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GEOSCIENTIFIC SURVEILLANCE AND PERFORMANCE ASSESSMENT OF BOSSO DAM, NORTHCENTRAL NIGERIA

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ABSTRACT
Monitoring of Bosso dam by integrating geoscientific principles was executed. The dam was constructed in 1949 to provide fresh water for human consumption. Physical deterioration, evidence by structure material wear out, concrete cracks and mechanical equipment worn-out among others are visible on the dam and its appurtenant structure. The basement rocks underlying the dam area are weathered and fractured as evidence on the outcrops within the proximity of the dam. Geotechnical characteristics of soil obtained from the dam site includes: Liquid limit range of 30% - 35%, plastic limit range of 26% - 38% and Plasticity index range of 4% to 15%. The classes of the soils fall within the MI, MH and ML soil categories of the USCS, indicating silt of medium, high and low plasticity's. VES models show 3 geoelectric layers which includes regolith/organic silts layer with average resistivity value 50 Ωm. The 2nd layer shows a resistivity range of 9 Ωm to 43 Ωm to the depth range of 3.3m to 4.7m. The 3rd layer is composed of silty-clay and saprolite with resistivity of 163 Ωm. From the 2D tomography, the low resistivity anomalous noticed at the western section of the dam embankment toe is attributed to the effect of possible seepage caused by internal erosion. The effect of ageing and global warming has led to safety deficiencies of Bosso dam that were not apparent at commissioning until recently, therefore urgent remedial measures are needed for the safety of the dam.

Keywords: Dam, Appurtenant Structures, Toe, Geotechnical, Safety, Resistivity

INTRODUCTION
The Bosso dam was commissioned in 1949, aimed at supplying potable water supply to the host community. The need to conduct an integrated geoscientific investigation of the dam to provide onsite evidence-based approach to identify the impact of aging, weathering and climate change on the dam and its appurtenant structures cannot be overemphasized. Every structure that impounds fluid such as water is a potential danger whose safety should not compromised (International Commission on Large Dams, 2003). Dam can be considered as an artificial barrier or wall-like structure, and its appurtenant structures designed or modified to divert, store or retain water in volume under constant or static pressure so as to form a volumetric reservoir (Ko's *et al*., 2021; Berhane et al., 2017).
Dams as a component of both geogenic and anthropogenic factors are subjected to several forces that can cause its failure such as aging coupled with the action of external forces acting on the dam components (New Zealand Society on Large Dams, 2015). The longevity (aging) of dams which results in dam degradation is a natural phenomenon which occurs resulting from dynamic and consistent interactions within the dam and its components leading to structural weaknesses of various aspect of the dam components (Nasrat *et al*., 2020; Nasrat *et al*., 2020). The forces that act on dams are active over the entire life spam of the structure, and the fact that a dam has withstood external and internal pressure for some period of years is not necessarily an indication that it cannot experience safety deficiencies (García, 2020; Mohammad. and Amirhossein; 2019; Lukman *et al*., 2011; Iloeje and Eze, 2014).
Some safety deficiencies in dam's are made manifest within a short time period post-commissioning (e.g. excessive leakage, internal erosion, differential settlement and wall cracking), while other deficiencies may not manifest immediately after several years of post-commissioning (examples include; backward erosion piping, lack of capacity for the discharge of flood events, lack of stability as a result of large tremors, long-term geomorphic activity of physical and chemical weathering) (Martin, 2014; The State of Victoria Department of Environment, Land, Water and Planning, 2016; Samaila, 2020). Almost all dams have seepage potential, which can lead to structural failure resulting from internal erosion or "piping" (Nasrat *et al*., 2020; Zhaozhao, 2024; International Commission on Large Dams, 2003).
The dam reservoir will usually express a fluctuating water level during normal operation and during the wet season characterised by flooding events (Li, *et al*., 2024; Downing *et al*, 2023; Jimoh & Adetoro, 2018). This can result to instability or structural disturbance along the reservoir margins where there exist steep slope and unfavorable geology (United State Society on Dams, 2015). Similarly, the drawdown level in reservoir will result to deficiencies along the reservoir end margins if the reservoir experiences a quick drawdown and the maintenance of the reservoir is at optimum level for a longer duration of time (International Commission on Large Dams, 2003). The reservoir of most dams poses as the principal potential hazard component of the dam, and the maintenance of it will improve the dam safety measures (Umoren *et al*., 2016). Dam post-construction vigilance can identify defects in the structural composition of the dam which could impact on the dam safety resulting in failure (Rizal and Pulung, 2024; Downing *et al*., 2003).
The protection of downstream life and property as well as the natural ecosystem is the principle aim of dam safety inspections. Dam safety inspection will help to unravel unsafe conditions and determine why they exist. The inspection is aimed at recommending remedial measures to mitigate the deficiency or defect that will safeguard the dam structure and appurtenances (International Commission on Large Dams, 2003).

