ASSESSMENT OF SEEPAGE IN AN EMBANKMENT DAM USING VERY LOW FREQUENCY ELECTROMAGNETIC AND GEOELECTRICAL METHODS

ABSTRACT

Geoephysical surveys involving Very Low Frequency Electromagnetic (VLF-EM), Vertical Electrical Sounding (VES) and 2D resistivity imaging were conducted along the embankment of Asejire dam to detect potential seepage zones and assess the integrity of the dam. 750 VLF-EM measurements were made at 10 m station interval using the VLF-EM Equipment. 24 Schlumberger VES were conducted at 20 m interval using resistivity meter and its accessories. The current electrode spacing (AB/2) was varied from 1 m to 100 m. The 2D resistivity profiling employed the dipole-dipole configuration with electrode spacing, a = 20 m and expansion factor, n = 1 - 5. The VLF-EM data were processed and modelled using Fraser Filtering and Karous-Hjelt software to delineate subsurface zones of varying conductivities suggesting anomalous seepage. The VES data were quantitatively interpreted using the partial curve matching technique and 1D resistivity inversion algorithm while the dipole-dipole data were inverted using 2D resistivity inversion procedure. The VLF-EM inverted sections revealed prominently conductive zones indicating anomalous seepage zones beneath the dam embankment. The relatively less conductive zones possibly indicate reduced seepage. The results of VES interpretation revealed three geoelectric layers beneath the dam embankment representing the caprock, core and bedrock. The 2D inverted resistivity sections delineated zones with anomalously low resistivity generally less than 10 Ωm, indicating anomalous seepage, beneath the embankment. This study has demonstrated the effectiveness of combining the VLF and geoelectrical methods for delineating anomalous seepages in the assessment of dam safety. The anomalously low resistivity/high conductive zones identified beneath the dam embankment are suspected anomalous seepage zones which can threaten the integrity of the dam. Routine monitoring and remedial measures are therefore recommended to forestall the failure of the dam.

Keywords: Embankment, resistivity low, high conductivity, anomalous seepage, Asejire.

INTRODUCTION

A dam is a structure built across a river or stream to impound water for irrigation, domestic, industrial, hydropower generation, or recreational use (Camarero and Moreira, 2017, Ahmed *et al*., 2023). It also helps to control flooding by slowing down water flow during heavy rainfall on the upstream side to prevent over flooding downstream. An embankment dam is typically composed of fragmented independent rock and/or soil materials compacted into a complex, semi-plastic mound whose heavy weight helps to resist the pressure of the water from the reservoir. The friction and interaction of the soil and rock particles bind them together into a stable mass without cementing substance. The surface is covered by waterproof natural materials to make the dam impervious to surface erosion while the core is made of dense, impervious soil such as clay to prevent seepage through the structure.

Dams are designed to allow very low amount of seepage through it beyond which seepage becomes a problem as it threatens the structural integrity of the dam (Mugawata *et al*., 2020b). Anomalous seepage is prominent among the major causes of dam failure which also include internal erosion, foundation failure, overtopping, static and seismic instability (Boneli, 2013, Lyu et al., 2019).

The existence of faults, fractures, joints, fissures or shear zones in bedrock and discontinuities in the embankment provides pathways for seepage which may reduce impoundment of water in the reservoir area if it becomes intolerable. Anomalous seepage constitutes serious threat to structural integrity of dams and may lead to dam failure and loss of lives and property on the downstream side if it is not redeemed (Okpoli and Tijani, 2016).

It is therefore important to carry out post-construction checks and monitoring of dam regularly in order to detect possible breach or damage in the dam structure. Routine monitoring of seepage involves investigation of dams for changes within and beneath the embankment and is useful to detect seepage problem early and propose to execute remedial measures to avert structural failure (Ahmed et al., 2023). Most dam failure occurred because seepages through the dams were not checked and monitored after construction.

Geophysical methods are generally employed in damsite feasibility studies involving foundation investigation, geological and structural mapping of both embankment and reservoir floor. The methods are non-invasive, faster and cheaper than other direct investigative methods (Sharma, *et*

al., 2014, Sungkono *et al*., 2014, Adamo *et al*., 2020, Golebiowski *et al*., 2021). They are also applied during and after the construction phase to delineate subsurface geological sequences, and reveal lithological variation(s) which may threaten structural integrity in the dam.

Very Low Frequency Electromagnetic (VLF-EM) and Electrical Resistivity methods are the two principal geophysical methods usually employed in dam embankment investigation since they are rapid and cost effective. The VLF-EM and 2D resistivity imaging methods can detect anomalous seepages as high conductivity and resistivity low anomalies respectively. Both methods are capable of detecting internal erosion processes and anomalous seepage within a dam embankment at an early stage before the safety of the dam is at stake (Okpoli and Tijani, 2016, Camarero and Moreira, 2017, Akinlabi and Ayanrinde, 2018, Olasunkanmi *et al*., 2021, Hung *et al*., 2020, Mugawata *et al*., 2020a).

