Time-Lapsed Geophysical Investigation of the Mokuro Earth Dam Embankment, Southwestern Nigeria, for Anomalous Seepages.

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ABSTRACT

The Mokuro Earth Dam Embankment in Ile-Ife, Southwestern Nigeria, was investigated for anomalous seepages using the Magnetic, Spontaneous Potential (SP), and Resistivity methods. The Magnetic and SP methods utilized the profiling technique at station interval of 5 m, while the Resistivity method involved Vertical Electrical Sounding (VES) and dipole-dipole profiling. The three geophysical methods were adopted at the first phase of data acquisition shortly after the dam artificial lake was fully discharged and the upstream side of the earth dam embankment was rehabilitated with cement concrete. The second and third phases were carried out two weeks and three months after the artificial lake was fully restored and this involved the SP and 2-D resistivity measurements only. Geophysical measurements were made along a traverse established along the crest of the embankment. Corrected magnetic data and the SP data were presented as profiles and the resistivity data as VES curves and pseudosections. Qualitative, semi-quantitative and quantitative interpretation techniques were adopted for the SP, magnetic and VES/dipole-dipole data, respectively.

The two prominent magnetic anomalies identified were attributed to the steel rods within the spillway structure and the metallic bleeding pipe within the dam embankment. The geoelectric section delineated the topsoil/caprock, the lateritic layer, the weathered layer/embankment core, the partly weathered/fractured basement, and the fresh basement bedrock. Three zones with negative potential SP troughs were suspected to be due to seepages emanating from the interface between the spillway structure and the dam embankment and superposition of electrical responses from the metallic bleeding pipe and streaming potential in a partly weathered/fractured basement. All of the 2-D electrical images identified the topsoil/caprock, weathered layer/embankment core and the basement bedrock. Two anomalously low resistivity (34-51 Ωm) zones suspected to be precipitated by anomalous seepages through the interface between the spillway and the dam embankment, and a partly weathered/fractured basement within and beneath the embankment core were also identified. The Mokuro Earth Dam has a serious problem of anomalous seepages within and beneath it’s embankment.

(Keywords: Mokuro Earth Dam Embankment, anomalous seepages, rehabilitation, geophysical investigations)

INTRODUCTION

A dam is a barrier that impounds river or stream water. Dams are constructed for various purposes such as irrigation, potable water supply, fishing, recreation, hydroelectric power generation, flood control, silt or debris control, river canalization etc. Controlled seepage/spillage channels are usually incorporated in the design and construction of dam embankments. A good dam embankment is therefore not expected to lose water through any uncontrolled path. However, anomalous seepages may sometimes occur through permeable soils, rock aquifers controlled by their structure/bedrock topography, and faults/master joints (McLean and Gribble, 1979). Apart from the loss of impounded water through leakage under a dam or through the embankment, the uplift pressure by the percolating water may also affect the foundation.

Progressive erosion of weak rocks and soils along leakage paths produces piping, which can occasion dam failure. Other possible causes of uncontrolled leakage/failure include age of dam, poor construction materials, defects in design, etc. (Olorunfemi *et al*., 2000 a & b).

The Mokuro Earth Dam was constructed in 1954 with the intent to serve as a source of potable water supply to the people of Mokuro and some parts of Moore area of Ile-Ife. The water level in the dam artificial lake has dropped significantly over the years, due to anomalous seepages. Physical evidence of distress resulting from anomalous seepages, manifesting itself as cracks at the upstream side and verdant vegetation at the downstream side of the earth dam embankment, necessitated rehabilitation works with cement concrete on the upstream side of the earth dam embankment.

The dam embankment is about 30 m long, 5 m high and about 3 m wide at the top. The geophysical investigation carried out on the crest of the dam embankment was therefore aimed at investigating the seepage condition of the dam embankment over a period of time and determining the effectiveness of the rehabilitation works in controlling seepages through the embankment.

The geoelectric equivalence of an idealized competent embankment section (Figure 1) is such that a low resistivity, impervious clay core (or fill) occurs between more resistive caprock and competent bedrock. The geoelectrical model is that of an H-type. This makes the electrical resistivity method very relevant in earth dam embankment investigation (Olorunfemi *et al.,* 2000 a and b).

GEOMORPHOLOGY AND GEOLOGY OF THE DAM SITE

The Mokuro Dam-Site is located in Ife-East Local Government Area of Ile-Ife with geographic coordinates approximately between Latitudes 7^0 30.350^I N and 7^0 30.380^I N and Longitudes 4^0 36.520^I E and 4^0 36.650^I E (Figure 2).

The earth dam was erected across the Mokuro River. The river has a NW-SE course where it was dammed. The topography at the site is gently undulating with elevation of between 236 m (at the floor of the reservoir) and 250 m in the surrounding hills that roll towards the dam artificial lake. The area surrounding the dam-site is covered with thick vegetation typical of the tropical rain forest vegetation belt of Nigeria (Olorunfemi *et al*., 2004).

The area around the Mokuro dam-site is located on pegmatized schist which lies within the Ife-Ilesha Schist Belt (Figure 2). The Ife-Ilesha schist belt is a member of the Precambrian Basement Complex of southwestern Nigeria (Rahaman, 1988).