MATERIALS AND METHODS

Latitude 9°40′40.6″ of the Equator and Longitude 6°31′53.1″ of the Greenwich meridian on an average hight above mean sea level of 322 m defines the spatial location of Bosso earth dam. Nigerian Meteorological Agency (NiMet) defined the study area's climatic condition to be semi-arid as its alternation with two regimes (wet or rainy and dry seasons) showing a range of seasonal variation in temperature between 35ºC during dry season and 21ºC during wet/rainy season. Annual precipitation is about 1000 mm, with high surface run-off during the wet season between the months of April and October and low run-off is experienced between November to March (dry season). The dam reservoir under study is feed by a network of seasonal stream channels. Thus, these channels have significant influence on the dam dynamics. The vegetation is of the Guinea Savannah comprising of scattered clusters of trees, shrubs and short grasses.

The study area is within the Basement Complex of Nigeria, which is Precambrian in age (>600 million years). The major litho-petrological components of the Basement complex comprise of the Metasedimentary and Metavolcanic rocks (Schist Belt), Undeformed Acid and Basic Dykes, Migmatite–Gneiss Complex (MGC) and the Pan-African Precambrian Older Granites. The dominant mineral in the granitic rocks is feldspar which weathering products are rich in clay (Ajibade *et al.*, 2008). Outcrops are found on high elevations around the vicinity of the dam and are also exposed along the stream channels.

Reconnaissance and geological investigation of the area under study was systematically carried out for effective familiarisation of the area to identify the geotechnical and hydrogeological challenges that may be encountered on the field. Potential areas of key investigation interest were also identified at this stage. Onsite evidence-based approach to identify the impact of aging, weathering and climate change on the dam and its appurtenant structures was carried out through multi-scientific approach involving, physical component measurement, geotechnical and geophysical investigations. Physical measurement of each vital aspect of the dam was carried out. The preliminary geological mapping and geophysical surveys indicate approximately uniform near surface lithology within the dam reserviour which sponsored the establishment of 2 trial peats were soil samples were collected for further geotechnical analysis.

Index geotechnical investigation in line with the British Standard Institute (BSI) 1377 (British Standard Institution, 1990) was performed on the soils collected within the dam reservoir to accertain the moisture content, particle grain size distribution and Atterberg consistency limits. Geophysical investigation using the VES employing the Schlumberger array was executed to study the shallow subsurface of the dam reservoir (Rauff *et al*., 2025; Adetokunbo *et al*., 2024). The geoelectrical resistivity data were processed and inverted utilizing the Winresist software. 2D electrical resistivity tomographic profile (Ahmed *et al*., 2025: Loke, 1999) was established at the downstream toe of the dam using Alpha Wenner electrode configurations on a profile length of 70m with 15 electrodes and 5 m minimum spacing establishing 30 total number of datum points with 4 number of datum level. This electrode array was established to provide optimal resolution to detect the subsurface anomalies while ensuring adequate depth penetration to assess seepage characteristics of the dam toe area. The result was interpreted with the aid of the RES2DWin software.

RESULTS AND DISCUSSION

Visual Inspection and Components Measurements

The Bosso dam has a height of 41 meters extending from the dam toe, embankment crest length of 162 meters and an average width length of 4.2m. the height of the spillway barrier is 2 m and the spillway barrier length is 20.3 m.

