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A TWO-DIMENSIONAL ELECTRICAL RESISTIVITY IMAGING OF AN EARTH DAM, ZARIA, NIGERIA

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A 2D electrical resistivity survey was carried out at the Ahmadu Bello University (Zaria, Nigeria) farm dam in order to identify and characterize possible seepage paths within the dam and its foundation. A three hundred meter long profile spanning the entire axis of the dam was obtained on the crest of the homogeneous earth dam. On the basis of analysis of the data, three zones of relatively uniform resistivity were identified and mapped. Portions within a layer of anomalous low resistivity are interpreted to represent weak zones within the embankment favoring seepage. Also the foundation of the dam shows evidence of intense weathering and is suspected to also provide a seepage path for water from the reservoir.

INTRODUCTION

It has long been established that results from a geophysical survey of a dam can contribute significantly toward its maintenance, repairs or rehabilitation (e.g. Bogoslovsky and Ogilvy, 1970; Butler et al., 1989; Abuzeid, 1994; Sirles, 1997; Aal et al., 2004; Lim et al., 2004; Song et al., 2005). Earth dams need periodic inspection and monitoring against the development of anomalous seepage paths either through the embankment, foundation or the abutment materials. The Ahmadu Bello University (A.B.U.) located in Zaria, Nigeria, owns a farm dam that is more than 40 years old. The dam is, for the first time, subjected to an intensive survey involving electrical resistivity tomography.

Anomalous seepage is one of the major reasons for embankment dam failures. Geophysical methods have the ability to detect anomalous seepage paths at an early stage before the safety and integrity of the dam is at risk. These seepage paths are in the form of sinkholes and other piping features which are products of internal geodynamic processes. Increasing filtration velocities as water seeps through the embankment usually results in suffusion followed by subsidence and finally collapse of the embankment. Electrical resistivity methods have proven to be one of the most sensitive in detecting changes in soil moisture and it is a very effective tool in determining depth to water saturated zones and groundwater flow patterns (Aal et al., 2008).

The A.B.U. farm dam is a homogeneous earth dam constructed by the Nigerian Tobacco Company in about 1966 across a small stream creating a lake for irrigation of the tobacco farm. In July 1971 the dam together with the farm was handed over to A.B.U. The purpose of acquiring the property was to provide facilities for practical teaching of Agriculture and Veterinary Medicine. Analysis of the water economy of the lake in 1971 showed that the existing lake could make a substantial contribution to the University's urgent water needs without jeopardizing the teaching function of the University farm with respect to both irrigation and wildlife study. The dam has a storage capacity of 5.6×10^8 liters of water and there are plans to develop this huge body of water for domestic water supply.

Reports from the farm management from 1973 to date show that: the earth embankment is deteriorating; its wall is severely eroded by water waves during the harmattan winds; and there is evidence of rat holes and severe rain cuts on the embankment at several places. A frequently occurring geotechnical problem associated with such an aging infrastructure is the development of possible anomalous seepage routes (Butler et al., 1989). This is evident in our case study as the down stream portion of the dam is marshy all year round despite the fact that the water level in the reservoir stays below the spillway for a greater potion of the year and the lake is underutilized. No geophysical survey has ever been carried out after the construction of the dam and probably was not prior to the construction of the dam due to the then non acceptance of engineering geophysics as an integral part of dam engineering (Butler et al., 1989). A visual assessment of the embankment was carried out in 1977 and the top 1-2 m portion was recommended for scraping and refilling. This recommendation was not implemented until recently when the attention of the University management was focussed on the condition of the dam, and plans were developed to rehabilitate the infrastructure.

This work aims at investigating the subsurface conditions of the dam, to detect weak zones favorable for seepage or a consequence of seepage within the dam and its foundation thereby providing additional information needed for the repair of the dam.

