Original Research Article

Recruiting the Very Low Frequency Electromagnetic Geophysical Technique for the analysis of Tunnel Erosion: A Case Study of Awka, Anambra State, Nigeria

Abstract:

Many Soil subsidence are as a result of 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 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 "6.22320N and 7.08240E" and "6.22200N and 7.08190E," respectively. The Very Low Frequency Electromagnetic (VLF-EM) geophysical 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. The results indicated that the study areas have developed a void-like vertical structure of approximately 2m and 0.5m in depth from the profile's top. The Karous-Hjelt filtering indicated low conductivity (0.01 -0.5S/m), 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.

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],[2],[3],[4],[5],[6].

Tunnel erosion popularly called soil piping is the formation of underground tunnel 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 forest [10] and Karst region where the soils are thickly patched [11]. It occurs in areas having high seasonal contrast with/or high rainfall variability [7], and usually begins as small pores (flute holes) within subsurface, with time they become enlarged [12], [13] forming channels where soil from the surface and other materials are transported [5]. Hence, soil pipings can lead to both surface and subsurface erosions [14]. It begins in many ways, but the most common is the action of rainfall [7], [8], [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], [20], [21]. However, during the last two decades land subsidence due to collapse of subsurface roof and tunnel roofs have largely been reported from various part of the state [19], [22], [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 structures and roads [24]. In many of these events, there have been loss of lives and properties, and people's means of livelihood have been cut short. Finances have also been sunk into the control of this soil subsidence in order to reclaim the road, people's property and valuable farmland by members of the community and the government, using filling up method [24], but little progress has been recorded. Therefore, an urgent to look for an alternative scientific method becomes paramount.

In order to estimate the extent at which soil piping has built up without carrying a major excavation process which will require the need for heavy machineries that will disturb the top soil, geophysical techniques are employed, which generally incur a low cost but provide a robust investigation of the environment at large[24], [25] [26],[27],[28].
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.

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 persons as of 2006 census with an area of approximately 1,870sqmi or 4,844km2, some parts of the state are densely populated that the estimated density is about 1500-2000 person 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 (figure 1). The first site (Awka Site I) is located close to Paul University, Awka with a geographical coordinate of (6.22320N and 7.08240E). The piping hole that is about 5cm in diameter is visible and it has done a major damage to the constructed road by creating double sinkholes (soil subsidence) which 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 (6.2220^0N and 7.0819^0E). The piping hole on this site has existed for about 10years creating multiple holes of average diameter 10cm and a visible sinkhole with a diameter of about 200cm [39].

Geology and Lithostratigraphy of Study Area

The study area forms a part of the Anambra sedimentary basin of the southeastern Nigeria. The Anambra basin, figure (2) covers about 40,000sq.km [36].The southern boundary coincides with the deltaic swamps of the Niger Delta basin and extends northwards 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 activities of the lower Benue Trough. Figure 2 shows the geologic map of the southern Anambra [40].
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. Beneath the weak lateritic and acidic soils are unstable and poorly consolidated geologic rocks and material. 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. The lateritic and sandy soils are easily eroded by storm water runoffs [36].

