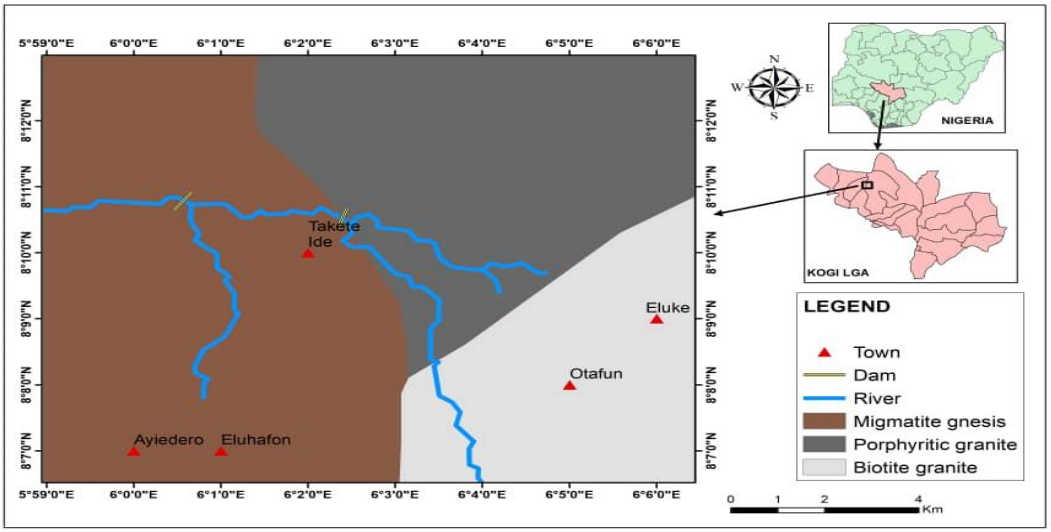
Variation in the climate and precipitation results in the fluctuations of groundwater levels. This is responsible for the physical and chemical weathering of the lithologic units, hence the formation of residual laterite soil in the area (Fatoyinbo et al., 2020). The southern part of the study area is characterized by elevated topography while the northern part of the study area is characterized by low lying terrain (Figure 1a). The drainage system of the area is typical of dendritic pattern. It flows from the elevated topographical area to the downstream area in a North-west direction (Figure 1a). The topography and river channel is expected to determine the suitable location of the dam site. The site (Dam Axis) is accessible through farm paths undulating with an uneven topography, with thick vegetations surrounding the Dam axis.

The area falls within the Nigerian Basement Complex as part of the Pan-African mobile belt that lies between the West African and Congo Cratons and South of the Tuareg Shield (16. Black and Girod, 1970) (Figure 1b). The complex has been severely affected by the Pan-African orogeny dated 600Ma which occupied the galvanized region (Dada 2006). This is as a result of convergent plate movement between the flaccid continental margin of the West African craton and the active Pharusian continental margin (Rahaman and Ocan, 1978; Rahaman, 1988; Rahaman and Malomo, 1978). The field observations and study of the lithologies indicates that the rocks belong to the Migmatite-Gneiss Complex of the Southwestern Basement Complex of Nigeria. The area is underlain predominantly by Migmatite, porphyritic Granite, medium to coarse Biotite Granite. The Migmatite Gneiss in the study area had undergone extensive migmatisation which may have nearly obscured and obliterated many of the earlier structures hence preventing comprehensive measurement and further interpretation of the structural evolution of the area (Obaje, 2009).

Migmatite is defined by alternation of mafic and quartzo-feldspathic materials with the latter occur mostly. The felsic component of the group, which is usually granitic varies in texture from aplitic, through granite to pegmatite. However, the extent or degree of tectonism is expressed in the occurrence and the magnitude of metamorphism and metamorphic structures of the area such as foliation, minor faults, joints and fractures (Ayodele, 2015). There is the presence of deformed minerals and tectonic brecciation of some of the crystals like tourmaline, feldspar and quartz in pegmatite which is a tectonic imprint in the area. Most of the rocks observed occurred as low-lying outcrops on stream channels with several discontinuities such as joints, fault zones and caves.