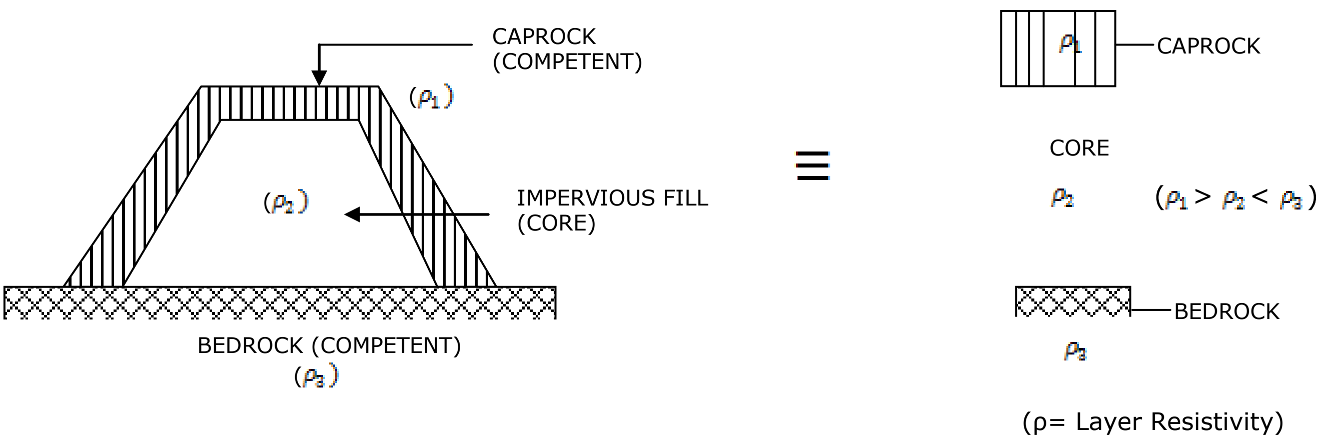


Figure 1: Earth Dam Embankment Core Section and Equivalent Resistivity Model (Modified after Olorunfemi *et al*., 2000a).

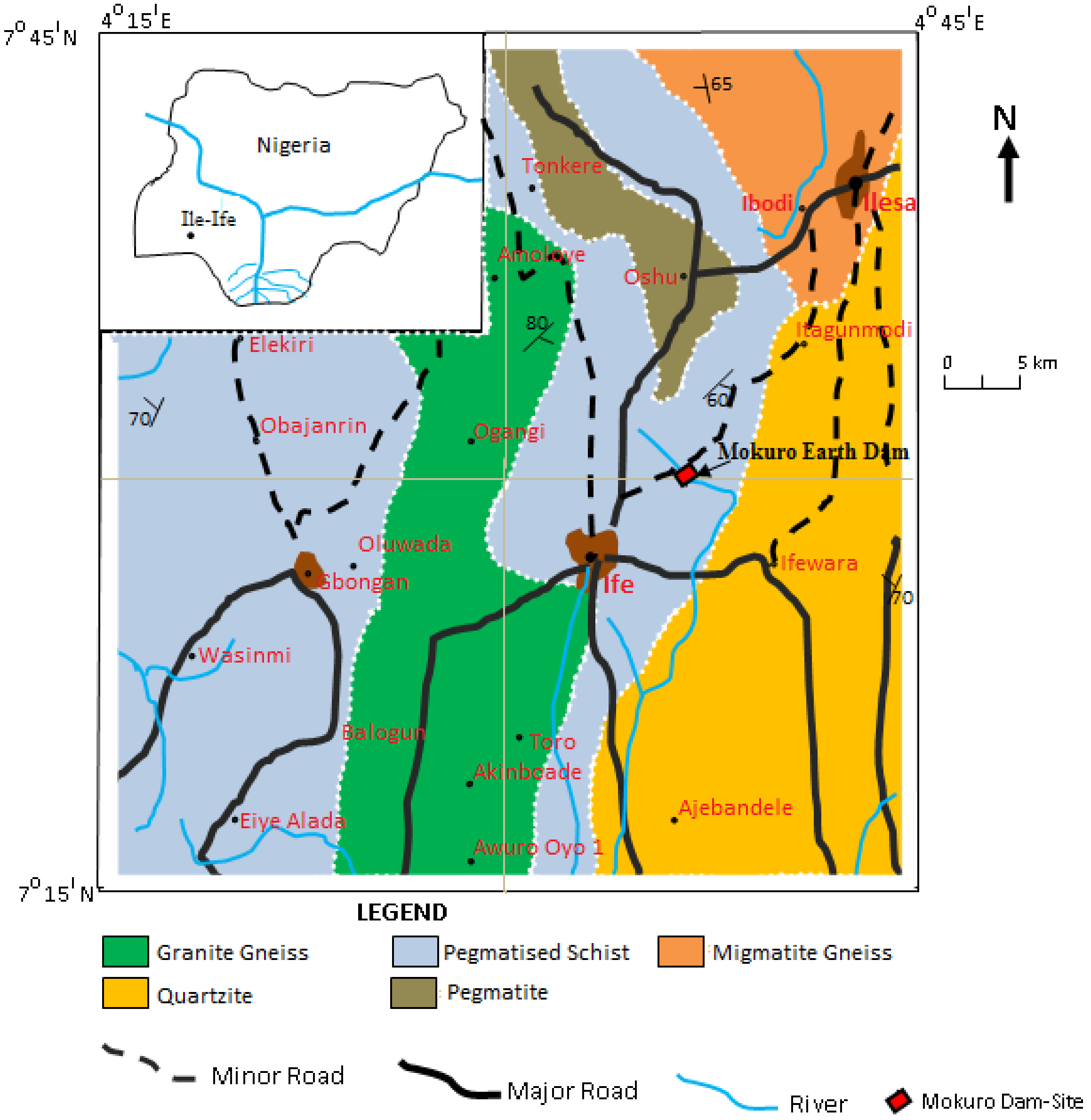


Figure 2: Geological Map of the Area Around Ile-Ife (Adapted from Microsoft Encarta 2009 and Iwo Sheet 60 Geological Map).

METHOD OF STUDY

The geophysical data acquisition was carried out in three phases. The first phase, carried out in March, 2011, involved the Magnetic, SP, and Resistivity (utilizing VES and dipole-dipole profiling) methods shortly after the dam artificial lake was fully discharged and the earth dam embankment was rehabilitated with cement concrete, at the upstream side. The second and third phases were carried out two weeks (in April) and three months (in June) after the dam was gated and the artificial lake was fully restored and this involved the SP and 2-D resistivity measurements only. The magnetic data were acquired along the traverse established on the crest of the dam embankment (Figure 3) with station separation of 5 m using the Proton Precession Magnetometer. The SP data were acquired along same traverse using the total field array at a station interval of 5 m. The Electrical Resistivity survey involved 1-D Vertical Electrical Sounding (VES) and 2-D electrical imaging techniques.