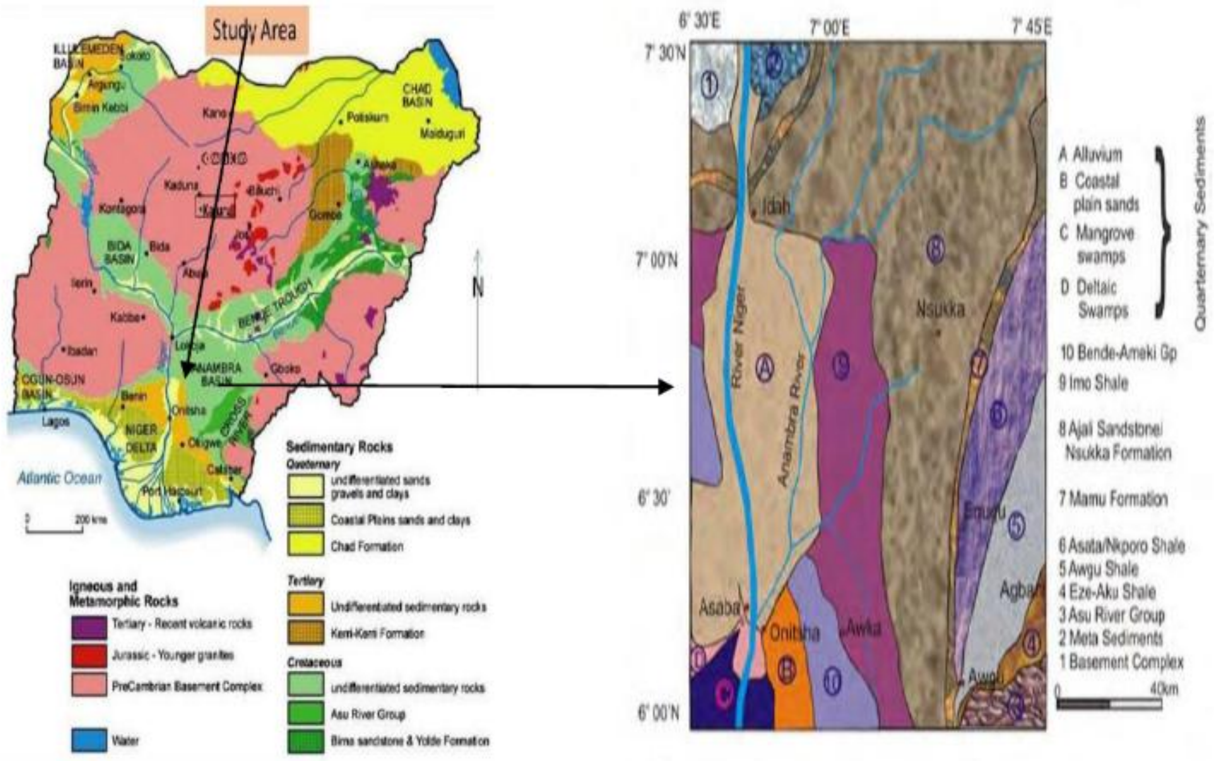

Figure 1. Map of the geological setting of Nigeria and Anambra Basin

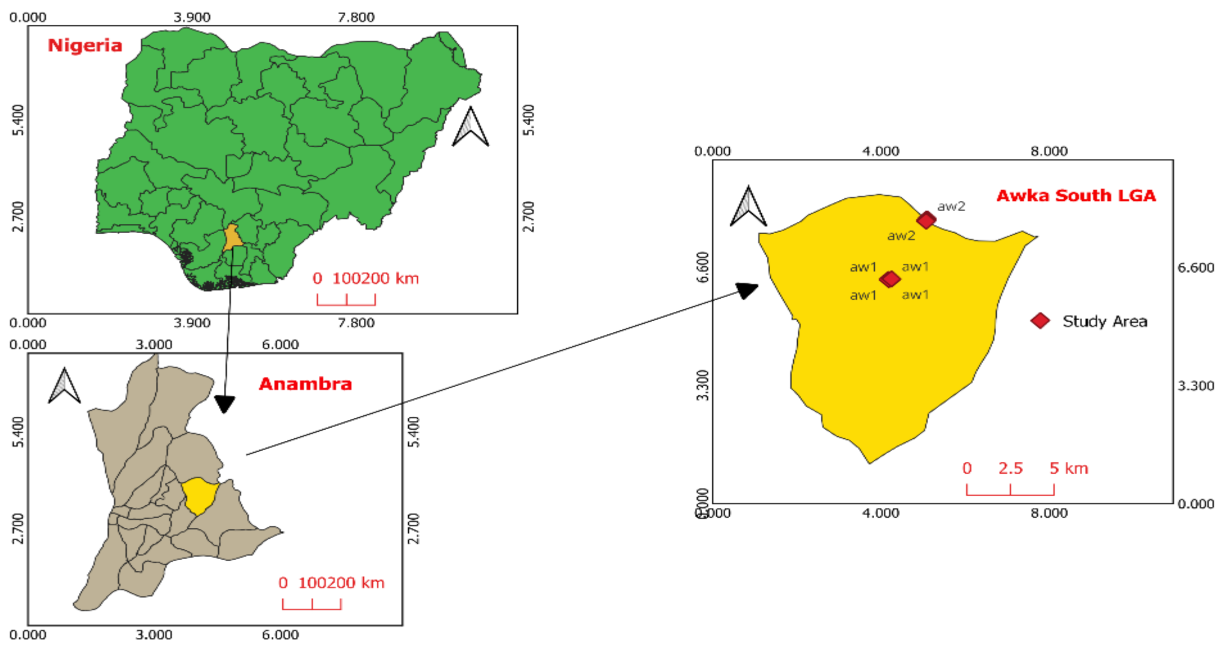

Figure 2. Map showing the surveyed state and LGA

Method

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 a secondary EM wave 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 (poor conductor) will cause the secondary EM field to lag behind the primary field by a period of 90^0 [32], [33].

For the analyses of VLF-EM data, a RAMAG and KHFfilt software [29], [34] are used to find the characteristic 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 (∅) 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 . $H_i = \left|H_z e^{i\Delta\emptyset} sin\theta + H_x Cos\theta\right|$ (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 percentage.

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].

A total of 4 profiles with transverse length 100m and 5m spacing was surveyed, Figure 3 and 4. 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 coordinate of the particular point in which the reading was collected 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.

Results

Figures 4a to 4h 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 piping 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 2km 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 four, 1.7km from profile 3.

All profiles in this section run from NW to SE, with each measurement station separated by 5 meters, except for Profile 4, which had a different orientation due to space restrictions. The pseudosection for Karous-Hjelt filtering has revealed an uneven distribution of conductivities in the subsurface. Different shades of blue are 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 a very low conductivity

