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Recruiting the Very Low Frequency Electromagnetic Geophysical Technique for the Characterisation of Two Eroded Soil Pipes in Awka, Anambra State, Nigeria

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

Many soil subsidences are due to tunnel erosion, popularly called "soil pipe, which generally begins as a tiny flute hole in the ground but may cause significant environmental implications when left uncontrolled. Varieties of damages resulting from soil subsidence have been reported in several regions within Anambra State, Nigeria. Therefore, the study focuses on examining areas in some parts of the state where soil pipes, a subsurface form of erosion, are prevalent. The research aimed to investigate soil pipes located inside soil subsidence at two Awka sites: Awka site I, and Awka site II, which are geographically positioned at "6.22320^{o}Nand 7.08240^{o}E" and "6.22200^{o}N and 7.08190^{o}E," respectively. The Very Low Frequency Electromagnetic (VLF-EM) geophysical

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technique was used to survey the areas, generating four profiles. Two profiles in each of the study areas, each with a traverse length of 100m and spacing of 5m. Results indicated that the study areas have developed a void-like vertical structure of approximately 5m in depth from the profile's top and has extended to about 4m in length. The Karous-Hjelt filtering has also indicated low conductivity (-10 to 0.5 Mhos), corroborating the maximum negative response of the Fraser filtering inside the soil subsidence structure of each site, while profiles distant from the piping structures did not indicate any cavity or low conductivity.

Keywords: Soil piping; tunnel erosion; erosion; soil subsidence; VLF; conductivity.

1. INTRODUCTION

Geoscientists have identified erosion as a geological process that results in the natural wear and transportation of Earth materials via wind and water. The four main categories of erosion include gully, sheet, rill, and tunnel. While surface erosion (gully, sheet, and rill) has been widely studied and researched by various geoscientists, tunnel erosion, or subsurface erosion, has not experienced similarly significant exploration [1-6].

Tunnel erosion, popularly called "soil piping," is the formation of underground tunnels due to the wearing away of the soil beneath the surface of the Earth [7,8]. Soil piping is a very common phenomenon in lateritic terrains [9], tropical rain forests [10], and Karst regions where the soils are thickly patched [11]. It also occurs in areas having high seasonal contrast and/or high rainfall variability [7], and usually show up as small pores (flute holes) within the subsurface; with time, they become enlarged [12,13], forming channels where soil from the surface and other materials are transported [5]. Hence, soil piping can lead to both surface and subsurface erosion [14]. It begins in many ways, but the most common is the action of rainfall [7,15]. Here, percolating water carrying finer silt and clay particles forms passageways that create pipes, [16,5], which are mainly a few millimeters to a few centimeters in size but can grow to a meter or more in diameter [12,13]. They may lie very close to the surface of the earth or extend several meters below the ground [13]. Once they are initiated, and are not monitored, they become cumulative [16], and with time, the conduit they form will expand, leading to roof collapse and subsidence features on the surface [17,18]. Since it happens underground, in many cases, the phenomenon goes unnoticed until major damage has occurred [15].

Gully erosion, landslides, and floods are the common environmental hazards facing Anambra State in the rainy season [19-21]. However, during the last two decades, land subsidence due to the collapse of subsurface roofs, and tunnel roofs have largely been reported at various parts of the state [19], [22], and [23]. The agricultural productivity has been affected enormously, and the terrain often becomes inhospitable [19]. Developments of these subsurface tunnels have altered the hydrogeology features of the area, and the formations of underground cavities usually affect erected structures and roads [24]. In many of these events, loss of lives and properties may occur, and people’s means of livelihood may be cut short. Finances have also been sunk into the control of this soil subsidence in order to reclaim the roads, people’s properties, and valuable farmlands by members of the community and the government, using the filling up method [24], but little progress has been recorded. Therefore, the urgent need to look for an alternative scientific method becomes paramount.