Based on the afore-mentioned, Very Low Frequency Electromagnetic (VLF-EM) and Electrical Resistivity surveys involving Schlumberger vertical electrical sounding (VES) and 2D resistivity imaging using the dipole-dipole array were carried out along the embankment of Asejire dam, Ibadan, southwestern Nigeria, to assess the level of seepage and integrity of the dam in. The objectives are to determine the geoelectric parameters of the subsurface layers, determine the lateral and vertical resistivity/conductivity variations in the subsurface strata, delineate the subsurface lithological units, and map possible seepage zones within the embankment.

Study area

The study area is located in Asejire town about 30 km east of Ibadan. It lies within latitude 7° 21.5’ N - 7° 22’ N and longitude 4° 07.68’ E - 4° 08.26’ E (Fig. 1). Asejire embankment dam is a combination of earth-fill and rock-fill dam separated by a spill-way which provides controlled passage for surplus water downstream when the reservoir is full. to prevent overtopping. It was built in the late 1960s to impound water from River Osun and provide water for the Asejire and Osegere water treatment plants to supply domestic and industrial water for Ibadan and its environs (Asibor, 2015). The dam embankment is about 818 m long while the dam crest elevation of about 159.4 m. The dam has a capacity of about 8 million litres per day, 80% of which is used for domestic purposes (Oladimeji and Olaosebikan, 2017, Utete and Fregene, 2020). The area is covered by an admixture of savanna and high forest trees with palm,

characteristic of secondary rainforest vegetation (Ajani *et al*., 2014). It has numerous low hills with very gentle slopes and is mainly accessible by Ibadan-Ife expressway, secondary road and foot paths.

The study area is underlain by Precambriam crystalline basement rocks of southwestern Nigeria typically migmatite gneiss (Fig. 2) exposed as low lying outcrops on the downstream side. Migmatite gneiss is a high-grade foliated, fine-to-medium grained metamorphic rock characterized by distinct banding of alternating light (felsic/potasic) and dark (mafic) minerals reflecting partial melting (Ajigo *et al*., 2019, Balogun *et al*., 2019, Ademila, 2022). The main constituent minerals are quartz, feldspar, plagioclase, hornblende biotite and muscovite (Pawley *et al*., 2015, Akinola and Obasi, 2020).

METHODOLOGY

Electromagnetic Profiling

The VLF-EM and resistivity surveys were carried out along both flanks of the dam embankment (Fig. 3). 750 VLF-EM measurements were made at station interval of 10 m with the WADI VLF-EM Equipment. Both filtered real and filtered imaginary were recorded. The VLF-EM data were processed using the Fraser filtering technique, to improve the signal-to-noise ratio and improve the resolution of the anomalies (Fraser, 1989). They were then subjected to 2D inversion using Karous-Hjelt software which inverted the ratios of the secondary to primary