(a)



(b)

Figure 1: The study area : (a)Topographical map (NGSA, 2006), (b) geological map of the study area (NGSA, 2006)

3. Materials and Methodology

The methodology for this investigation involved several steps. First, a reconnaissance survey assessed the area's characteristics and determined suitable locations for detailed dam investigations. This included geological mapping to identify rock and soil types, as well as structural features. Soil samples were then collected from four trial pits and four borrow pits in the study area. Eight samples were collected, with each trial pit excavated to a depth of 1.0m. These soil samples were analyzed in the laboratory. The laboratory tests performed on the soil samples included soil classification tests such as moisture content, Atterberg limits, specific gravity, and particle size distribution. Additionally, soil strength tests such as standard proctor compaction tests, consolidation, permeability, and in situ density were conducted. All laboratory analyses were carried out in accordance with British Standards Institute 1377 and 5930 (1990)

4. Results and Discussion

4.1 Natural Moisture Content

The moisture content of the soils ranged from 14.0% to 19.4% (Table 1). Factors such as drainage conditions, rainfall patterns, and sampling depth contribute to the variation in moisture content (Daramola et al., 2018). High moisture content in the underlying soils can cause significant changes in the volume of clay minerals, leading to issues like shrinking and swelling in the dam foundation (Daramola et al., 2018; Olabode and Asiwaju-Bello, 2018). Comparing our results with the moisture content classification by Emesiobi, it is clear that the samples fall within the sand and gravel category (Emesiobi, 2000). This suggests that the soil samples beneath the proposed dam contain a substantial amount of moisture due to prevailing climatic conditions. Consequently, this can lead to high infiltration and low water storage in the reservoir, potentially accelerating erosion of the dam foundation and ultimately resulting in dam failure.

4.2 Specific Gravity

The specific gravity values for the studied soil samples ranged from 2.60 to 2.68 (Table 1). This indicate that the samples are laterite soils and has not deviated from those obtained for residual soils within the basement terrain (Jegede, 1998). The variation in the principal classes of soils ranges from coarse grained to clay soils, characteristic of laterite soils makes it of interest to dam construction (Oyelami and Van-Rooy, 2016). Earth fill dams are mostly composed of natural materials such as, clay, sand, gravel having the impervious materials, essentially clayey soils placed in the middle of the embankment body.

4.3 Atterberg limits

The behavior of soils under different moisture content can be assessed by analyzing the Atterberg limits. These limits provide information about the strength and settlement characteristics of soils. On the Casagrande plot, the liquid limit and plasticity index of four (4) samples are above the A-line. This indicates that these soils consist of inorganic clay materials. The remaining four (4) samples fall below the A-line, suggesting the presence of organic matter or inorganic silt materials (Figure 2a). The liquid limit, plastic limit, and plasticity index of the soil samples range from 33% to 46%, 22% to 32.5%, and 6.5% to 22.2%, respectively (Table 1). When compared to Bell's 2007 liquid limit specifications, the samples exhibit low to intermediate plasticity. This classifies them as clay or silt and makes them suitable for dam site construction due to their good strength and minimal settlement characteristics.

Upon examining the results, it was observed that an increase in the linear shrinkage of the soils corresponds to an increase in the plasticity index (Table 1). This finding aligns with Ruddock's work, which suggests that linear shrinkage provides an approximate indication of the soils' plasticity characteristics (Ruddock's, 1967). Additionally, the plasticity index serves as an indicator of the swelling potential of the soils, which is influenced by the clay types present in the mineralogy of the soils. The plasticity chart shows that the soil plots are closer to the A-line, suggesting the prevalence of kaolinitic clay. This clay mineral is non-swelling, meaning that the dam walls will not be prone to cracking due to heaving and swelling of the clays in the foundation materials (Umoren et al., 2016).