To estimate the extent at which soil piping has built up without carrying out a major excavation process that will require the need for heavy machinery that will disturb the topsoil, geophysical techniques are employed, which generally incur a low cost but provide a robust investigation of the environment at large [24-28]. Thus, in this study, we investigate some soil piping areas using Very Low Frequency Electromagnetic Survey (VLF-EM), specifically to locate the depth of the soil pipes and the lateral changes in the subsurface around the soil pipes, in order to deduce the characteristics of soil pipes found in Awka, Anambra State.

1.1 Study Area

The study area is Awka, the capital of Anambra State, Nigeria, and it is bounded by latitude (6.15N and 6.31667N) and longitude (7.18333E and 7.2E). The population of this state is 4,177,821 as of the 2006 census, with an area of approximately 1,870 square miles, or 4,844km^2, some parts of the state are so densely populated that the estimated density is about 1500-2000 people per square kilometer [37,38].

The study was conducted at two sites, both of which are located in the center of Awka town in Awka South Local Government Area, the capital of Anambra State, Nigeria (Fig. 1). The first site (Awka Site I) is located close to Paul University, Awka, with a geographical coordinate of (6.22320^{o}N and 7.08240^{o}E). The piping hole that is about 5cm in diameter is visible, and it has done major damage to the constructed road by creating double sinkholes (soil subsidence) that are about 60cm in diameter. The second site (Awka Site II) is located along the popular Jerome Udorji Secretariat Complex with a geographical coordinate of (6.2220^{o}N and 7.0819^{o}E). The piping hole on this site has existed for about 10 years, creating multiple holes of an average diameter 10cm and a visible sinkhole with a diameter of about 200cm [39].

1.2 Geology and Lithostratigraphy of Study Area

The study area forms part of the Anambra sedimentary basin in southeastern Nigeria. The Anambra basin, shown in Fig. 2), covers about 40,000km^2 [36]. Its southern boundary coincides with the deltaic swamps of the Niger Delta basin and extends northward beyond the Bende-Ameki formation. The basin is said to have originated contemporaneously with the folding and uplift of the Abakaliki-Benue area during the Santonian age. The Anambra basin constitutes a major depocenter of elastic sediments and deltaic sequences, resulting from the second tectonic activity of the lower Benue Trough. Fig. 2 shows the geologic map of southern Anambra [39].

The soils of Anambra State particularly have groundwater reservoirs that severely contribute to ecological problems in the region. They are mainly typified by the coastal plain sands and are highly susceptible to erosion. Under the weak lateritic and acidic soils are unstable and poorly consolidated geologic rocks and materials. The sandy members of these geologic units contain huge groundwater reservoirs that are referred to as aquifers, with pore water pressures that become threatening when overlying structures carry uncompromising loads. Lateritic and sandy soils are easily eroded by stormwater runoff [36].