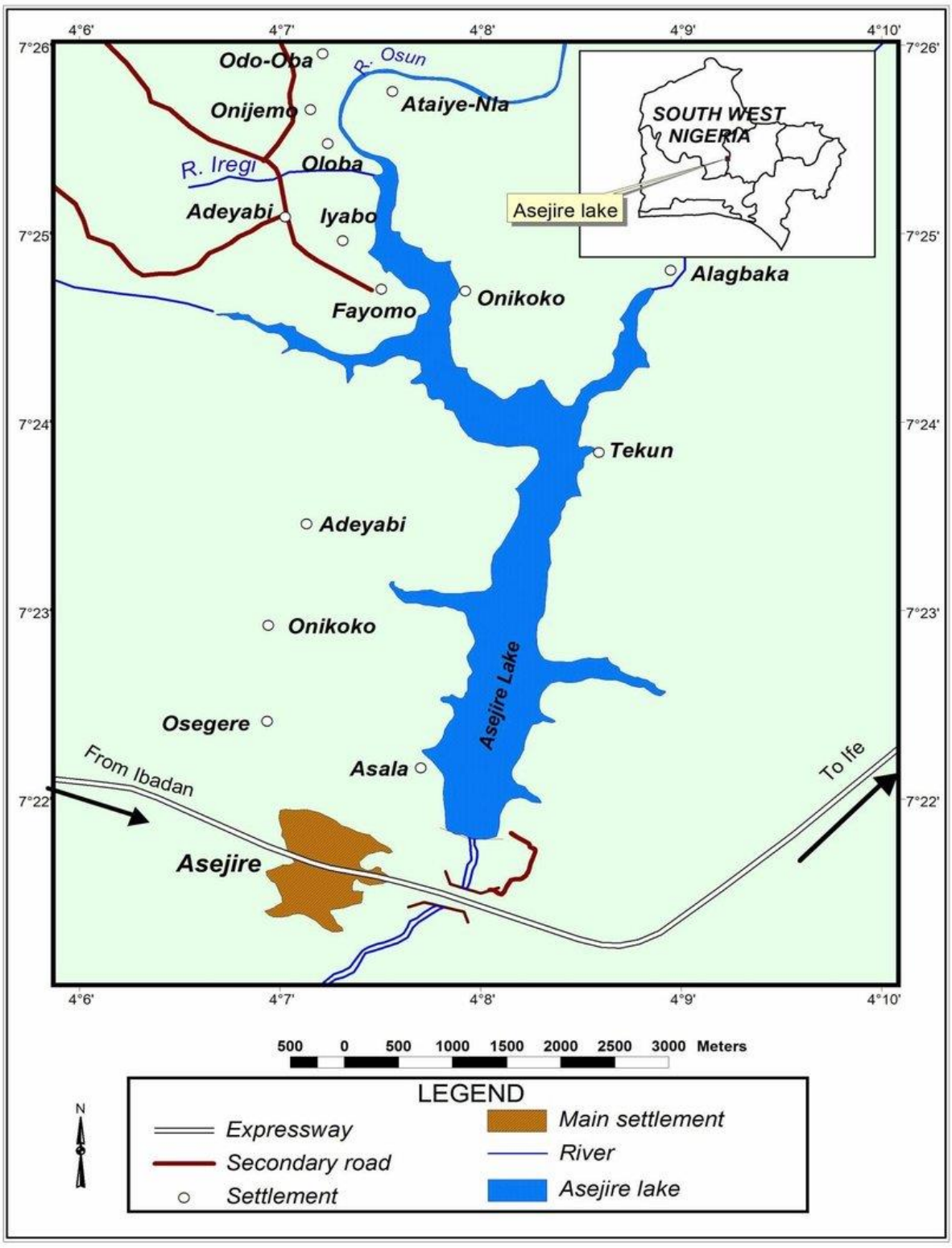

Fig. 1: Location map showing Asejire dam (Ajani *et al*., 2014)

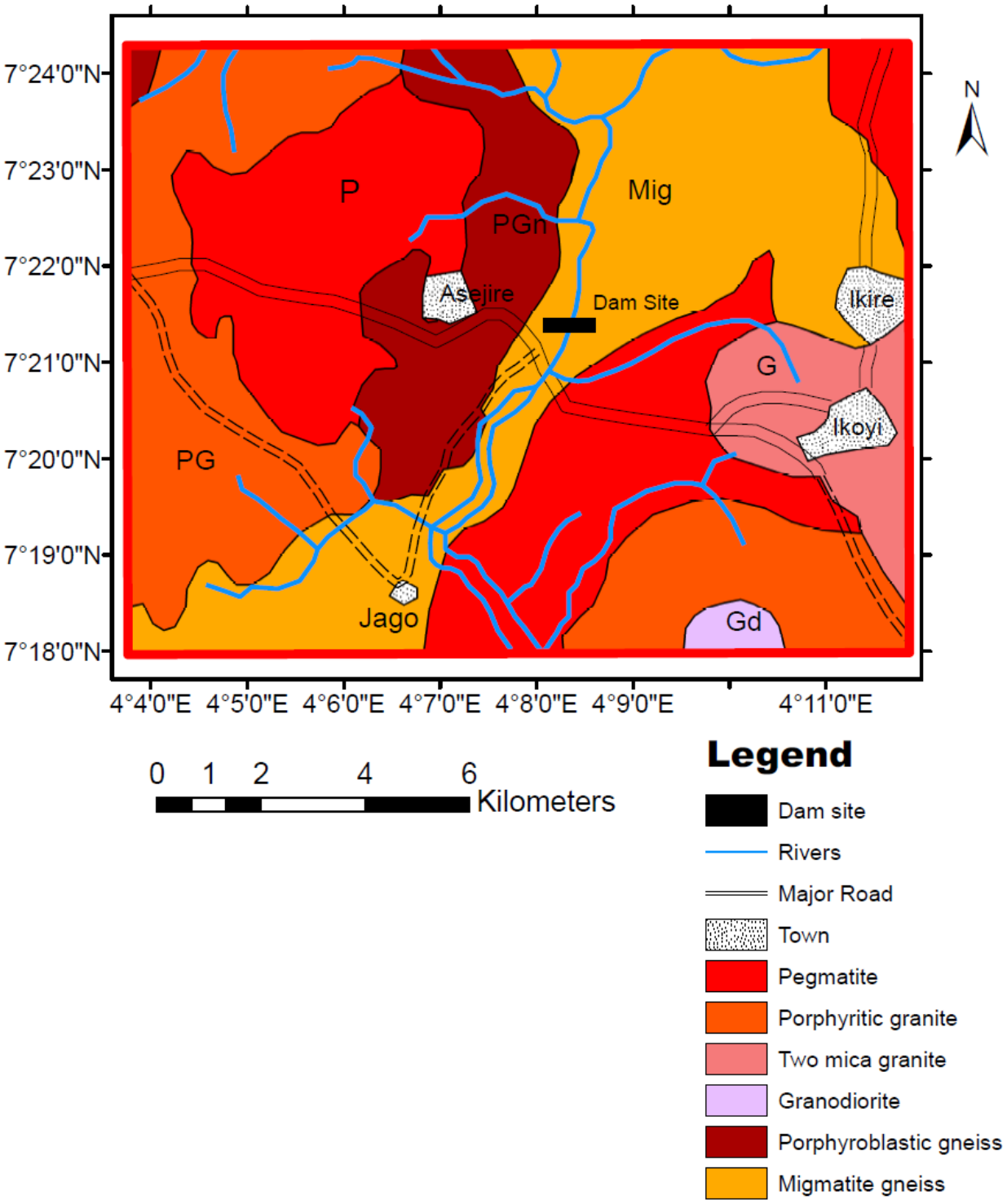

Fig. 2. Geological map showing the study area (modified after Nigerian Geological Survey Agency (NGSA, 2020)