PHYSICAL ENVIRONMENT, GEOLOGY AND HYDROGEOLOGY OF THE STUDY AREA

The impounding reservoir known as the A.B.U. Farm Dam with its drainage basin (19,247,000 m^2) is situated within the highly degraded former Guinea Savanna which has been mostly converted to farm land. It has a typical Savannah climate of distinct wet and dry seasons, with a moderate rainfall of about 1,047 mm/a. The rainy season usually starts in May and ends in October and the dry season lasts from late October to April (Walter, 1977).

The reservoir together with its drainage basin (watershed) is underlain by the biotite gneiss belonging to the Precambrian basement complex of northern Nigeria (Figure 1). It is therefore a metamorphic terrain bounded in the west by quartz-mica schist and in the east by biotite granite believed to have intruded the basement gneiss during the Pan African Orogeny according to McCurry (1970). The greater part of the area is covered with thick regolith mainly derived from in-situ weathering of the basement rocks. Some areas on the watershed are capped by lateritic material.

METHODOLOGY

Resistivity determinations are usually made by injecting a specified amount of electric current into the ground using a pair of current electrodes and measuring the potential difference between any two points at the surface caused by non uniform distribution of the electric current in the subsurface. From the measured current (I) and the voltage (V) values, the apparent resistivity is determined (Telford et al., 1990).

The ABEM Lund Imaging system comprising a Terrameter SAS 4000 supplemented with an automated multi-electrode system (the electrode selector) was used in collecting the 2D