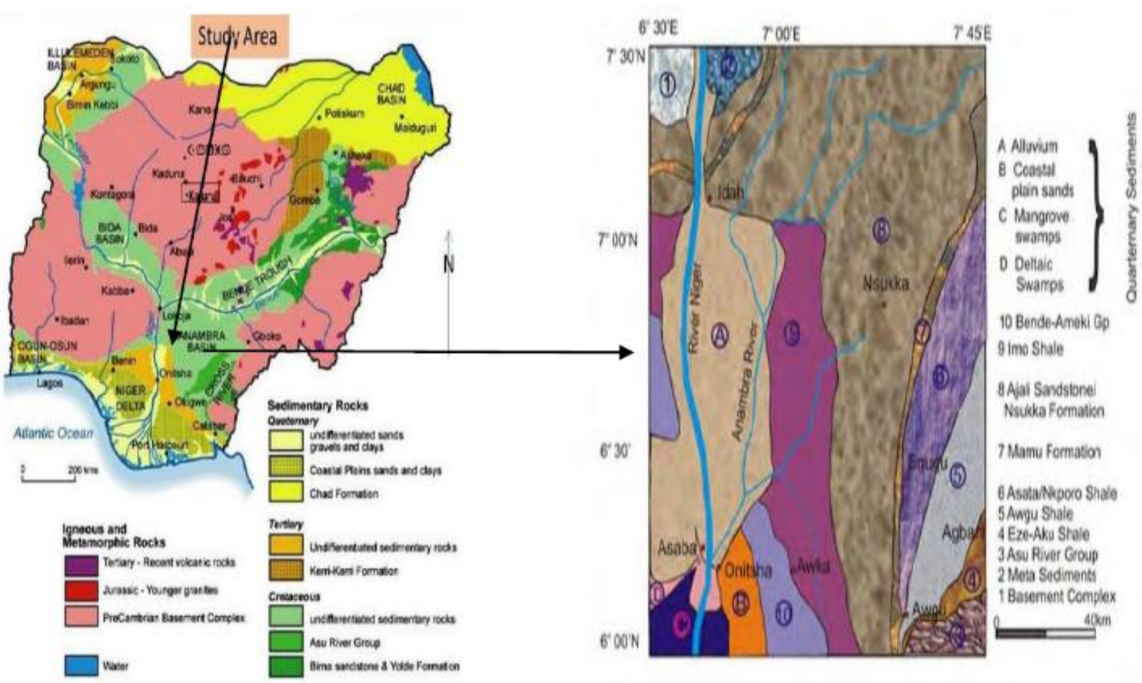


Fig. 1. Map of the geological setting of Nigeria and Anambra Basin, [39]

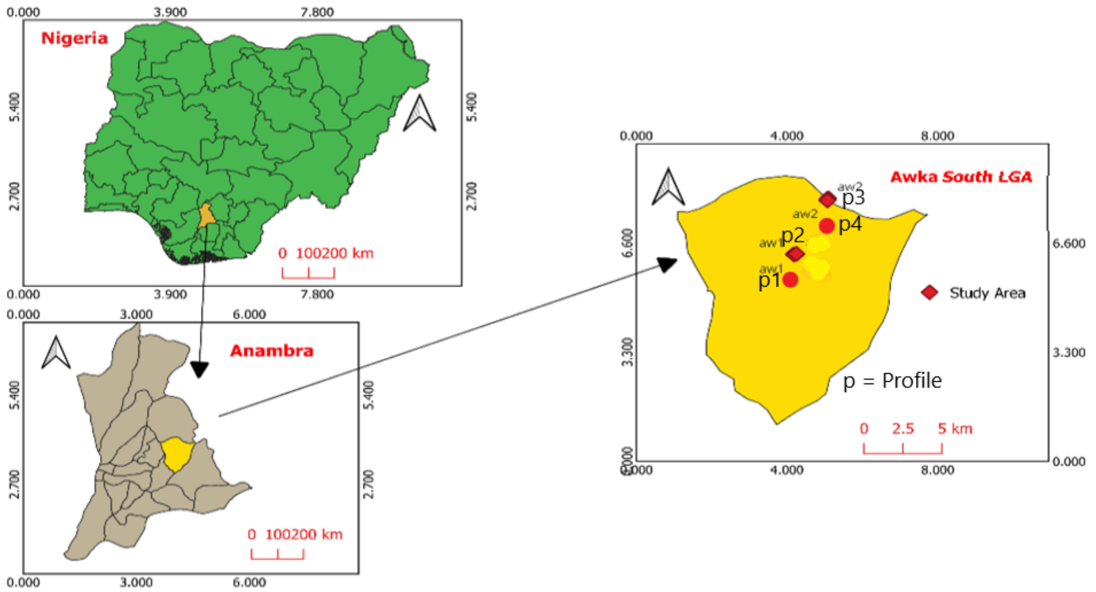


Fig. 2. Map showing the surveyed state and LGA [39]

2. METHODOLOGY

2.1 VLF-EM Method

The VLF-EM method is a low-cost and less cumbersome geophysical technique. It primarily uses primary EM waves, from a nearby satellite to induce secondary EM waves in the form of eddy currents to map shallow subsurface structural features [28].

The VLF meter, ABEM WADI VLF EM, is a battery powered digital indicator that uses a transmitter operating between 15KHz and 25KHz from a powerful radio satellite to generate a time-varying very weak electromagnetic field, the primary field, which can travel very long distances, penetrating the subsurface to induce eddy current, the secondary field, in the buried conductor [28,29].