4.4 Grain size distribution and AASHTO classification

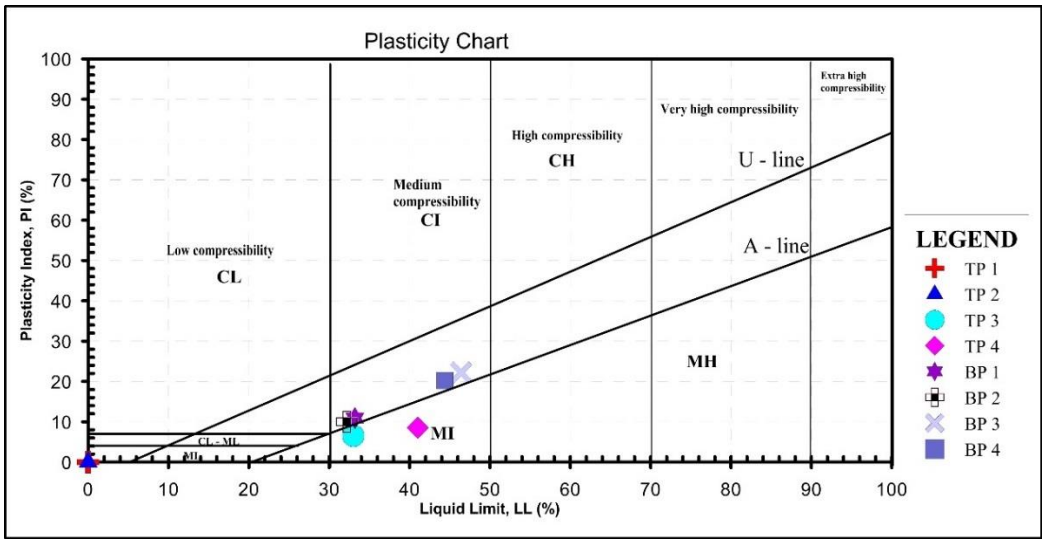
The disturbed samples underwent mechanical and hydrometer analyses. The results of the grain analysis show that the percentage of fines ranged from 7.1% to 52.4%, and the percentage of coarse content ranged from 44.4% to 91.4% (Table 1). Except for BP3, the percentage of fines in the obtained results is less than 50%. The amount of coarse content in all the samples is higher than 35%. This indicates that the soil samples consist of gravelly and sandy materials (Figure 2b). According to the Unified Soil Classification System (USCS), the soils are classified as inorganic clay-silt with low to intermediate plasticity. The quantity of fines (silt + clay) in the soils is found to be lower than the coarse fractions, indicating that the materials are suitable for construction. The nature of the curves shows that the samples are well-graded soils, except for TP 1 and 2, which consist of particles that will form a good framework for stress transfer (Olabode and Asiwaju-Bello, 2018: Oluwaniyi et al., 2020). These samples will be relatively stiff and strong because the fine particles fill the pores as binders between the larger particles.

According to the American Association of State Highways and Transportation Officials (AASHTO) standards of classification, five out of eight tested soil samples fall within the group of granular materials. This group is expected to have an average percentage of material passing the no. 200 sieve of more than 35%, a liquid limit of more than 40%, and a plasticity index greater than 11. Therefore, the soils are classified as A-3, A-2-4, A-2-6, and A-5. The remaining three samples fall within the group of clay-silty materials, characterized by an average percentage of material passing the no. 200 sieve of less than 35%. These soils are classified as A-7-6, signifying clayey soils with high compressibility and high-volume change (Umoren et al., 2016). The principal features that distinguish fine-grained soils from coarse-grained soils in the design of embankment dams are that fine-grained soils have lower permeability, shear strength, and higher compressibility (USBR, 2012).