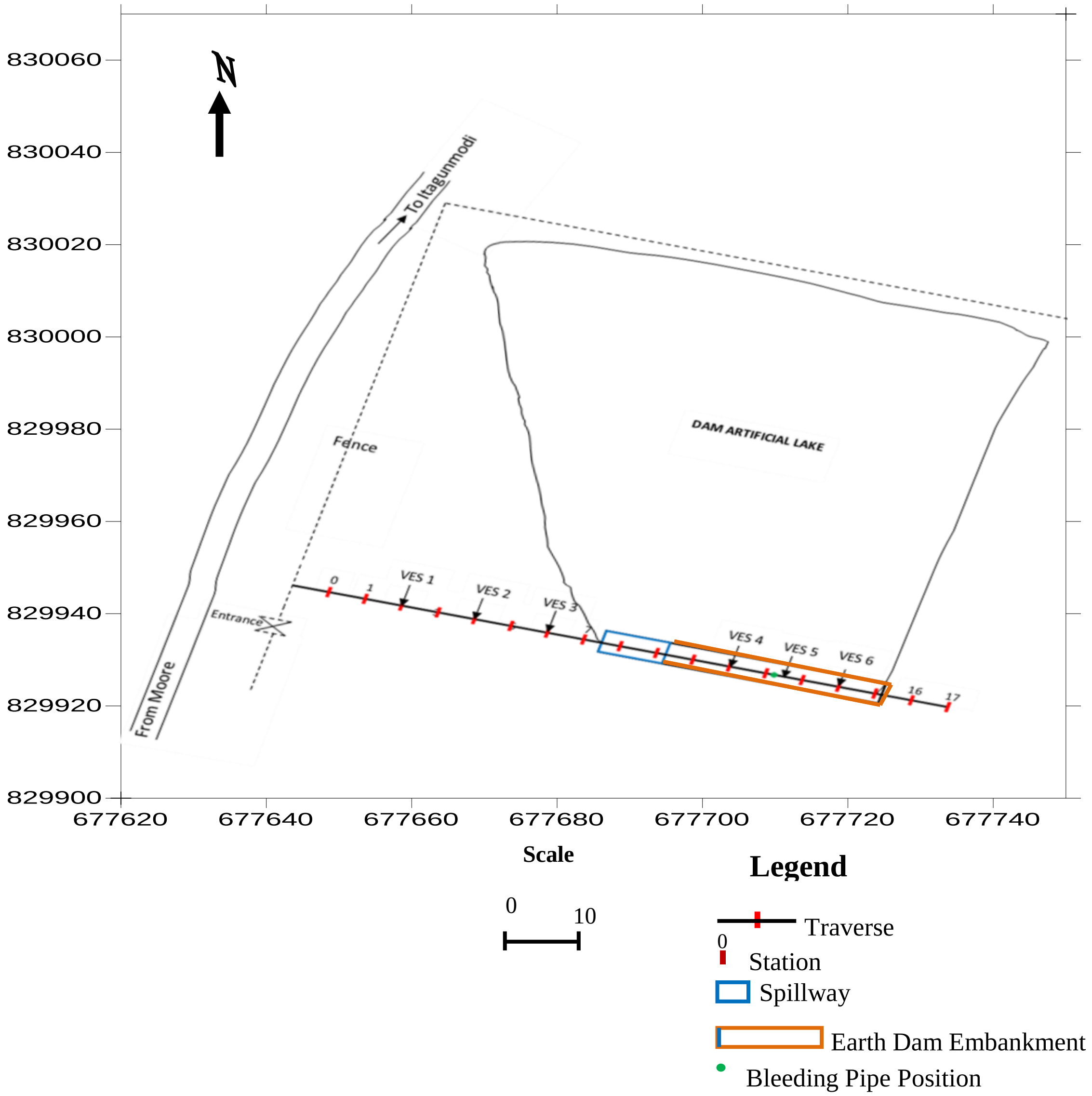


Figure 3: Geophysical Data Acquisition Map Showing the Traverse and the Measurement Stations.

The VES utilized the Schlumberger electrode array with electrode spacing (AB/2) ranging from 1 m to 65 m. Six (6) VES stations were occupied. The 2-D subsurface electrical imaging utilized the dipole-dipole electrode array with electrode spacing of 5 m and expansion factor (n) ranging from 1-5.

DATA PRESENTATION AND INTERPRETATION

The raw magnetic data were corrected for diurnal variation and offset and the corrected data were used to generate a magnetic profile (Figure 4). The magnetic profile was interpreted qualitatively by visual inspection and semi-quantitatively for target position and depth to the top of the magnetic source using Parasnis, 1986 method. The SP data were presented as profiles (Figure 5) and were interpreted qualitatively by visual inspection. The observed VES curves (H, HA, KH, KHA and KQH types (Figures 6 a-e)) were interpreted quantitatively by partial curve matching and 1-D forward modeling using WinRESIST 1.0 Software (Vander Velpen, 2004). The final VES interpretation results obtained were used to generate a geoelectric section (Figure 7) beneath the dam embankment. The dipole-dipole data were inverted to 2-D electrical images (Figures 8 a-c) using the DIPRO for Windows Software.