The ABEM WADI VLF measures the primary field, the secondary field, and the phase lag between the primary and secondary fields. When analysed, this information can be used to detect the presence of a conductor or conductive zone in the ground. For example, a phase lag of the secondary EM field relative to the primary EM field of about half a period (180^0) indicates a conductive ground. A ground with a high resistivity (a poor conductor) will cause the secondary EM field to lag the primary field by a period of 90^0 [32,33]. For the VLF-EM data analyses, the RAMAG and KHFfilt software [29] and [34] were used to find the characteristics of the cross-sectional depth wise of a single profile and filtering, respectively.

Karous-Hjelt filters are an example of linear filters that process the real and imaginary components of the magnetic field, while Fraser filters operate on the tilt angle [30-32]. The ellipticity and tilt angle of the polarization ellipse are used in the calculation of the real and imaginary responses. The tilt angle (Ø) is the angle of the major axis of the ellipse, while the ellipticity (e) [30] is the ratio of the minor axis to the major axis, as described by the following equations below [35].

$$Tan(2\theta) = \pm\frac{2(H_z/H_x)Cos\Delta\emptyset}{(H_z/H_x)^2} \quad (1)$$

$$e = \frac{H_z H_x cos\Delta\emptyset}{H_i{}^2} \quad (1b)$$

Where $H_z$and H_x are the amplitude of the phase difference, $\Delta\emptyset = \emptyset_z - \emptyset_x$, and in which $\emptyset_z$is the phase of *Hz* and $\emptyset_x$is the phase of *Hx* and .

$$H_i = \left|H_z e^{i\Delta\emptyset} sin\theta + H_x Cos\theta\right| \quad (2)$$

From the ellipticity and tilt angle, the real and imaginary responses for a conductor can be calculated from the following equations [11,13]:

$$Real = 100Tan\theta \quad (3)$$

$$Real\% = 100\theta(\theta - inRadian) \quad (4)$$

$$Imaginary = 100e \quad (5)$$

The tangent of the tilt angle is a good approximation of the ratio of the real component of the vertical secondary magnetic field to the horizontal primary magnetic field. The ellipticity is a good approximation of the ratio of the quadrature component of the vertical secondary magnetic field to the horizontal primary field [33]. These quantities are called the real (= tan a × 100 %) and imaginary (= e × 100 %) anomalies, respectively, and they are normally expressed as percentages.

Only the inphase and outphase components are recorded by the ABEM WADI VLF. The ratio of the real component to the imaginary component determines the degree of conductivity [35].

Four profiles with transverse lengths of 100 m and 5 m spacing were surveyed (Fig. 3). On each profile, the inphase and outphase were collected on the interface of the Abem Wadi Meter after a confirmed connection to the external satellite. The geographical coordinates of the particular point at which the reading was collected were recorded. Each profile was oriented in a NW-SE direction to follow the stress formation of the study area. This was done to reduce complications due to anisotropic effects associated with the study area.

3. RESULTS

Fig. 3a–3h illustrate the outcome of the VLF-EM geophysical survey, which utilized both Fraser filtering for the current density data response and pseudo-sections of the Karous-Hjelt filtering to visualize the current density data against subsurface depth. The purpose of this survey was to investigate the distribution of soil pipes in the subsurface.

Profiles 1 and 2 were carried out at Awka site I; profile 1 was done directly on top of a known soil pipe, while profile 2 was done 2 km from profile 1 where there is no evidence of soil pipe, sinkhole, or gully erosion. Similarly, profiles 3 and 4 were projected just as the former profiles, with profile 4 being 1.7 km from profile 3.

All profiles in this section run from NW to SE, with each measurement station (a transverse of 100m) separated by 5 meters of spacing, except for Profile 4, which had a different orientation due to space restrictions. The pseudosection for Karous-Hjelt filtering revealed an uneven distribution of conductivities in the subsurface. Different shades of blue were used to represent the various conductivity zones and distinguish distinctive zones in the subsurface. The light blue color represents the intermediate conductivity of the clay zone, while the sandy zone is represented by the not-too-light blue color, indicating low conductivity. The dark blue color represents eroded structures, such as fractured or anomalous zones resulting from very low conductivity.