The rock pitching to resist erosion in the upstream and downstream embankment faces have been overgrown by grasses of different varieties. The downstream portion of the dam is exposed to erosion and as a result of this the downstream portion suffered from occurrence of deep gullies and cracks which could affect the stability of downstream slope (Plate 1). The spill way channel is suffering from cracks and erosion activities (Plate 1). The reservoir drawdown as at the time of this investigation is almost zero.

Inspecting Upstream Reservoir

Two major and three minor seasonal stream inlets channel water into the dam reservoir. The seasonal streams flow along strikes and do not leave any fine matter at their banks composed of crystalline basement rock. As at the time of this investigation the dam reservoir is void of water except for a minute portion close to the dam outlet. The rapid drawdown condition of the dam can be attributed to the effect of global warming leading to the problems of drought which could cause a slope stability failure. Internal erosion failures due to hydraulic fracturing may have occurred due to the development of cracks as a result of the differential settlement at dam floor leading to shrinkage in clayey soils on drying as observed in the reservoir (Plate 1). It is possible that water drains through these cracks into the subsurface. Precipitation runoff and stream channel erosion has constantly supply sediment in large volume equivalent to multiple-years sediment supply from the dam upstream which are hydraulically transported and deposited in the dam reservoir. Due to the low velocity experienced within the dam reservoirs, sediments flowing from the inlets are trapped in their volumes thereby reducing the volume of the reservoir over time.

Inspecting Spillways, Outlets and Mechanical Equipment

Some existing or developing dangerous conditions were identified and potential challenges which might serve as risk to the downstream areas were also observed. Three general problem types were identified in-situ which suggest that the dam might be internally and physically challenged resulting to improper functioning of the dam. A number of cracks and structural damage were visually observed on the spill way barrier and on the spillway channel (Plate 1). Part of the spillway is already overtaken by erosion activities which suggest inadequate erosion protection. The mechanical appurtenant structures are currently in deteriorating stage. The discharge outlet is in a structurally deformed state (Plate 1). This may be attributed to old age and lack of maintenance. This deterioration of the structures could cause absolute failure of the dam or its components and severe damage to downstream properties, or even death of downstream residents which are noticed to be very proximate to the dam, about 300 m away from the dam site.

Plate 1: Different Aspects of Bosso dam Deficiency

Geotechnical Analysis
The geotechnical analysis gives the general index and engineering properties description of the soils obtained from two trial peats at the base of the dam reservoir. All analysis was carried out in line with the British Standard Institute (BSI) 1377(1990).

Soil Test
The soil matrix is predominantly silty. The soil aggregation directly influences the dam embankment and performance of the reservoir. The most aggregated soils possess a higher amount of macropores, which is related to the soil isotropy, low resistance and permeability.

Grain Size Distribution
5 soil samples were collected from 2 trial peats (2 samples from peat 1 and 3 samples from peat 2). Samples were collected at the surface, 1m and 1.5 m interval below the reservoir. The grain size distribution data and curves obtained by sieving are shown on Table 1 and Figures 1. This soil classification analysis is in agreement with the material tactile-visual analysis. The availability of sand and the predominance presence of silt attributes the soil, its particular characteristics. This suggests that the dam reservoir might be prone to leakage considering that silt or silty-sand are cohesionless soils.

Table 1: Grain Size Distribution

		Sample label				
		S1 1m	**S1 2m**	**S2 0m**	**S2 1m**	**S2 2m**
Sample weight →		**211.2**	**205.09**	**188.2**	**222.9**	**217.6**
Sieve No	**Opening (mm)**	**Quantity Retained**				
10	2.000	0	0	0	0	0
20	0.850	0.28	0.98	123	0.81	1.51
40	0.425	0.88	9.79	3.48	6.13	9.09
60	0.250	6.66	14.52	10.6	9.10	15.26
80	0.180	22.18	18.42	11.02	18.69	15.56
100	0.150	42.6	66.67	8.98	45.56	1918
Pan		137.94	92.98	151.61	141.22	154.87