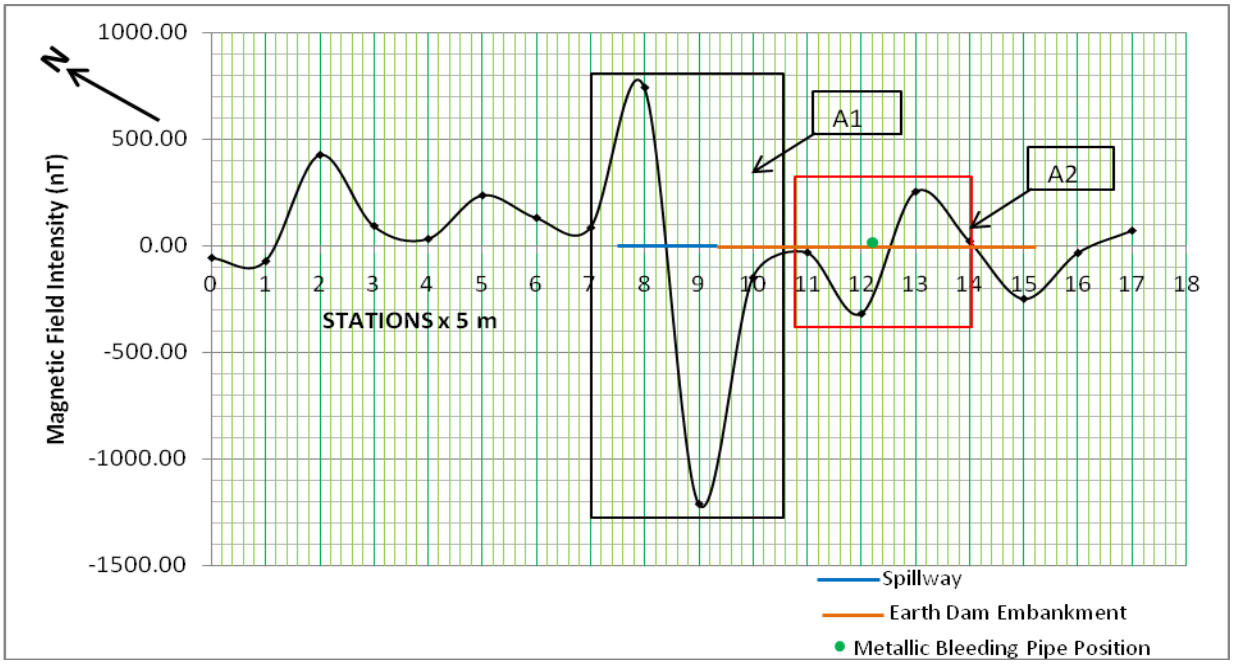


Figure 4: Magnetic Profile along the Dam Embankment.

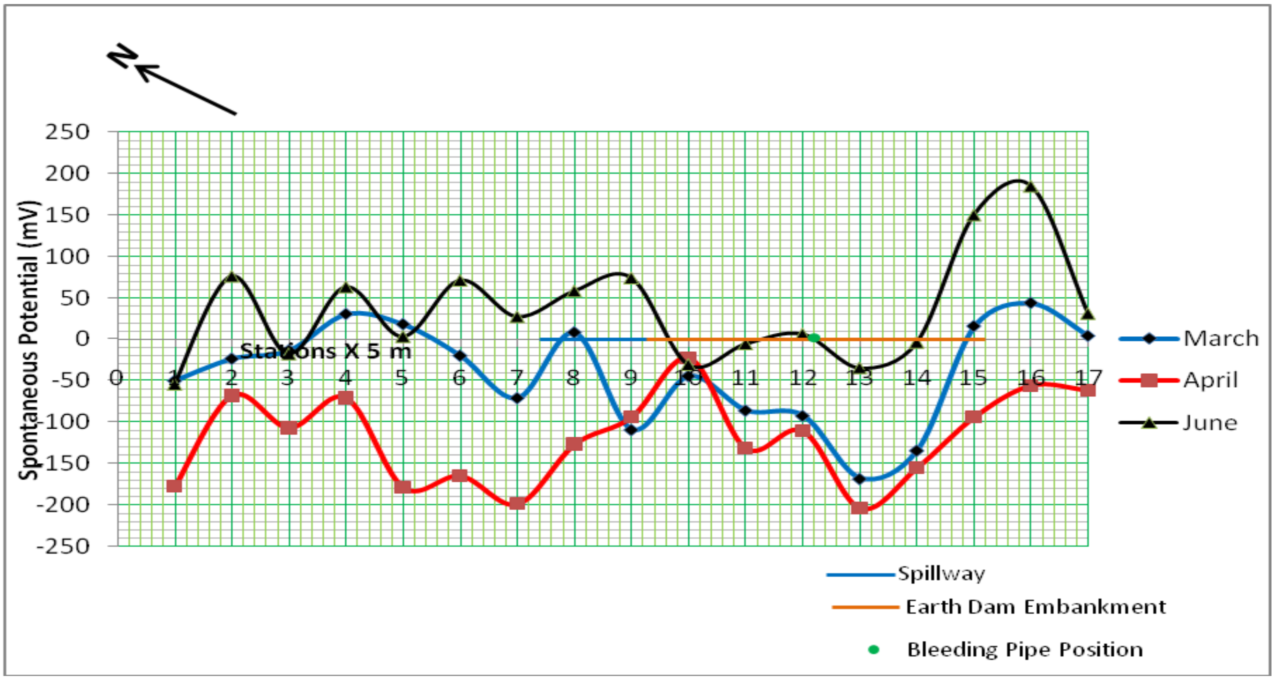
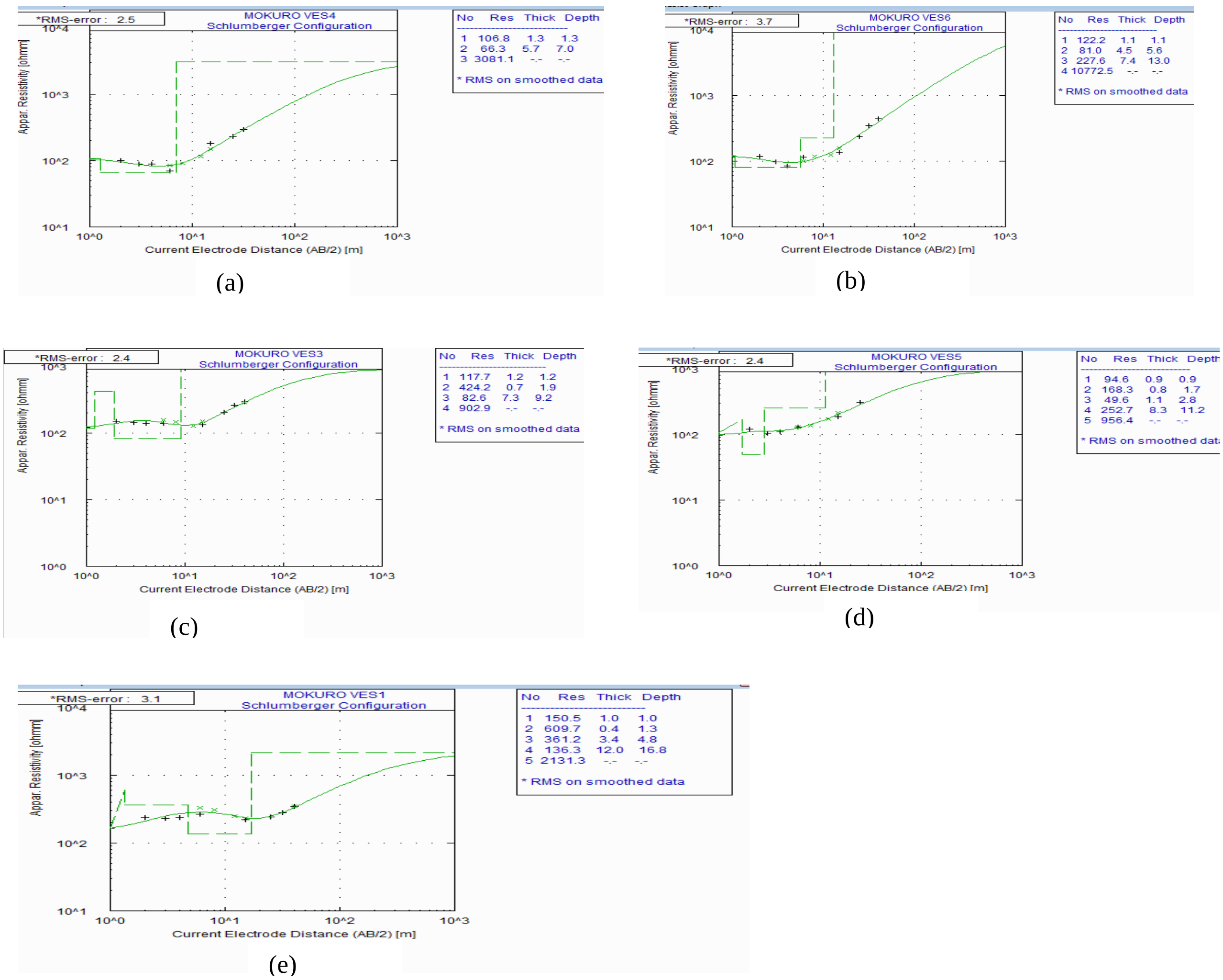