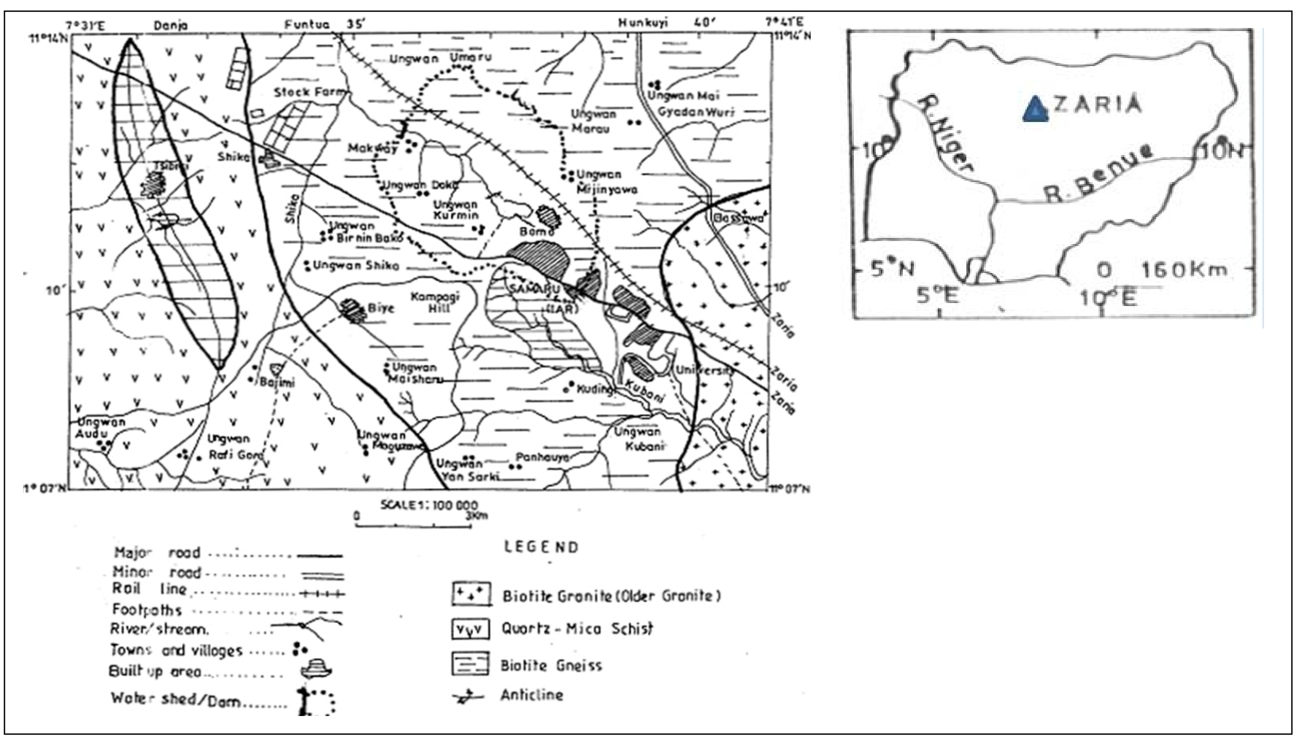

Figure 1. Geological map of the study area (McCurry, 1970).

electrical resistivity data. The Wenner 32SX protocol dedicated for Wenner-á CVES roll-along measurement with 2 cables was employed because of its high signal–to–noise ratio. The 300 m long profile was taken on the crest of the dam spanning it's entire axis (Figure 2) at a unit electrode spacing of 5m. Figure 3 shows the sequence of measurements used to build a pseudo section, with the raw data comprising the determined apparent resistivity registered against each dotted point.

The raw data was processed and analyzed using the computer program RES2DINV (Loke and Barker, 1996). The 2D model used by the program divides the subsurface into a number of rectangular blocks. The program then determines the resistivity of the rectangular blocks that

Figure 2. A satellite map of the reservoir of the A.B.U farm dam with the profile line indicated on the embankment (Modified from Google Earth, 2009).

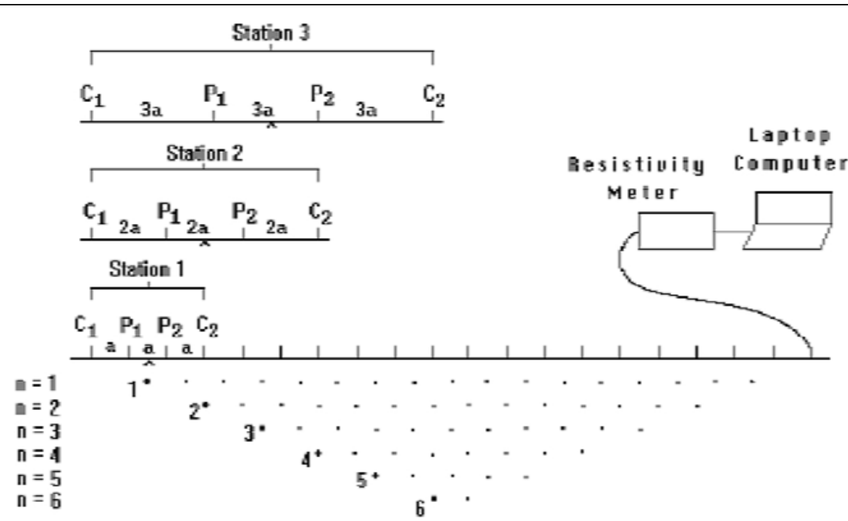

Figure 3. Sequence of measurements to produce a pseudosection using a computer controlled multi-electrode survey setup (Loke, 2001).

produces an apparent resistivity pseudo section (calculated apparent resistivity) which agrees with the actual measurement.

A finite-difference forward modeling subroutine was used to calculate the apparent resistivity values with a relatively dense mesh grid of 4 nodes per unit electrode spacing to increase the accuracy of the calculated apparent resistivity. The thickness of the first layer of blocks was set at 0.5 times the unit electrode spacing with the thickness of each subsequent deeper layer increased by 10%. The model discretization is such that the number of cells used was equal to the number of data points, which is the best option for a large data set of this nature (Loke, 2001). A non-linear least-squares optimization technique (deGroot-Hedlin and Constable, 1990; Loke and Barker, 1996) was used for the inversion routine. The optimization method basically tries to reduce the difference between the calculated and measured apparent resistivity values by iteratively adjusting the resistivity of the model blocks. A measure of this difference is given by the root-mean-squared (RMS) error. The model at the iteration after which the RMS error does not change significantly is usually considered the "best" model and in this work, this occurred at the 5th iteration (see Figure 4).