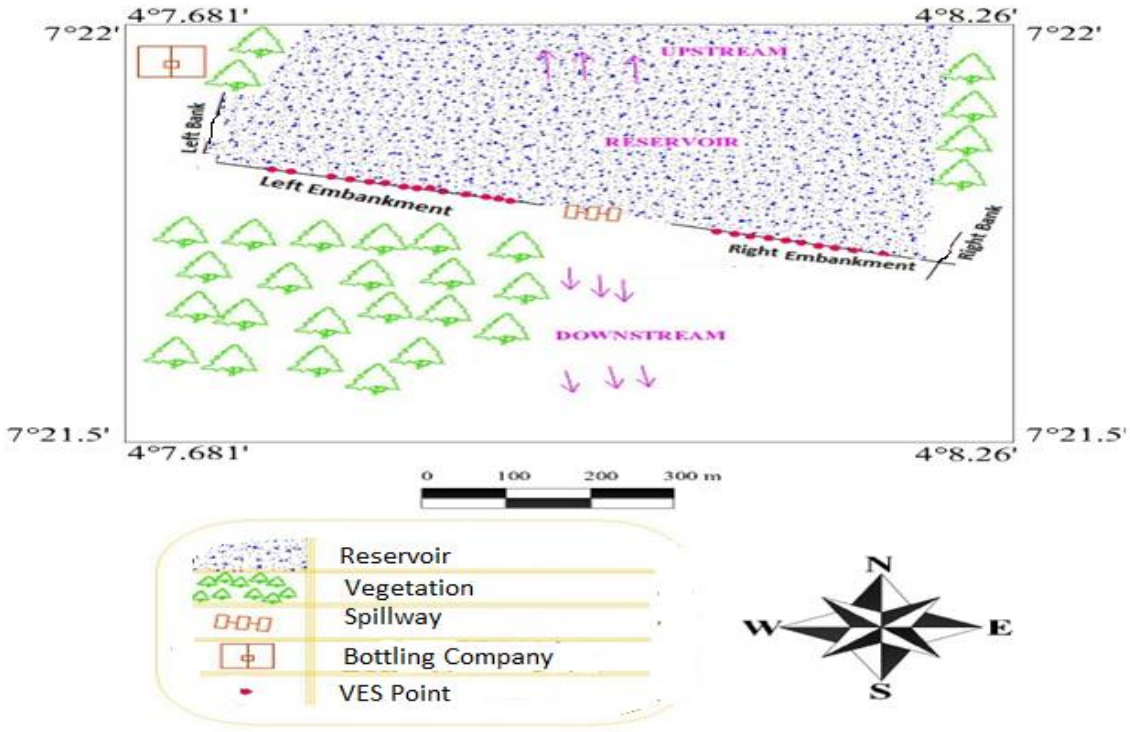

Fig. 3. Field Layout at the study area

electromagnetic fields to produce the characteristic VLF-EM sections beneath the traverses, in which zones of differing conductivity values were delineated (Karous and Hjelt, 1983).

Vertical Electrical Sounding

The geoelectrical srveys involved Schlumberger vertical electrical sounding (VES) and 2D resistivity profiling. The data were acquired with the aid a resistivity meter and its accessories.

24 sounding stations were occupied along the dam axis with station spacing of 20 m and current electrode spacing (AB/2) varied from 1 m to 100 m. The VES data were interpreted by using partial curve matching techniquue in which the field curves were superimposed on two-layer master curves and their corresponding auxiliary curves (Orellana and Mooney, 1966) to obtain the starting model parameters which were input for 1D inversion iterative algorithm (Zohdy, 1989). The RMS errors were less than 5%. The layer parameters obtained were used to construct the geoelectric sections on the different geoelectric layers interpeted beneath the sonding points were correlated by using appropriate resistivity ranges inferring lithologies.

2D Resistivity Profiling

The 2D resistivity profiling was carried out along the traverses using dipole-dipole electrode array with electrode spacing, a=20 m and expansion factor, n varied from 1 to 5. The dipole-dipole data were interpreted using 2D resistivity inversion procedure which iteratively computes the resistivity response of a two-dimensional model until a reasonable match is achieved between a theoretical pseudosection and the observed pseudosection, based on the finite element method (FEM) of modeling using a 2nd order smoothness constraint (Hohnmann, 1982; Loke, 2010).
Integration of different methods is desirable in geophysical investigation so that the results of one method may resolve the ambiguity arising from those of the other(s) and hence enhance the quality of the interpretation (Sharma *et al*., 2014, Golebiowski *et al*., 2021).

RESULTS AND DISCUSSION

Inverted VLF-EM Sections

The results of interpretation of the VLF-EM data show two prominently conductive zones suggesting anomalous seepage within the left embankment, lying at horizontal distances of about 280 m and 290 m – 325 m, and depths of about 30 m and 40 m - 55 m respectively (Fig. 4). The relatively less conductive zones observed at other locations within the embankment possibly indicate reduced seepage. They extend from the surface in a somewhat linear and dipping form to about 15 m depth at horizontal distance of about 50 m, about 45 m depth at distance 90 m – 130 m, and about 57 m – 66 m depth between distance 180 m -320 m.