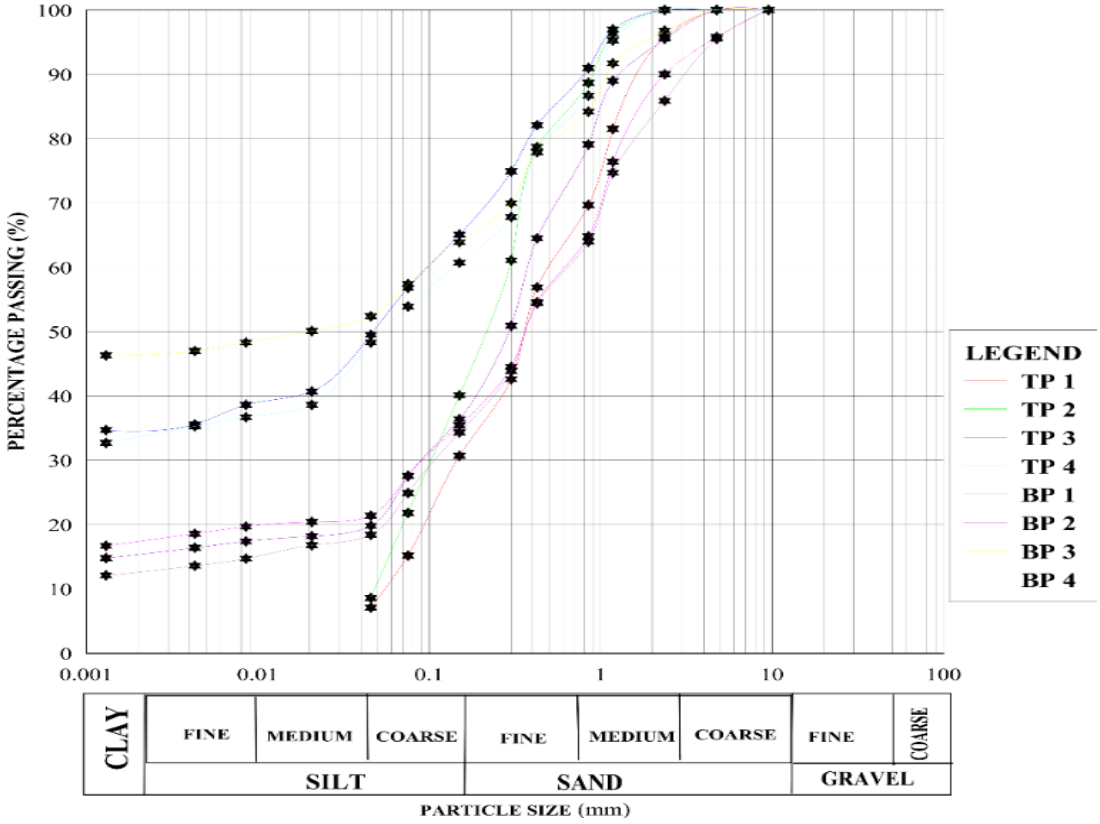
Fine-grained soils are typically used as water barriers in embankment dams, either in a homogeneous section or as the core in a zoned embankment (SBR, 2012). Coarse-grained soils are susceptible to surface erosion under wave action and surface runoff. Erodible materials can be protected by bedded riprap, soil cement, or other revetments on the upstream slope, and by coarse gravel, rock blankets, and shallow-rooting vegetation on downstream slopes (USSD, 2011). Coarse-grained soils can be found in the shells or transition zones of zoned embankments, as well as in filters and drains (USSD, 2011). Gravels and sandy gravels are sometimes used as the primary section of an embankment with an upstream facing of Portland cement concrete (USSD, 2011). The results of the grain distributions indicate that the soils are suitable for earth dam materials.

4.5 Clay minerals and activity

Clay is a finely textured material that is abundant and formed from the weathering products of Precambrian Basement rocks and low-temperature hydrothermal alteration products (Akinyemi et al., 2014). Clay minerals, which are part of the phyllosilicate family, are hydrated alumino-silicates that contain elements such as Mg, K, Ca, Na, Fe, and sometimes Ti, Mn, or Li (Lopez-Galindo et al., 2007). The formation of clay minerals depends on the physicochemical conditions of the weathering environment, the nature of the starting materials, and other external environmental factors, resulting in various types of clay materials (Fatoyinbo et al 2024). These types include Kaolinite, Illite, Montmorillonite, and Chlorite. Skempton introduced the concept of "activity" as a single parameter that combines atterberg limits and clay size content (Skempton, 1953). This parameter is defined as the ratio of the plasticity index to the percentage of the soil fraction finer than two microns. Skempton suggested three classes of clays based on their activity values: inactive clays with activity values less than 0.75, normal clays with activity values ranging between 0.75 and 1.25, and active clays with activity values greater than 1.25 (Table 1). The activity values in this study ranged from 0.12 to 1.25, classifying the clay in the soil as inactive to normal active clays. Therefore, the possible clay mineral that can exhibit such activity is referred to as Kaolinite (Figure 3a).



(a)



(b)

Figure 2: (a) plots of plasticity chart and (b) Grain size distribution of the soils

4.6 Swelling potential

The shrinkage values ranged from 10.7% to 15.1%, and the plasticity index ranged from 6.5% to 22.2% (Table 1). The swelling potential is determined by the relationship between the shrinkage limit and plasticity index. It depends on the susceptibility of the clay minerals to water supply and the increase in thickness of the diffuse ion layer due to the exchange of cations and anions (Umoren et al., 2016). The negative structural layers in clay minerals attract water molecules into the interlayer area, causing expansion and swelling. Factors such as soil mineralogy, suction, water conditions, geometry, and structure stiffness largely control the amount of swelling (Houston et al., 2011: Ombaka, 2016). Ola, relates the plasticity index to the swelling potential of the soils (Table 2) (Ola, 1983). The swelling potential of the soils at Takete Ede dam was also evaluated based on the criteria established by the USBR, 2013 for identifying expansive soils (Table 3). The relationship of swelling potential parameters indicates that the soil samples have a low to medium swelling potential (3b). This corresponds to low to medium plasticity and compressibility of the soils. The compressibility and swelling potential classify the soils as suitable materials for earth dam structures.