One advantage of this method is that the damping factor and the flatness filters can be adjusted to suit different types of data. Since the data obtained in this work are less noisy, an initial damping factor of 0.1 was used and the minimum was fixed at 0.02 (one-fifth of the initial) to stabilize the inversion process. The inversion routine generally reduces the damping factor after each iteration and the smooth models obtained have the ability to suppress model structures not required by the data. The generated models therefore contain the minimum possible structures and it is then likely that the true Earth is at least as rough as the models (deGroot-Hedlin and Constable, 1990) thereby increasing the probability that identified anomalies actually exist.

RESULTS AND DISCUSSION

The complete set of geophysical images comprising of the measured apparent resistivity pseudosection, the calculated apparent resistivity pseudosection, and the inverse model resistivity section are shown in Figures 4a, 4b and 4c, respectively. The inverse model resistivity section, Figure 4c, representing the true subsurface resistivity distribution was further interpreted using information from the geologic log of a borehole drilled within the study area (Table 1).

Combining the information provided in Table 1 with the range of resistivity values obtained from the inverse model resistivity section (40-526 ohm-m), a lithological unit-based model classification is derived as shown in Table 2.

About eleven geoelectric segments are encountered in the inverse model resistivity section with each geoelectric segment represented by a distinct colour. The reliability of the inverse model resistivity section (Figure 4c) is reflected in the degree of agreement between the measured and calculated apparent resistivity pseudosections (Figures 4a and b). This can be easily seen by visual inspection of the images of the two apparent resistivity pseudosections (Figures 4a and b) and also from the low RMS error which is 2.0%.

The eleven geoelectric segments in the inverse model resistivity section constitute three distinct geologic layers based on the new classification (Table 2). The top layer with resistivity value ranging from 40 to 85 ohm-m and thickness from 10 m to 18 m is interpreted as a lateritic clay soil with varied moisture content. This is the anthropogenic construction material used as