Conductivity is relatively high within the right embankment (Fig. 5). Two prominently conductive zones indicating anomalous seepage occurs beneath horizontal distances of about 250 m and 260 m at depths of about 20 m and 0 m-5 m respectively. The relatively less conductive zones at horizontal distances of 45-50 m (to about 10 m depth), 50- 80 m (to about 15 m depth), 110-150 m (at depth ≥35 m), and 135-150 m (at 15-25 m depth) possibly suggest reduced seepage. The lower background conductivity beneath the right embankment reflects the fact that it is rock-fill compared to the left embankment which is earth-fill.

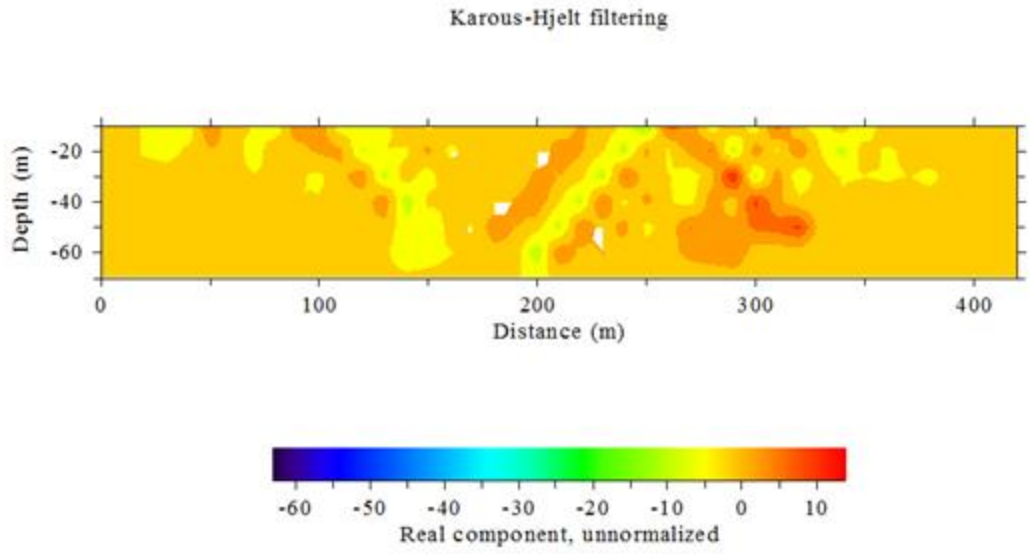

Fig. 4: Inverted VLF-EM section beneath the Left Embankment

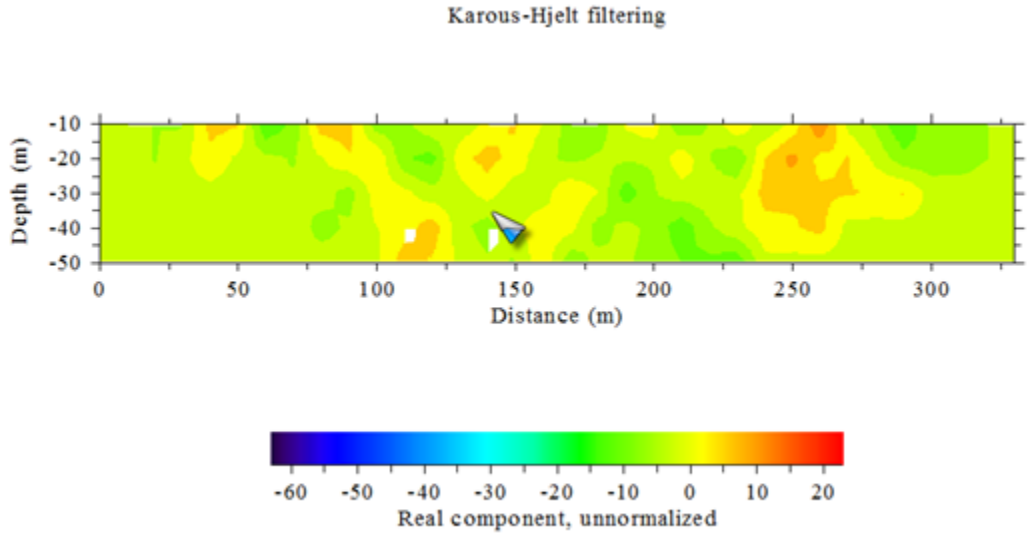

Fig. 5: Inverted VLF-EM section beneath the Right Embankment

Geoelectric Sections

The characteristic depth sounding curves obtained from the survey are the H-type (Fig. 6). The layer parameters obtained from the interpretation of the VES data are presented in Table 1. The geoelectric section beneath the left embankment reveals three geoelectric layers comprising the caprock, core and the bedrock (Fig. 7). The caprock is has resistivity values ranging from 59 Ω m to 252 Ω m, suggesting a clay-sandy clay mix. The layer is 0.7 m-5.2 m thick. The resistivity the core ranges from 23 Ω m to 64 Ω m and is characteristic of clay. Its thickness varies from 2.9 m- 37.6 m and is underlain by a more resistive layer which is presumably the basement rock whose resistivity ranges from 121 Ω m to 1033 Ω m.