4.7 Compaction

The Maximum Dry Density of the tested soils ranged from 1630 to 2015 Kg/m3, and the Optimum Moisture Content ranged from 9.9% to 27% (Figure 3c). The high value of maximum dry density is influenced by the granular composition of the samples, which corresponds to the low plasticity and compressibility of the soils. According to Wood's classification in 1937, five out of the eight samples were classified as good earth dam materials (Table 1). The results align with the AASHTO classification, indicating that the granular materials produced good foundation materials. These materials can be considered suitable for dam foundations. The poor foundation materials can be improved through mechanical and chemical stabilization to achieve desirable properties for dam construction (Fatoyinbo et al 2024). The modification process will increase the strength and bearing capacity of the soils and reduce their compressibility and permeability.

Table 1: Summary of the geotechnical properties of the soils

S/N	NMC	SG	LS (%)	LL (%)	PL (%)	PI (%)	Fine %	Coarse %	Group index, (GI)	AASHTO	CA	MDD (Kg/m3)	OMC	CR (WOOD, 1937)	(K) cm/s	Degree of (K)	(Φ)	(Cu)
TP1	14.0	2.60	0.0	0.0	0.0	0.0	7.1	88.7	0.8	A-3	0	1997	10.3	Good	0.002197	Medium	35.4	63.7
TP2	14.8	2.62	0.0	0.0	0	0.0	8.6	91.4	0.6	A-3	0	2015	9.9	Good	0.001639	Medium	34.8	41.9
TP3	16.3	2.58	4.3	33.0	26.5	6.5	19.8	75.8	0.0	A-2-4	1.09	1983	11.1	Good	0.000819	Low	30.5	61
TP4	19.3	2.60	10.0	41.0	32.5	8.5	49.5	50.5	2.5	A-5	0.41	1630	27	Poor	0.000001	Very low	27.6	81
BP1	15.9	2.57	5.7	33.2	22.3	10.9	21.4	68.6	0.0	A-2-6	0.51	1985	10.1	Good	0.000546	low	32	96.1
BP2	15.2	2.60	5.7	32.2	22.2	10.0	18.4	67.5	0.0	A-2-4	1.45	1981	10.2	Good	0.000797	Low	30	73
BP3	19.4	2.68	9.3	46.4	24.2	22.2	52.4	44.4	8.6	A-7-6	0.67	1713	24.3	Poor	0.000003	Very low	25	114.1
BP4	17.4	2.61	9.3	44.4	24.2	20.2	48.3	51.7	6.3	A-7-6	0.68	1732	23.7	poor	0.000004	Very low	24.3	107

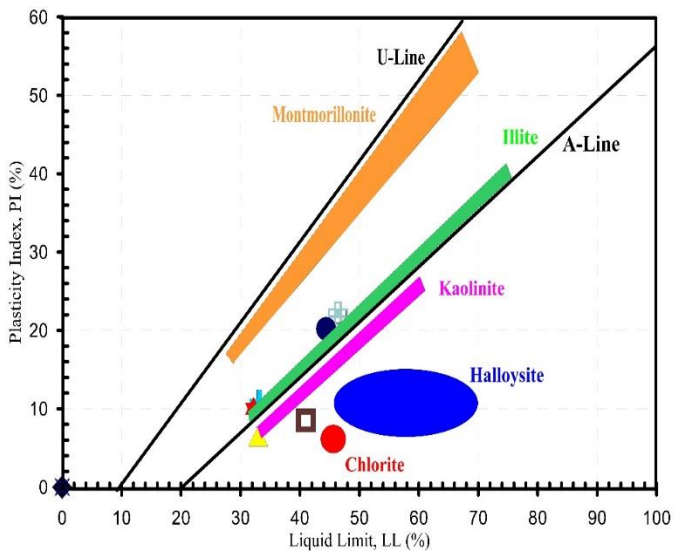
SN sample number , NMC natural moisture content, SG specific gravity, LS linear shrinkage, LL liquid limit, PL plastic Limit, PI plasticity index, CA clay activity, OMC optimum moisture content, MDD maximum dry density (Kg/m3), CR compaction rating, K coefficient of permeability, Φ frictional angle, Cu Undrained shear strength

Table 2: Swelling potential of the soils and dam site suitability (Ola, 1983)