Figure 5: Multiple Plot of all the SP Profiles.



```
*RMS-error :  2.5        MOKURO VES4
                         Schlumberger Configuration

No   Res    Thick  Depth
---------------------------
1   106.8    1.3    1.3
2    66.3    5.7    7.0
3  3081.1    -.-    -.-

* RMS on smoothed data
```

(a)

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*RMS-error :  3.7        MOKURO VES6
                         Schlumberger Configuration

No   Res    Thick  Depth
---------------------------
1   122.2    1.1    1.1
2    81.0    4.5    5.6
3   227.6    7.4   13.0
4 10772.5    -.-    -.-

* RMS on smoothed data
```

(b)

```
*RMS-error :  2.4        MOKURO VES3
                         Schlumberger Configuration

No   Res    Thick  Depth
---------------------------
1   117.7    1.2    1.2
2   424.2    0.7    1.9
3    82.6    7.3    9.2
4   902.9    -.-    -.-

* RMS on smoothed data
```

(c)

```
*RMS-error :  2.4        MOKURO VES5
                         Schlumberger Configuration

No   Res    Thick  Depth
---------------------------
1    94.6    0.9    0.9
2   168.3    0.8    1.7
3    49.6    1.1    2.8
4   252.7    8.3   11.2
5   956.4    -.-    -.-