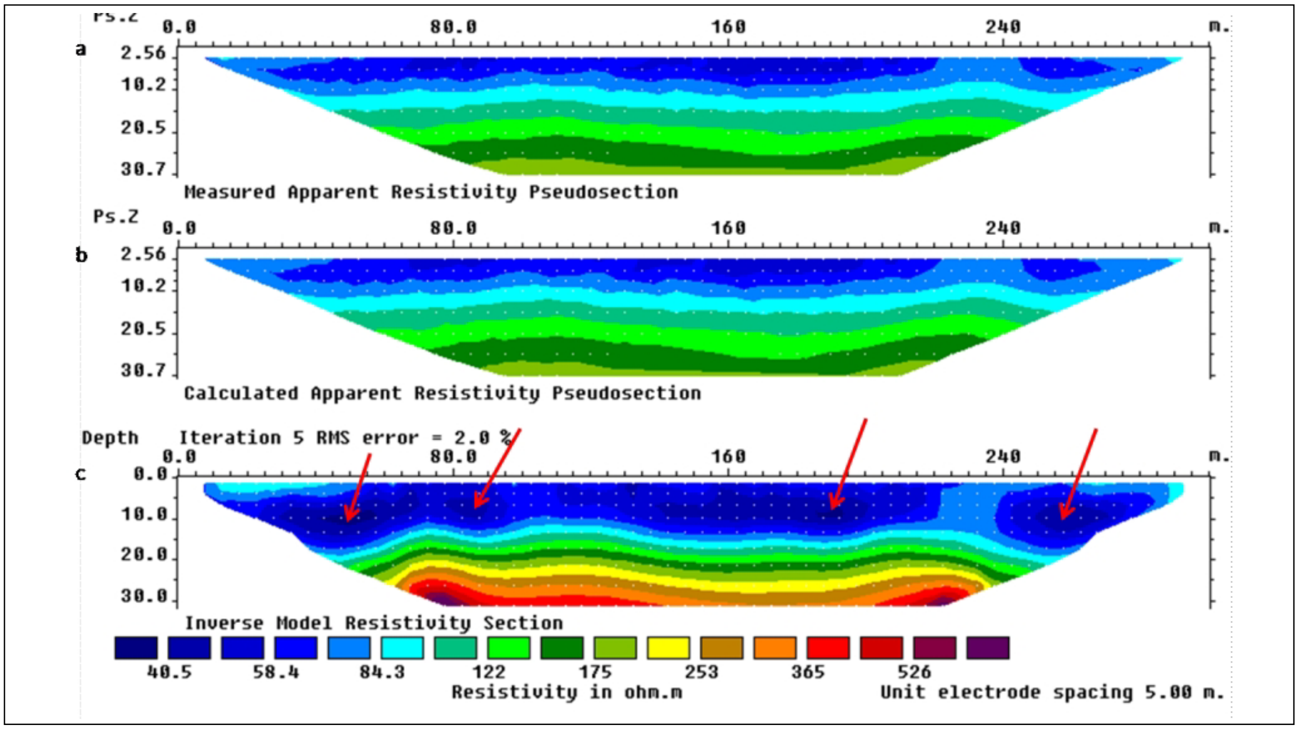

Figure 4. a) The observed and (b) the calculated apparent resistivity pseudo sections for the data set with (c) the subsurface model obtained from inversion. Arrows indicate zones of anomalously low resistivity.

refill after excavation of the overburden within the river valley during the construction of the dam. The layer shows evidence of heterogeneity with portions of anomalously low resistivity of less than 40 ohm-m (indicated with arrows in Figure 4). This is interpreted to be associated with differential compaction which led to formation of weak zones resulting in differential saturation as the reservoir got filled up with water. Four of these weak zones are identified as anomalies of interest in this work as they could serve as conduit for seepage of water from the impounding reservoir. The relatively low resistivity layer is underlain by a moderate resistivity layer (122 - 175 ohm-m) with average thickness of 10 m. This layer is interpreted as a highly weathered portion of the gneissic bed rock with the relatively moderate resistivity value due to saturation. Such a weak formation could favour the development of micro channels providing possible seepage path way. These account for the all-year- round marsh at the downstream portion of the dam and also for the inability of the reservoir to be filled to capacity except at the peak of the rainy season. A high resistive layer with resistivity range from 253 to 526 ohm-m is observed at a depth ranging from

Table 1. Lithology of a borehole log drilled within the study area (NWRI, 2002).

Depth of occurrence (m)		Thickness (m)	Lithology
FROM	TO		
0	15	15	Reddish brown laterite
15	21	6	Brownish sandy clay
21	42	21	Weathered basement
42	-	-	Fresh Crystalline Rock

Table 2. Model classification of lithology and resistivity from the data obtained.

Rock Types	Resistivity (? m)
Lateritic Clay	40-85
Highly weathered basement	122-175
Fairly weathered basement	253-526
Fresh basement	>1000

23 to 25 m estimated from the crest of the dam. This zone represents a fairly weathered and less saturated portion of the bedrock. The fresh basement associated with resistivity value of 1000 ohm-m was not encountered probably due to the limitation of the depth of investigation.

CONCLUSION

The inverse model resistivity section which is an image of the subsurface, showing a cross section of the embankment and the underlying rock units, reveals three distinct layers of relatively uniform resistivities. The first layer comprising of lateritic clay of construction material shows evidence of heterogeneity associated with differential compaction and saturation with weak zones favorable for seepage. The foundation of the dam is severely weathered and suspected to provide conduit for seepage of water from the dam. It is recommended that the four portions identified within the embankment be drilled and grouted. In the case of the suspected weathered portion of the bedrock, a cut off wall spanning the entire axis of the dam starting from a depth of 15 m to 25 m is recommended. These will increase the useful life of the infrastructure and enable the purpose for which the dam was acquired to be continuously accomplished.

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