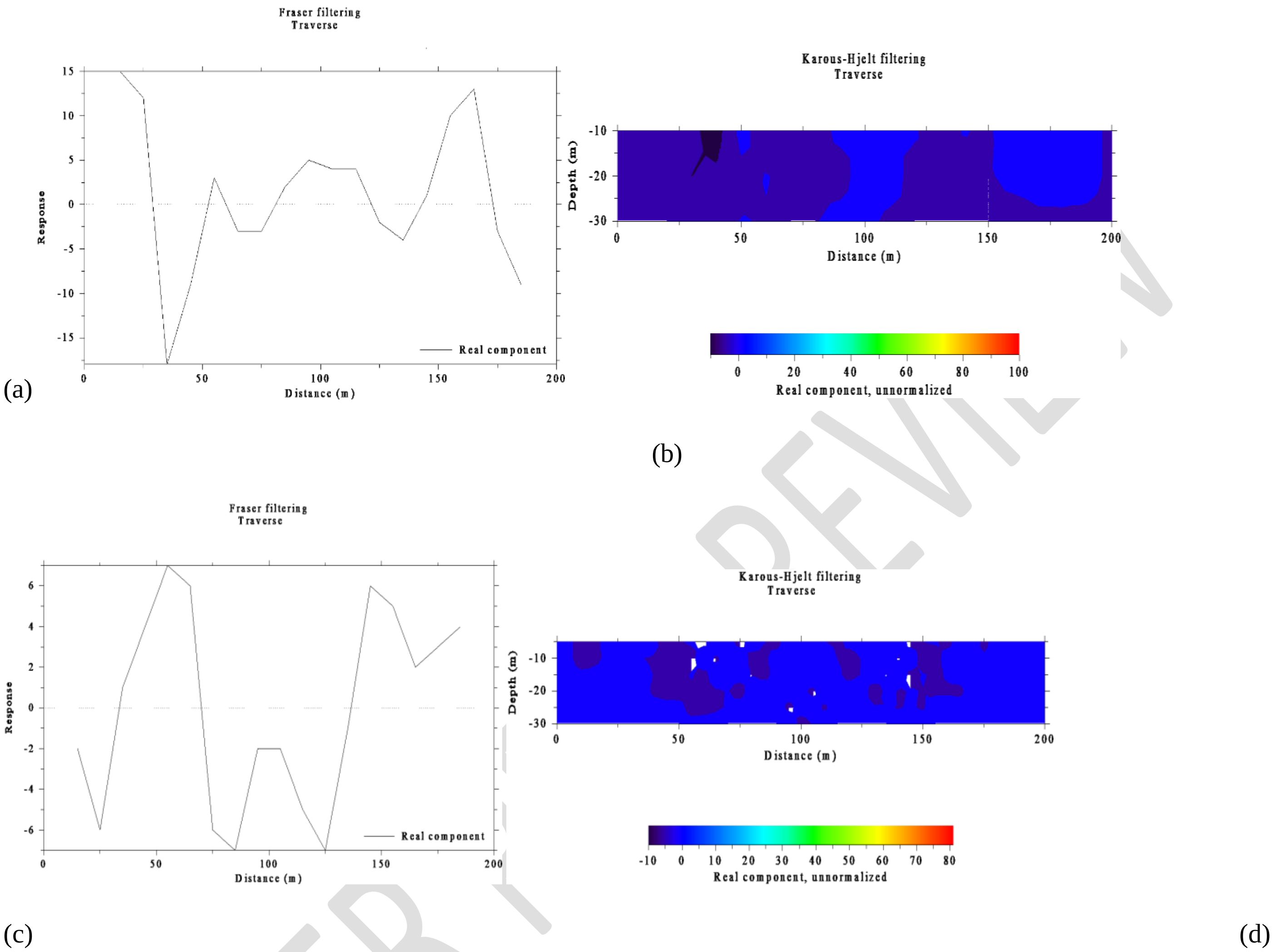

Figure 3a-3d. A graph of Frazer filtering (a and c) and Pseudosection of Karous-Hjelt filtering (b and d) for Awka site 1