* RMS on smoothed dat
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(d)

```
*RMS-error :  3.1        MOKURO VES1
                         Schlumberger Configuration

No   Res    Thick  Depth
---------------------------
1   150.5    1.0    1.0
2   609.7    0.4    1.3
3   361.2    3.4    4.8
4   136.3   12.0   16.8
5  2131.3    -.-    -.-

* RMS on smoothed data
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(e)

Figure 6: VES Curves (a) H Type, (b) HA Type, (c) KH Type, (d) KHA Type, (e) KQH Type.

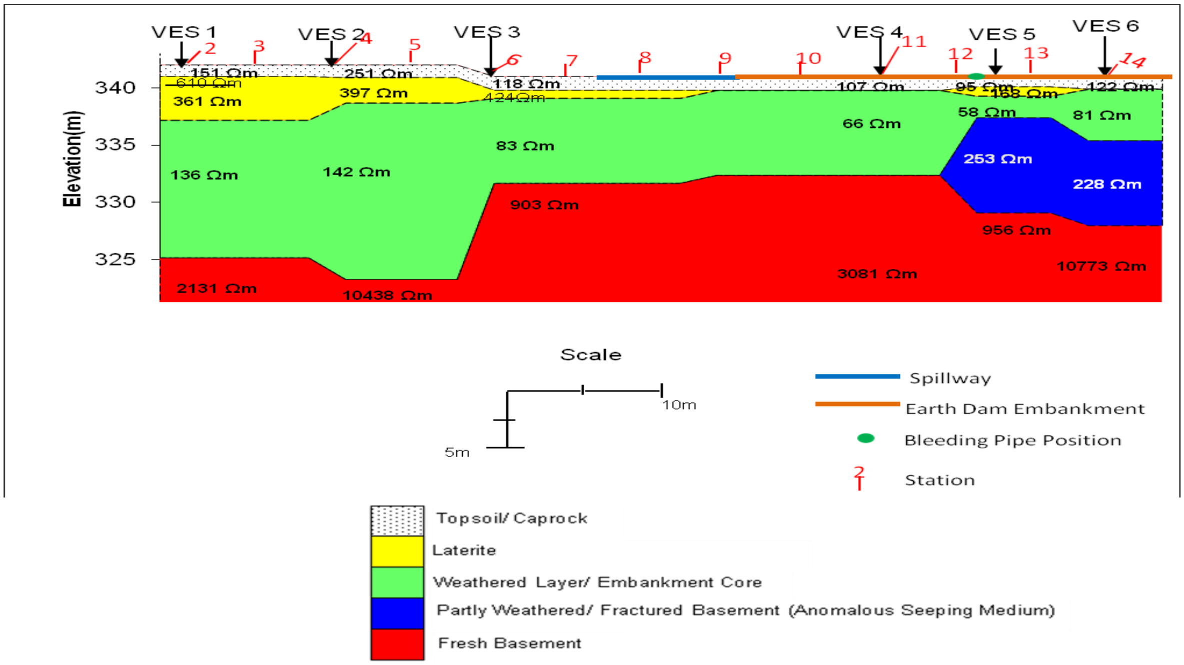

Figure 7: Geoelectric Section Beneath Mokuro Dam-Site.

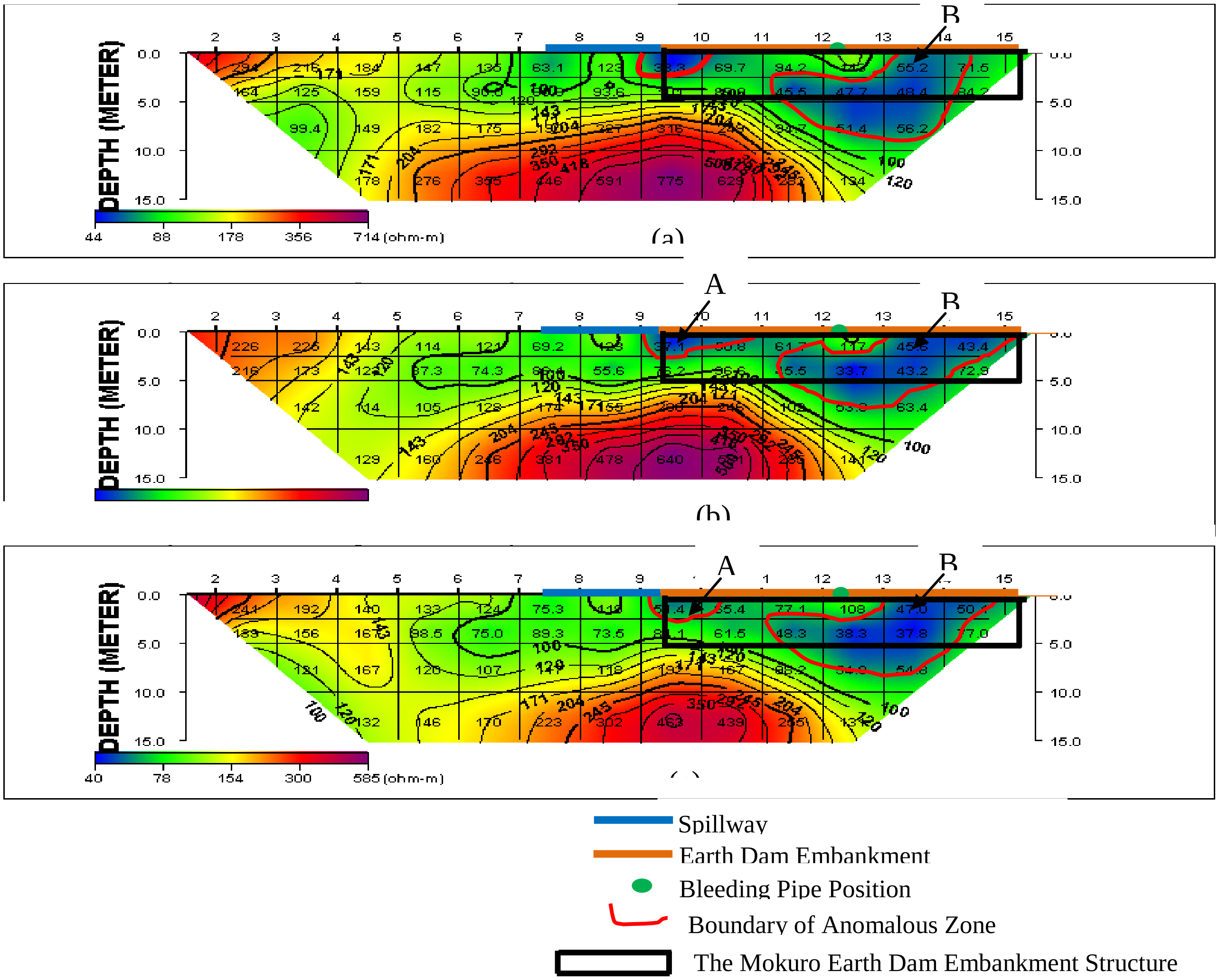

Figure 8: The 2-D Electrical Image (a) After a Discharged Artificial Lake, (b) Two Weeks after Artificial Lake was Restored, (c) Three Months After Artificial Lake Was Restored.

DISCUSSION OF RESULTS

The Magnetic Profile

Two significant magnetic anomalies A1 and A2 can be identified on the magnetic profile along the dam embankment (Figure 4). The first anomaly (A1) occurs between station 7 (35 m) and station 9 (45m) (Figure 4). The second anomaly (A2) occurs between station 11 (55 m) and station 14 (70 m) (Figure 4). Magnetic anomaly A1 (Figure 4) has relatively high peak positive (795 nT) and peak negative (-1220 nT) amplitudes. As shown in Figure 4, A1 is located on the spillway. The spillway is a steel rod reinforced concrete structure which constitutes a horizontal slab supported by underlying vertical beams. It is suspected that the iron mesh within the spillway concrete structure may have been responsible for the magnetic anomaly A1. Magnetic anomaly A2 (Figure 4) has a moderate peak positive (254 nT) and peak negative (-318 nT) amplitudes. Its amplitudes, compared to that of anomaly A1 could suggest a relatively deep causative body or a smaller dimension magnetic body located at shallow depth. However the metallic bleeding pipe located at a depth of about 2.5 m within the dam embankment at station 12.2 (61 m) may have been responsible for this anomaly. Using Parasnis, 1986 semi-quantitative interpretation technique, the depths to the top of the magnetic bodies causing anomalies A1 and A2 were estimated to be 2.9 and 2.5 m respectively. The 2.9 m depth estimated for anomaly A1 suggests that the magnetic anomaly A1 could be a cumulative response from the mesh of iron rods within the horizontal concrete slab and that of the iron rods within the vertical beams.

The SP Profiles

Figure 5 shows a multiple plot of the SP profiles obtained during the three phases of measurement. The profiles display similarities in shape/pattern or anomaly form. SP troughs which are indicative of zones along the dam embankment with high streaming potentials and/or diagnostic of highly conductive bodies were identified across the profiles at stations 3 (15 m); 5 (25 m); 7 (35 m); 9 (45 m); 11 (55 m); and 13 (65 m).

The troughs at stations 7 (35 m); 11 (55 m) and 13 (65 m) were consistently recorded during the three phases of measurement indicating prominent SP sources. The troughs at station 3 (15 m); 5 (25 m) and 9 (45 m) were observed only twice; in April and June for stations 3 and 5 which may be due to fluid streaming and March/April for station 9. SP negative troughs with peaks at stations 11 and 13 fall on the earth dam embankment.