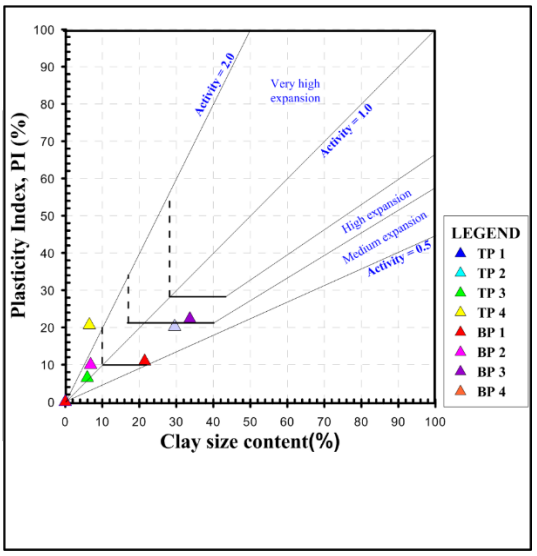
Plasticity index	Swelling potential	Suitability of the soils
0-15	Low	Excellent
15-25	Medium	Good
25-35	High	Fair
>35	Very high	Poor

Table 3: Identification Criteria for Expansive Clays (US Bereau of Reclamation (2013)

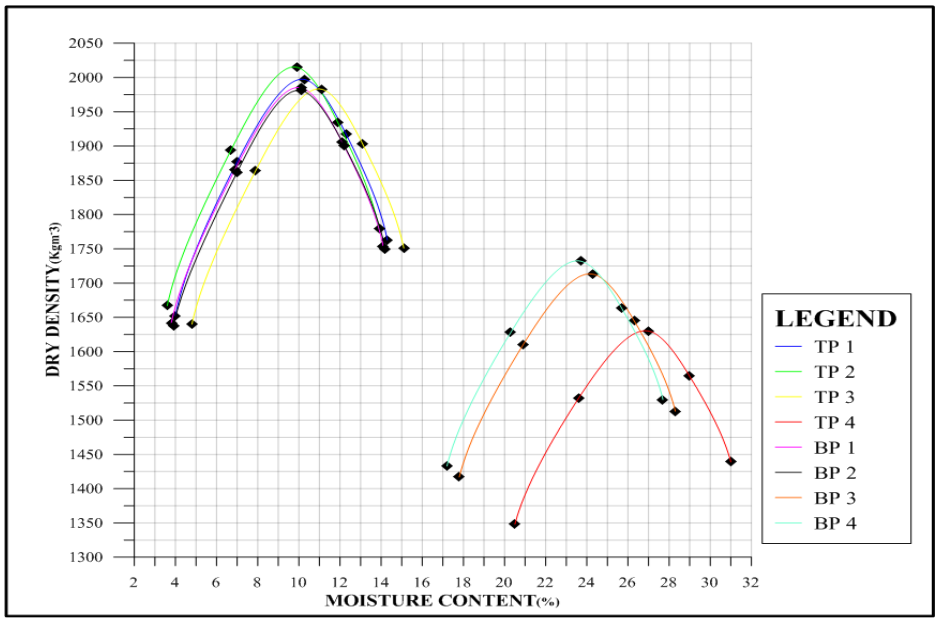
Plasticity Index (%)	Shrinkage Index (%)	Probable Expansion (%)	Degree of Expansion
<18	>15	<10	Low
15-28	10-16	10-20	Medium
25-41	7-12	20-30	High
>35	<11	>30	Very High



(a)



(b)



(c)

Figure 3: (a) plots of clay "activity", (b) clay mineral, (c) and typical compaction curves of the soils

4.8 Hydraulic conductivity

The coefficient of permeability of the soil samples ranged from 1.452×10-6 to 2.196950×10-3 cm/s (Table 1). Five (5) of the soil samples showed a significant amount of coarse content, ranging from 67.5% to 91.4%, while the remaining three (3) samples had a significant amount of fines in the silt and clay particle sizes. The variation in particle sizes accounts for the very low permeability in samples with relatively high amounts of fines and low to medium permeability for samples with high coarse contents. This can be explained by the fact that the coefficient of permeability of a soil is directly proportional to particle size. The granular soil samples have large pore spaces, which increase the amount of water that seeps into the dam embankment, while silty-clay materials with very low hydraulic conductivity decrease the amount of water that seeps into the dam embankment. The permeability of the coarse soils at the dam site is relatively high, supporting infiltration rather than retention, while the fine-grained soils have low enough permeability to retain water in the reservoir after impoundment (Umoren et al., 2016).