The geoeletric section beneath the right embankment also reveals three geologic layer beneath the rock-fill embankment (Fig. 8). The resistivity of the caprock ranges from 288 Ω m to 766 Ω m and its thickness is 0.7 m - 2.2 m. The core has resistivity ranging from 48 Ω m to 162 Ω m and thickness varying from 3.1 m to 36.7m. The resistivity of the basement rock varies from 334 Ω m to 3672 Ω m. The resistivity vales are higher in this rock-fill right embankment compared to the earth-fill left embankment.

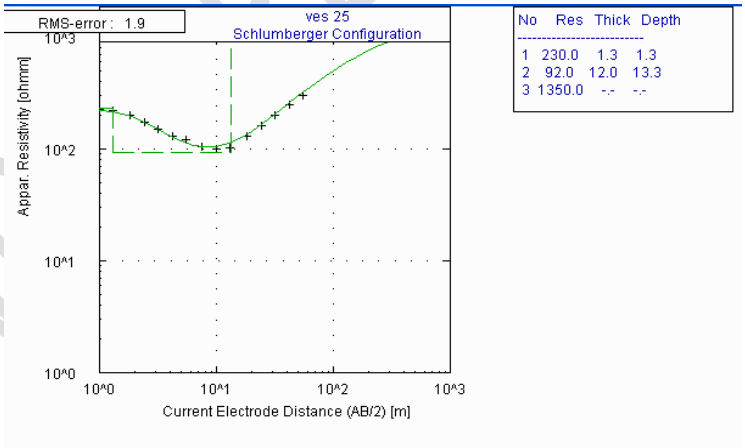

Fig. 6. Typical VES curve obtained in the study area

TABLE 1: Summary of VES Interpretation

VES No.	No. of Layers	Resistivity (Ω m) $\rho_1/\rho_2/\rho_3$	Thickness (m) $t_1/t_2/t_3$	Depth (m) h_1/h_2	Curve type
1	3	82/23/157	0.9/13.3/∞	0.9/14.2	H
2	3	252/63/96/208	0.7/10.0/∞	0.7/10.7	H
3	3	118/51/121	1.0/2.9/∞	1.0/3.9	H
4	3	77/39/910	1.9/25.7/∞	1.9/37.6	H
5	3	78/34/405	2.3/17.7/∞	2.3/20.0	H
6	3	93/29/405	1.8/27.1/∞	1.8/28.9	H
7	3	62/23/320	3.8/33.5/∞	3.8/37.3	H
8	3	59/44/1816	1.0/35.3/∞	1.0/36.3	H
9	3	109/43/322	1.0/14.3/∞	1.0/15.3	H
10	3	77/26/529	5.2/14.3/∞	5.2/19.5	H
11	3	72/33/499	3.3/27.6/∞	3.3/30.9	H
12	3	75/31/341	1.8/37.6/∞	1.8/39.4	H
13	3	129/50/469	1.0/26.9/∞	1.0/27.9	H
14	3	116/44/949	1.1/37.4/∞	1.1/38.4	H
15	3	186/55/1033	1.0/28.3/∞	1.0/29.3	H
16	3	286/73/245	2.2/11.1/∞	2.2/11.1	H
17	3	303/57/361	1.0/11.3/∞	1.0/11.3	H
18	3	499/48/857	1.0/12.1/∞	1.0/13.1	H
19	3	378/77/1407	1.0/3.3/∞	1.0/4.3	H
20	3	480/110/1608	0.7/8.9/∞	0.7/9.6	H
21	3	746/109/2027	1.0/36.7/∞	1.0/37.7	H
22	3	766/113/2209	1.2/36.7/∞	1.2/37.9	H
23	3	522/103/1764	1.1/3.1/∞	1.1/4.2	H
24	3	550/162/13672	1.1/12.8/∞	1.1/13.9	H