The negative peak at station 11 (55 m) may be due to the bleeding pipe located beneath station 12.2 while the second negative peak at station 13 (65 m) may be due to seepage path. It is suspected that the SP anomalies from these two sources may have been superimposed due to their closeness resulting in slight shift of their troughs. The low amplitude peaks at stations 3 (15 m) and 5 (25 m) outside the dam embankment may be indicative of minor linear features within the subsoil acting as water conduit.

The Geoelectric Section

The geoelectric section (Figure 7) delineates a maximum of five (5) geologic layers beneath the dam embankment. The first layer is the topsoil/caprock with resistivities and thicknesses of between 361 and 251 Ωm and 0.9 and 1.3 m respectively. The second layer is the lateritic layer with resistivities of between 361 and 1680 Ωm and thicknesses of between 0.7 and 3.8 m. The third layer which represents the embankment core shows resistivity and thickness ranges of 58-142 Ωm and 1.1-16.6 m, respectively. The fourth layer is a partly weathered/fractured basement with resistivities of between 228 and 253 Ωm and thicknesses of between 7.4 and 8.3 m. The last layer is the basal fresh basement bedrock with a resistivity range of 903-10773 Ωm.

The 2-D Electrical Images

Figures 9 a-c are the 2-D electrical images obtained during the three measurement periods. These images show that the resistivity variations during the three phases of resistivity measurements are 38-775 Ωm; 34-640 Ωm; and 38-468 Ωm, respectively. The gradual reduction in the terminal resistivity is due to increasing level of fluid saturation following the restoration of the dam lake. All the 2-D images identify the three major lithologic units, these include a thin topsoil (resistivities between 63 and 294 Ωm) that represents the caprock on the embankment with bluish/green/yellow/brownish color band which virtually merges into the clay/sandy clay weathered layer (resistivities of between 63 and 129 Ωm) whose upper segment is the embankment core with bluish/greenish color band and the fresh bedrock in yellow/brownish/purple color band.

Two anomalously low resistivity (34-51 Ωm) zones (designated A and B) suspected to be precipitated by seepages through the interface between the spillway and the embankment, and the metallic bleeding pipe/partly weathered/fractured basement beneath the embankment were delineated on all the 2-D resistivity structures (Figures 8a-c). The depth extent of both anomalous zones remain virtually the same (about 2.5 m and 7.5 m, respectively) irrespective of the status of the artificial lake. However, the lateral extent of anomalously low resistivity zone A delineated between stations 9-10.2 when the lake was discharged (Figure 8a) may have changed slightly. Similarly, the anomalous zone B initially identified between stations 11-14 in Figure 9 a extends laterally to station 15 in Figures 8 b and c.

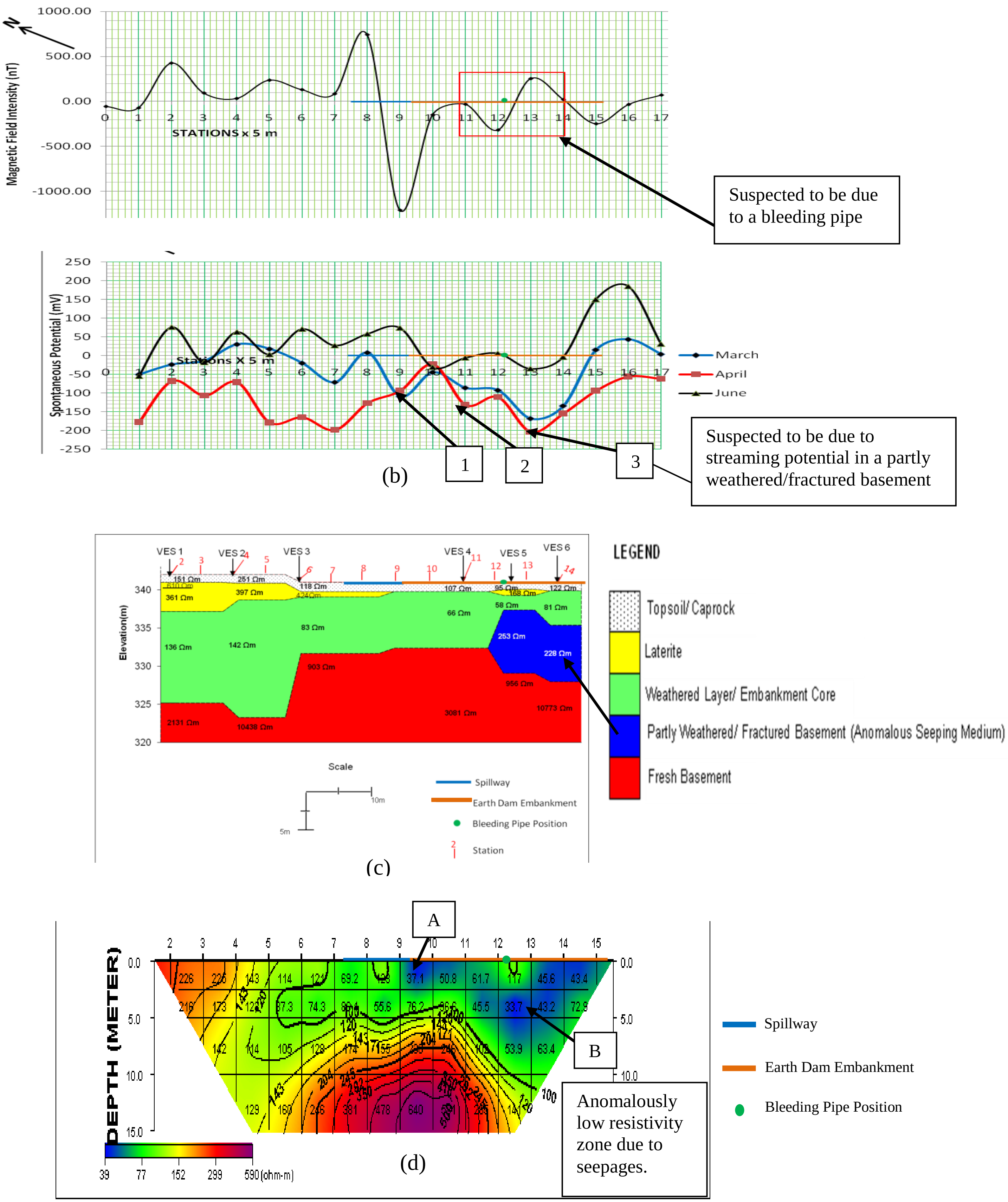

Figure 9: Synthesis of Results. (a) Magnetic Profile, (b) SP Profiles, (c) Geoelectric Section, and (d) 2-D Resistivity Structure.