For the Fraser filtering in Fig. 3, areas on the graph with amaximum negative anomaly amplitude are considered zones in the subsurface with layers of shallow overburden (eroded) and are likely to reveal major fractures, which in this case may contain air. The areas in profile 1 (Fig. 3a) that could be observed to have maximum negative anomaly amplitude are at response marks 15 and 30, within a profile length of 35 m and 170 m, respectively. For profile 2 (Fig. 3c), these maximum negative amplitudes are observed at response marks 6 and 7 under profile lengths 25 and 124, respectively. At a response mark of 25 under profile length 90m, for profile 3 (Fig. 3e). Profile 4 (Fig. 3g) has two specific areas for maximum negative anomaly amplitudes located at a response mark of 25 and 10 within a profile length of 80m.

For Karous-Hjelt filtering, the conductivity of the subsurface ranges from -10 to 100 Mhos. The areas considered to have low conductivity (-10 to 0.5 Mhos) that may favour the formation of soil piping are within profile lengths of 30 m to 40 m in profile 1, and the depth of this layer is approximately 10m (Fig. 3b). For profile 3 (Fig. 3d), it could be observed to have penetrated a depth of 6m in between profile lengths of 60 m and 65 m. There is no evidence of this low conductive zone in profile 2 (Fig. 3f), while a brief dot is observed in profile 4 (Fig. 3h).