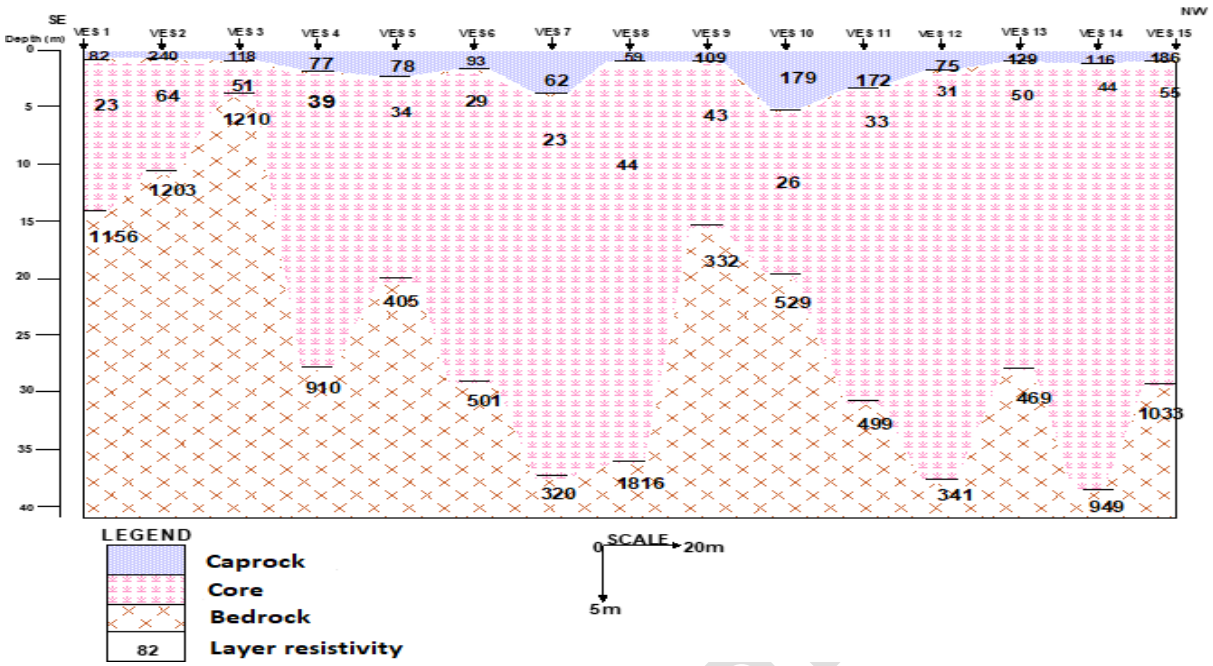

Fig. 7: Geoelectric section beneath the Left Embankment

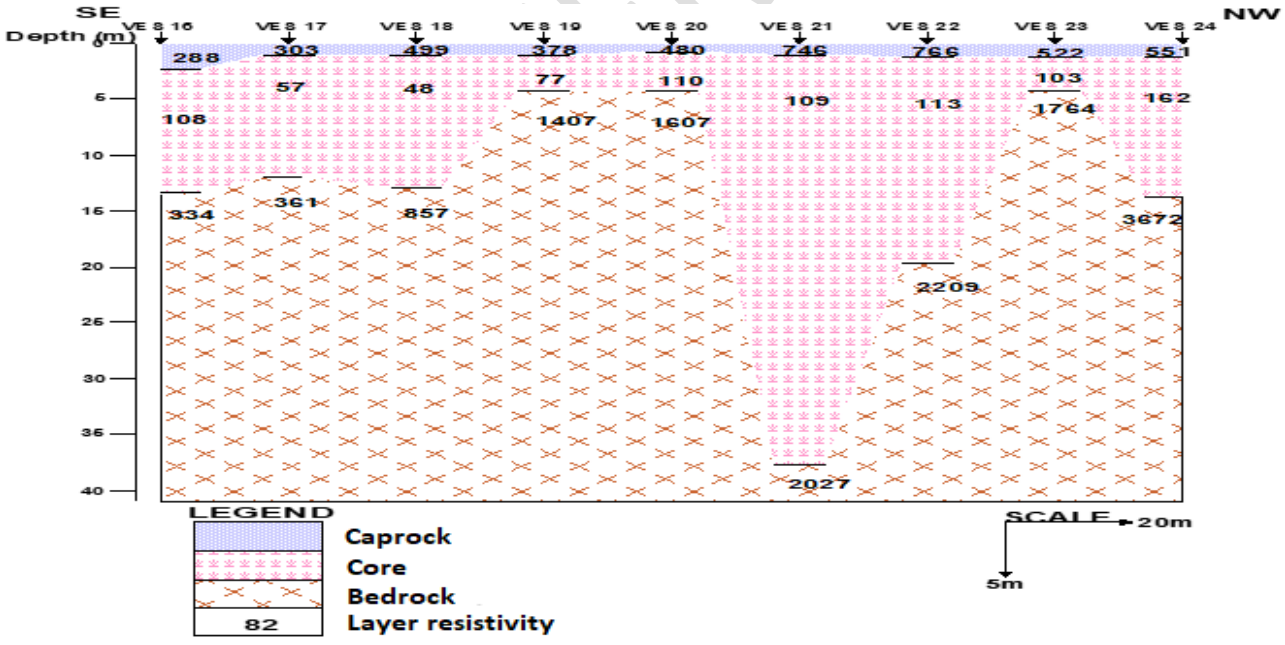

Fig. 8: Geoelectric section beneath the Right Embankment

2D Resistivity Sections

The 2D inverted resistivity section beneath the left embankment (Fig. 9) reveals a top layer of clay-sandy clay mix of resistivity ranging from 16.8 Ωm to 242 Ωm underlain by a more resistive basement rock of resistivity varying from 426 Ωm to 13201 Ωm. The resistivity values less than 1000 Ωm indicate weathering. Pockets of anomalously low resistivity values less than 2 Ωm observed at 10 m - 20 m depth beneath stations 10-14 are suspected anomalous seepage. The 2D inverted resistivity section beneath the right embankment reveals a top layer with resistivity ranging from 21.1 Ωm to 255 Ωm underlain by resistive basement with resistivity varying from 311 Ωm to 183319 Ωm (Fig. 10). Four zones of anomalous resistivity low suggesting anomalous seepage were observed beneath the right embankment beneath stations 2–3 from surface to about 8 m depth, stations 6 - 8, and 9 - 10 at depth from about 8 m to 20 m, and stations 12-15 at depth from 10 m to 30 m.