The Mokuro Earth Dam Embankment has design specifications of 30 m length and 5 m depth of core as delineated on the 2-D images in Figures 8 a-c. The resistivity images indicate that the embankment has anomalous seepage zones both within and beneath the dam embankment. About 50% of the embankment core shows evidence of anomalous seepages. The images of the anomalous seepages increase laterally after the restoration of the dam lake, indicating that the rehabilitation works carried out on the embankment upstream has no significant effect.

SYNTHESIS OF RESULTS

The black arrows in Figure 9 (a-d) serve the purpose of showing the principal anomalous zones identified by the magnetic, SP, and electrical resistivity (VES and dipole-dipole) methods along the crest of the dam embankment that are suspected to be associated with seepages and seepage structures. There is significant correlation in the positions of the identified anomalous zones. All the methods identify anomalous zones between stations 11-14.

The blocked out magnetic signature between stations 11 and 14 (Figure 9 a) is due to a metallic bleeding pipe located at a depth of about 2.5 m within the dam embankment. The magnetic signature was not expected to map non-metallic seepage path. The peak negative SP anomaly (1) at station 9 may have mapped the water seepage precipitated by the interface between the spillway and the dam embankment which could have resulted in the anomalously low resistivity zone A on the

2-D resistivity structure (Figure 9 d). The peak negative SP anomaly (2) at station 11 could have emanated from the bleeding pipe whose response is superimposed on the streaming potential (SP anomaly 3) from a seepage precipitating partly weathered/fractured basement identified on the geoelectric section in Figure 9 c and as anomalous zone B on the resistivity structure (Figure 9 d).

CONCLUSIONS

This study has identified two major anomalous seepage zones within the Mokuro Earth Dam Embankment. The first seepage zone occurs at the interface between the spillway and the embankment between stations 9 and 11. The electrical image of the seepage zone occurs within the embankment core and at depth of up to 2.5 m. The second seepage zone is located beneath stations 11.5 and 15 and is suspected to have been precipitated by a partly weathered/fractured basement column. The electrical image of the seepage zone occurs at depth of up to 7.5 m. Seepage within this zone therefore occurs both within and beneath the embankment core.

The extent of the identified seepage zones covers about 50% of the embankment indicating high level of stress on the embankment. Apart from loss of significant volume of reservoir water through anomalous seepages, the Mokuro Dam carries a high risk of structure breach, in the nearest future.

The general decrease in the embankment resistivity due to increasing saturation during the time-lapsed study and the increase in the lateral extent of the anomalous seepage zone are indications that the recent rehabilitation works on the embankment upstream, with cement concrete, has no significant effect.

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