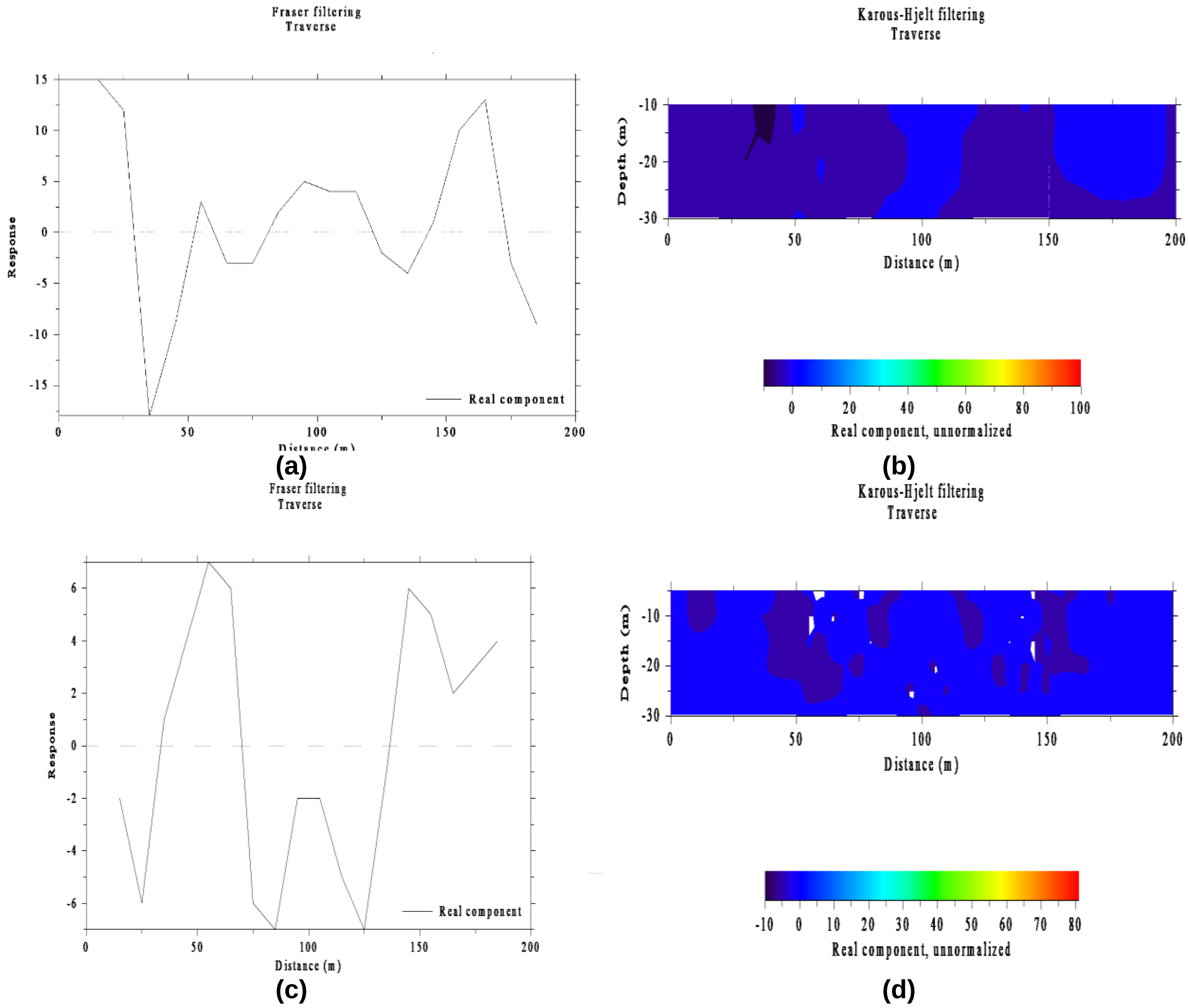
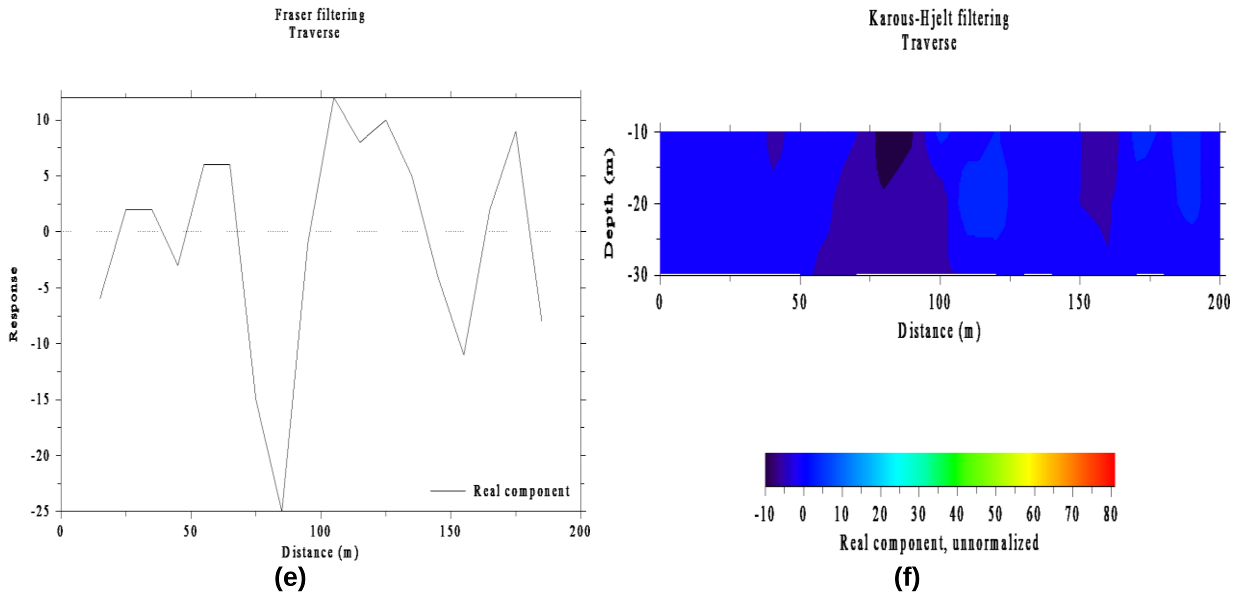
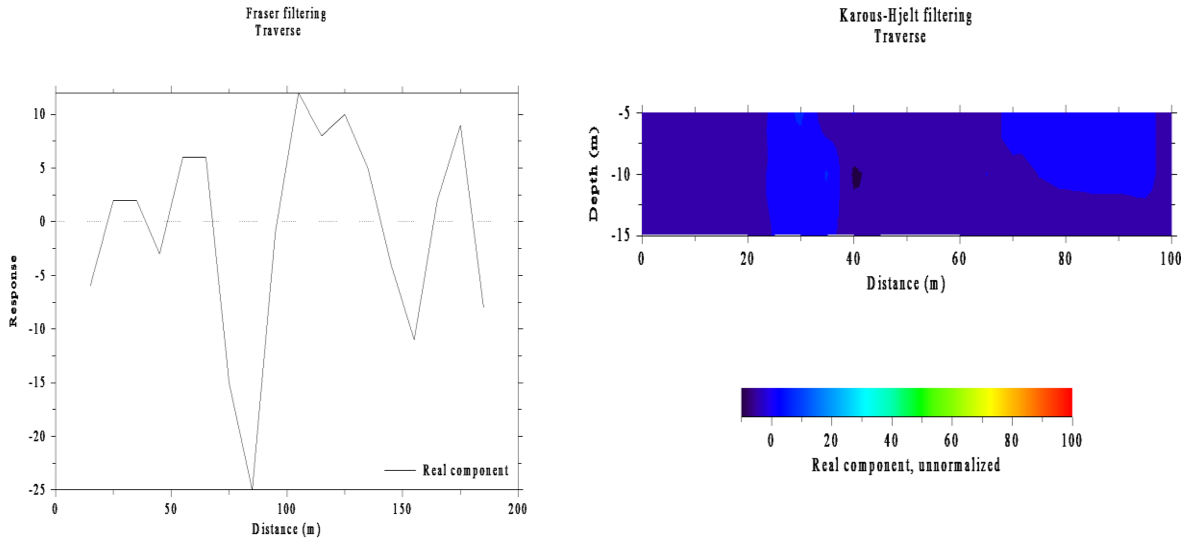