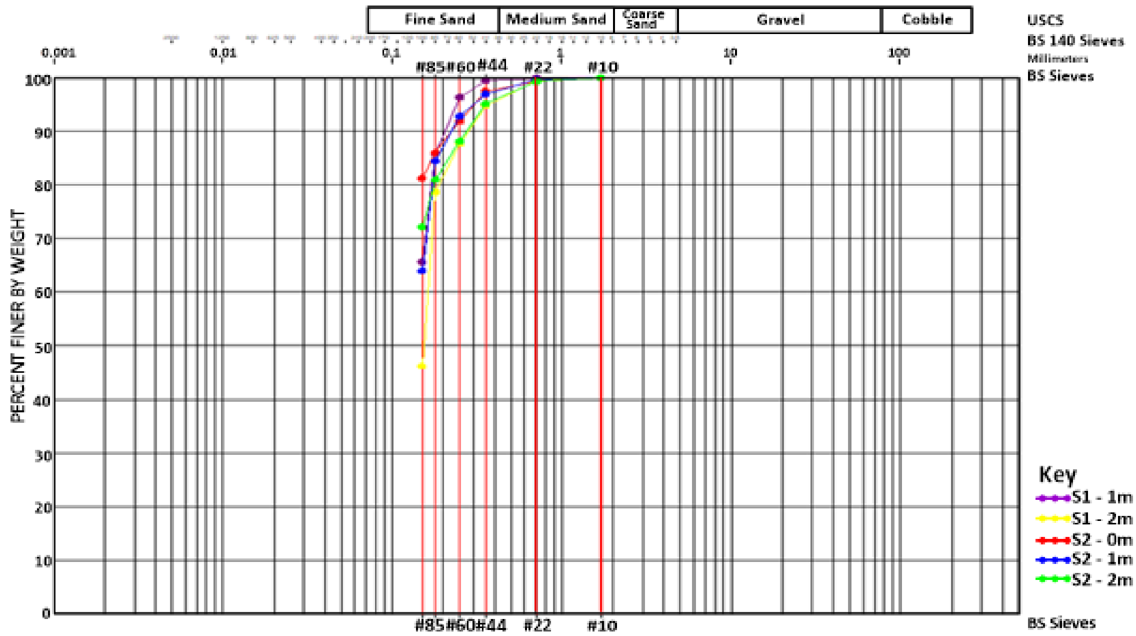

Figure 1: Sieve Diagram

Atterberg Consistency Limits (sieve No. 40 used)
The liquid and plastic limits tests were performed on samples collected from the trail peats and results obtained are summarized in Table 2.0. The USCS classified the analyzed soil as ML, MI, MH (low, medium and high plasticity silt) (Figure 1) which are in contrast with similar work by Berhane *et al.*, (2017) which indicated CH and CL soil of low permeability and high plasticity as suitable soil to underlain earth dam reservoir.

Table 2: Atterberg Consistency Limits

Sample ID	Atterberg Limits						
Peat No	Colour Code	Depth (m)	LL (%)	PL (%)	PI (%)	USCS Classification	Soil Description
S1	(purple)	1	36	32	4	MI	Silt of Medium Plasticity
	(yellow)	2	45	32	13	MI	Silt of Medium Plasticity
S2	(red)	0	53	38	15	MH	Silt of High Plasticity
	(blue)	1	30	26	4	ML	Silt of Low Plasticity
	(green)	2	33	27	6	ML	Silt of Low Plasticity