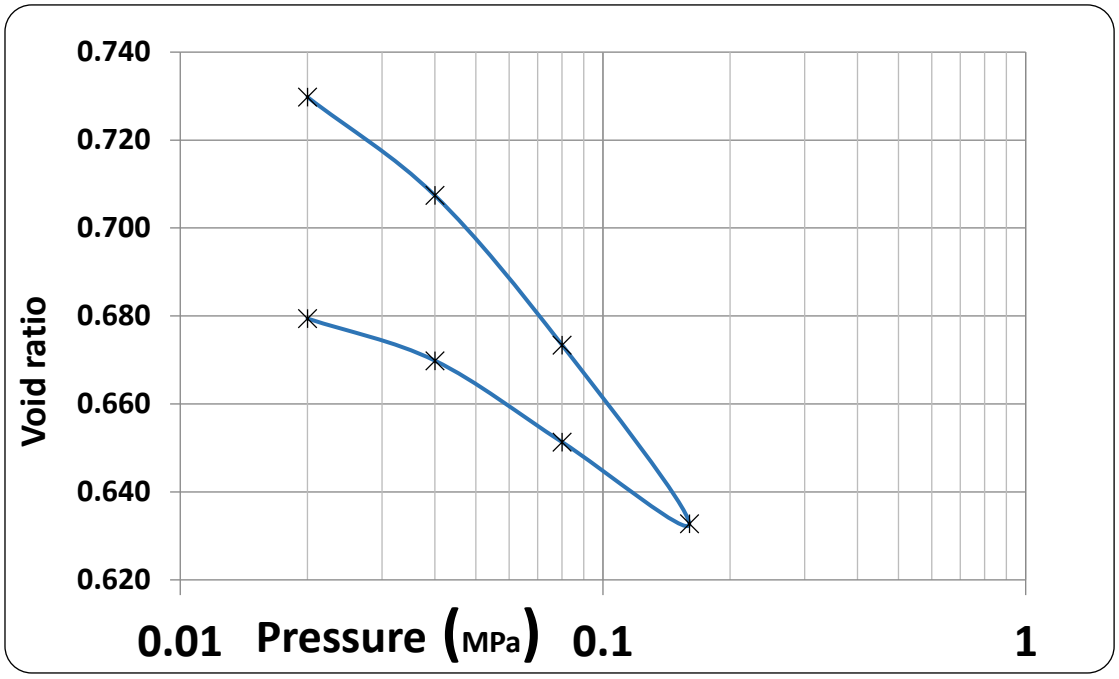
The results of the coefficient of permeability suggest that soil samples TP 4, BP3, and BP4, with very low hydraulic conductivity, could be considered suitable dam site materials. The suggested maximum coefficient of permeability by various authors is 1×10-9 m/s (Oeltzschner, 1992; Daniel, 1993; Rowe et al., 1995). In the compacted state, these soils are expected to have extremely low permeability values and can be considered for use in landfill barriers. Such soils will be useful as fills in embankments and homogeneous dams, as well as in cores of sectioned dams.