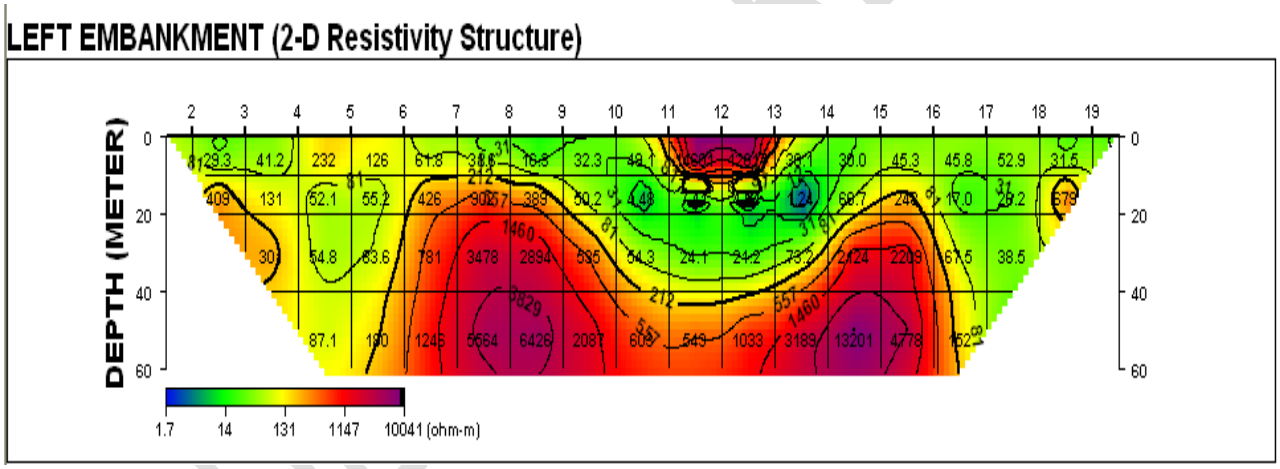

Fig. 9. 2D inverted resistivity section beneath the Left Embankment

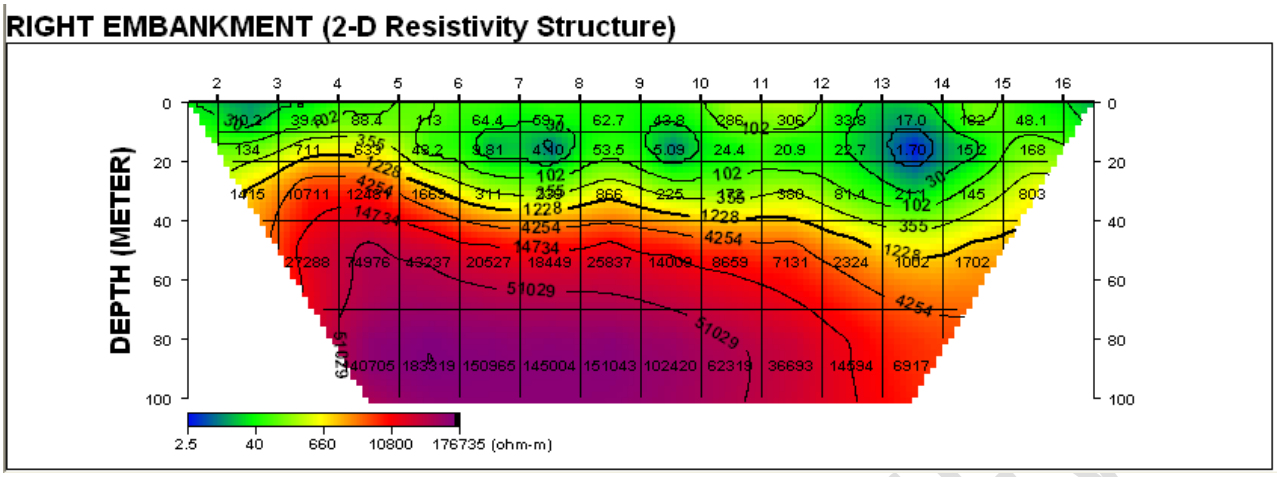

Fig. 10. 2D inverted resistivity section beneath the Right Embankment

CONCLUSIONS

EM-VLF and geoelectrical methods, involving Schlumberger VES and 2D resisitivity profiling employing dipole-dipole electrode array, were used to assess unravel occurrence of anomalous seepage in the embankment of Asejire dam in Ibadan, southwestern Nigeria. The 2D inverted VLF-EM sections revealed pockets of high conductivity anomalies suggesting anomalous seepage beneath both flanks of the dam embankment. The 2D inverted resistivity sections delineated zones with anomalously low resistivity generally less than 10 Ωm observed at 10 m - 20 m depth beneath stations 10-14 beneath the left embankment, and at 5 m–21 m depth between stations 6 and 10, and depth 0 m – 30 m between stations 12 and 15 beneath the right embankment suspected to indicate anomalous seepage.

This study has shown that the VLF and geoelectric methods are effective for detecting anomalous seepages in the assessment of dam safety. Routine post-construction geophysical investigation should be conducted to check for and monitor potential anomalous seepages in dam embankment and assess the dam integrity. Remedial measures can then be put in place as the need arises to save the dam from structural failure and its inherent catastrophe.

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