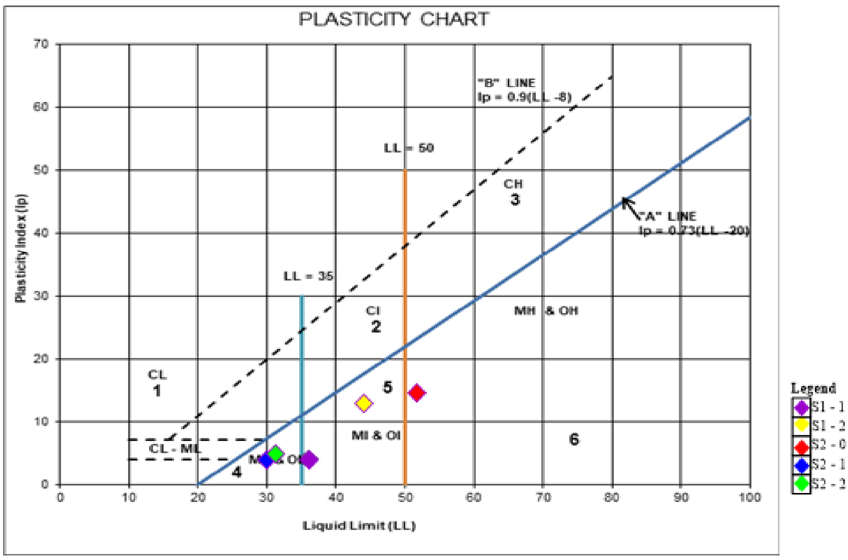

Figure 2: Plasticity Chart

Geophysical Investigation Interpretation
Despite the comprehensive geoscientific approach adopted in this research, certain limitations such as seasonal variability in resistivity due to moisture content were put into consideration in the data interpretation

1D Vertical Electrical Sounding (VES)
The VES results shows that the subsurface lithology is remarkably inhomogeneous in composition. The geoelectric section indicates three (3) lithologic layers defined by top dark debris/regolith forming decagonal cracks with geo-resistivity value range between of 39 Ωm and 62 Ωm to the depth rage of 0.9 m to 1.0m. The second layer depth ranges from 3.3 m to 4.7 m composed of arenaceous components of silty-sand with resistivity value range of 29 Ωm to 43 Ωm and a thickness range of 2.4 m to 3.8 m. Clayey materials to saprolite underlain the third layer with geo-resistivity value range of 129 Ωm to 197 Ωm. From the result of the findings and field observations it is reported that the dam reservoir section is underlain by high level of argillaceous/arenaceous matter transported into the reservoir section via the inlet streams with high porosity and potentially rife for great reservoir infiltration. Desilting the dam is very necessary if it must be retained at this stage.
The curves are HA model type. The geo-electric curve shapes and not the geo-resistivity values were employed in the geo-electric resistivity sounding data interpretation. This is because the values of resistivity may be altered due to saturation or moisture content of the lithology in response to seasonal variation (wet and dry seasons), but the absolute depths to geoelectric subsurface layers remain constant. Thus, curve shapes were utilized to infer for the subsurface geoelectric layers. Model interpretations of the VES results in the two established stations are indicated on Table 3 and the modeled geoelectric curve are shown in Figure 3

Table 3: Model Interpretations of the VES Results

VES	Layer Parameters								
	1st Layer			2nd Layer			3rd Layer		
	Depth(m)	ρ(Ohmm)	Lithology	Depth(m)	ρ(Ohmm)	Lithology	Depth(m)	ρ(Ohmm)	Lithology
1	0.9	39	Regolith	3.3	29	Silty-Sand	--	197	Clay/Saprolite
2	1.0	62	Regolith	4.7	43	Silty-Sand	--	129	Clay/Saprolite