4.9 Consolidation and Triaxial Shear Strength

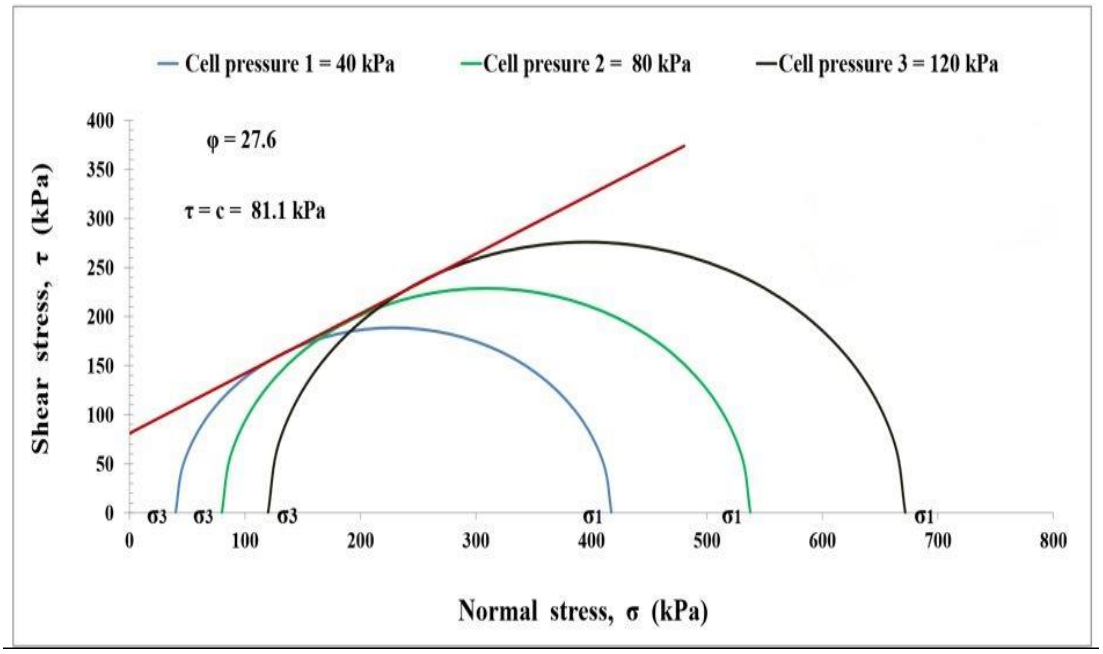
The disturbed soil samples underwent One Dimensional Consolidation tests to ascertain their consolidation and compressibility characteristics. The coefficient of volume compressibility (Cv) ranged from 0.00020 to 0.88 mm/yr, and the consolidation (Mv) ranged from 0.18 to 144 MPa-1 (Table 1). The test results indicate that the tested soil samples exhibit low to medium compressibility and consolidation characteristics. Therefore, the potential for collapse settlement or high initial settlement can be predicted based on gradation and plasticity characteristics. The relationship between void ratio and pressure is presented in Figure 4a. The shear resistance of soil is a result of friction between interlocking particles and possibly bonding at particle contacts (Oluwaniyi et al., 2020). The angle of internal friction ranged from 24.30° to 35.40°, and the undrained shear strength (Cu) values ranged from 41.9 KPa to 114.1 KPa (Table 1).

According to the British Standard 5930 (1999), cohesive soils are classified based on their shear strength. Cu values between 0-20 KPa indicate very soft soils, 20-40 KPa indicate soft soils, 40-75 KPa indicate firm soils, 75-150 KPa indicate stiff soils, and 150-300 KPa indicate very stiff soils. Based on this recommendation, the sampled soils are classified as firm to stiff. The results indicate that the underlying soils possess good shear strength. The soils would retain considerable strength, with high resistance to shear stresses and high bearing capacity throughout the lifespan of the dam structure. However, excess pore pressures often develop during the rapid construction of fine-grained fill zones, resulting

in reduced shear strength and potentially unstable conditions during or shortly after construction. The high values for the angle of internal friction can be attributed to the presence of coarse-grained particles in the sampled soils. The Mohr's failure curves are presented in Figure 4b.



(a)



(b)

Figure 4: (a) Void ratio - pressure relationship and (b) Mohr Failure Cycles of the soil

5. Conclusion

The study provides insight into the competence and integrity of the soils underlying an earth fill dam constructed for irrigation purposes, as well as its potential environmental impact. A geotechnical investigation was conducted to gather this information. The investigation revealed that the underlying soils have a significant amount of moisture due to climatic conditions. These soils are well graded, meaning they have good strength and minimal settlement. The index characteristics of the soils indicate low to medium swelling expansion, low to medium plasticity, and low compressibility, with no threat of settlement. Mineralogically, the soils primarily consist of non-swelling clay minerals, such as kaolinite. This relationship between compressibility, plasticity, and swelling potential is important in understanding soil settlement. Therefore, the tested soils have good strength and a low potential for settlement. Although the fine content in these soils is low, it still acts as a binder to resist substantial shear force. The soils also have low hydraulic conductivity, making them suitable materials for an earth dam structure. However, the coarse content of the soils, which has high hydraulic conductivity, can contribute to a high infiltration rate. This can lead to surface erosion under wave action and surface runoff. Ultimately, this can undermine the foundation of the dam and potentially cause the dam to fail, resulting in the loss of farm produce.

Author's Contributions

The authors read and approved the final manuscript.

Competing Interests

The authors declare that they have no competing interests.

Availability of Data and Material (Data Transparency)

All the analysis was carried out in accordance with the code of investigation and practice.

FUNDING

This research was personally sponsored

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