Fig. 3a-3d. A graph of Frazer filtering (a and c) and Pseudosection of Karous-Hjelt filtering (b and d) for Awka site 1





(g) (h)

Fig. 3e-3h. A graph of Frazer filtering (e and g) and Pseudosection of Karous-Hjelt filtering (f and h) for Awka site 2

4. DISCUSSION

For ease of comparison, soil pipes are mainly void spaces beneath the surface of the Earth or areas that have been greatly drained by run-off water in the subsurface. Generally, void spaces or drained soils have been known to have high resistivity [32,33,38,39]. Hence, the presence of these pipes in the subsurface will decrease the conductivity, leading to a negative current density anomaly for the Fraser filtering and dark blue to light blue colours for the Karous-Hjelt filtering. Consequently, areas showing negative current anomalies, or a dark blue colour, along the VLF-EM profiles are interpreted as soil pipes. The VLF model that identifies the soil pipes as low conductivity zones (-10 to 0.5Mhos, approximately), that ranges from 0m to 5m vertically for both profiles 1 and 3. Their horizontal dimension ranges from profile length of 33m to 37m in profile 1 and profile length 60m to 65m in profile 3 (approximately 5m respectively). Areas with moderate to high conductivity are interpreted as crystalline rocks, since the crystalline rocks are devoid of drained soil, and many of them contain saline pore spaces [34,35]. This implies that the affected areas or areas where there may be prevalent cases of soil piping in the subsurface are within profiles 1 and 3.

5. CONCLUSION

Results from the study show that subsurface low conductivity zones (from -10 to 0.5 Mhos) existing both within and surrounding the piping zones, suggest the presence of subsurface cavities. This observation is supported by the alignments between the negative amplitude responses of the Fraser filtering, the Karous-Hjelt filtering's thick blue patches (low conductivity areas) of the model, and the soil piping features found in the study areas. The obtained data also reveals that 80% of the pseudosection starts from the profile top, indicating the piping formation trend is downward. Subsurface voids in the study areas may have extended 10 m vertically downward and horizontally greater than 0.5 m on average.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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