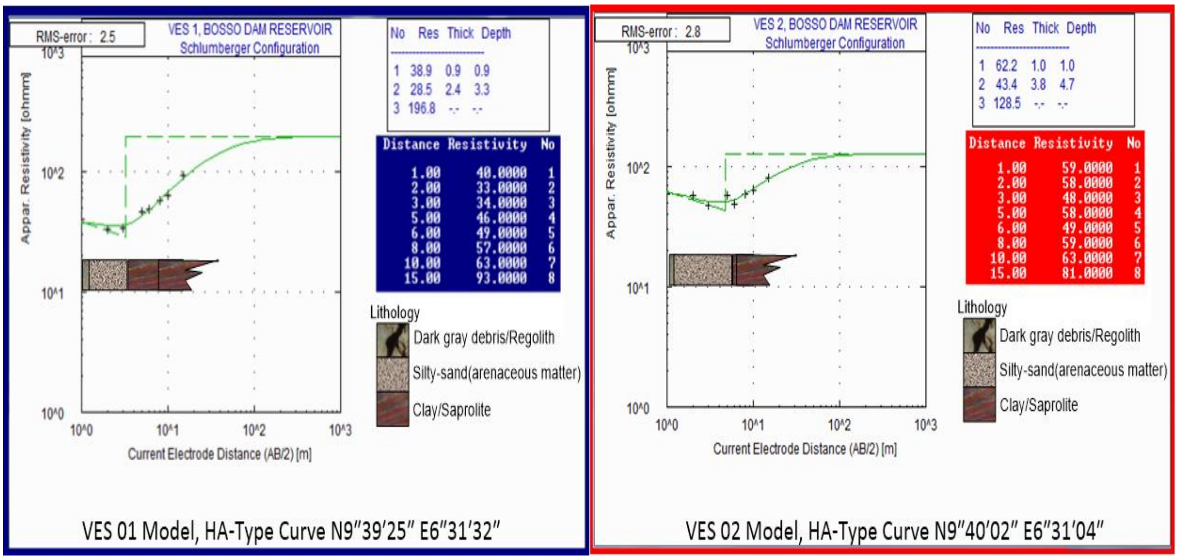

Figure 3: VES Curves

2D Electrical Resistivity Tomography
The result of the subsurface ERT profile obtained along the dam toe at the downstream section converged to a maximum of 5.8% RMS error in five iterations. The geoelectric profile imaged the earth interior at the dam toe extending to an average depth of 12 m below ground level (Figure 4). The resistivity distribution along the profile ranges from about 30 Ωm to > 486 Ωm Underlying the profile line from the surface distance of about 15 m to 45 m, the profile is delineated with distinct lenses of anomalous zones of low geo-resistivity values ranging from < 30 Ωm to < 70 Ωm. This finding corresponds to the observation of the presence of aquatic vegetation (like cattails, reeds etc.), wet spots with normal vegetation than is greener and lush than adjacent vegetation further downstream the path of the moist subsurface. These low resistivity anomalous zones and the wet conditions noticed on the profile distance of 15 to 45 m downstream toe section of the dam embankment suggest the presence of possible seepage caused by internal erosion, excessive internal pressure and or saturation. The profile distance of 0 m to 15 m shows no signs of low resistivity (>300 ohm-m), indicating a no seepage zone.

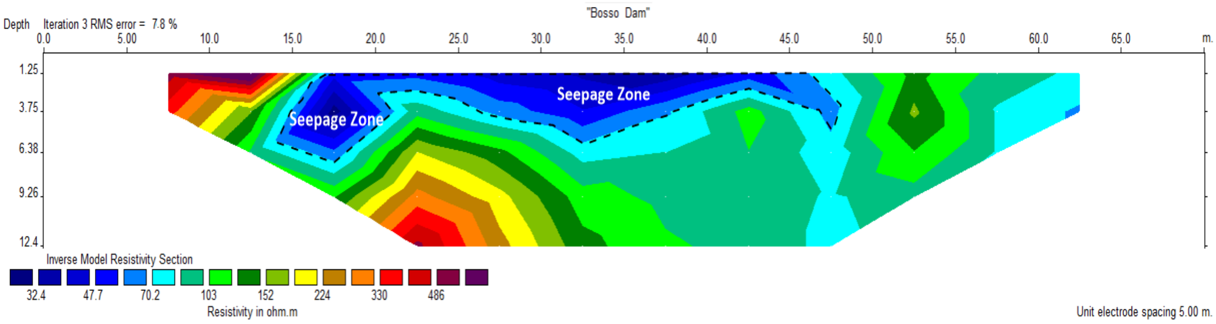

Figure 4: 2D Electrical Resistivity Tomography

CONCLUSION

A comprehensive surface and subsurface investigation of Bosso dam was carried out employing geoscientific integrated methods with the incorporation of geological, geotechnical and geophysical methods of geoelectrical resistivity involving Schlumberger method of VES and 2D ERT and invasive geotechnical investigation. These methods were used to characterized the subsurface of the dam reservoir and the downstream dam toe. The investigation approach was used to successfully assess and monitor the spatial and temporal conditions of the earth dam and its associate appurtenant dam structures with the precise identification of seepage zones below the dam component. The immediate risk associated with the cracks in the dam spillway cannot be overemphasized. The dam is highly silted and the spill barrier and spill way are not in good condition. Further investigation may be necessary to determine the cost-benefit analysis for repair or decommissioning of the dam and which will be more feasible.

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