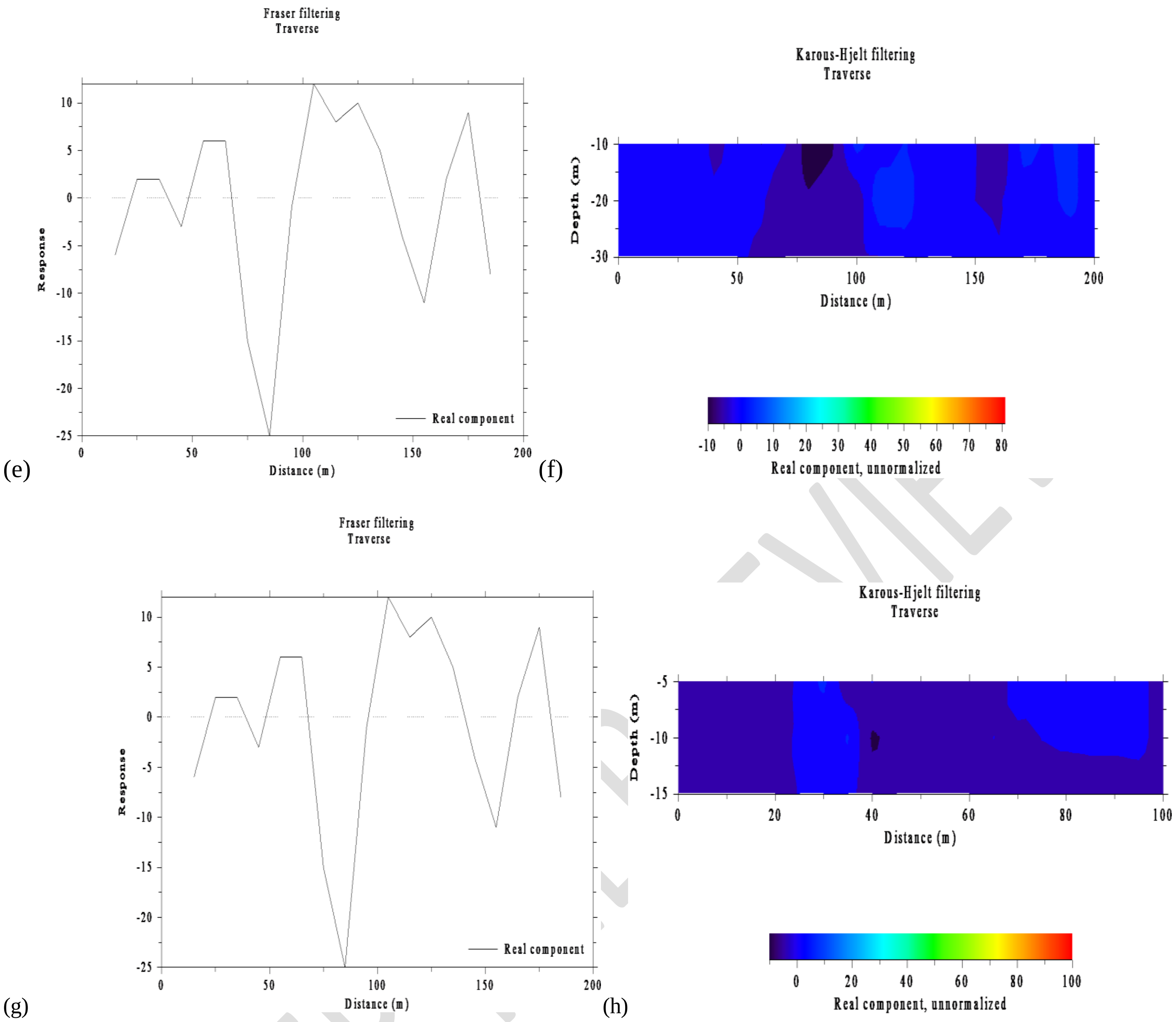

Figure 3e-3h. A graph of Frazer filtering (e and g) and Pseudosection of Karous-Hjelt filtering (f and h) for Awka site 2

For the Fraser filtering in figure 4, areas on the graph with a maximum negative anomaly amplitude are considered as zones in the subsurface with layers of shallow overburden (eroded) and are likely to reveal major fracture, which in this case may contain air. The areas in profile 1 (figure 3a) that could be observed to have maximum negative anomaly amplitude is at response mark 15 and 30 within profile length of 35m and 170m respectively. For profile 2 (figure 3c), these maximum negative amplitudes are observed at response marks 6 and 7 under profiles length 25 and 124 respectively. At a response mark of 25 under profile length 90m, for profile 3 (figure 4e). Profile 4 (figure 4g) has two specific area 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 100Mhos. The areas considered to have low conductivity (-10 to 0.5Mhos) that may favour the formation of soil piping is within profile length 30m to 40m profile 1, the depth of this layer is approximately 15m (figure 4b). For profile 3 (figure 4d), it could be observed to have penetrated a depth of 10m in between profile length 75m to 80m. There is no evidence of this low conductive zone in profile 2 (figure 4f) while a brief dot is observed in profile 4 (figure 4h).

Disscussion

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 soil 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 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 anomaly or dark blue colour along the VLF-EM profiles are interpreted to as soil pipes while areas with moderate to high conductivity are interpreted to as crystalline rocks, since the crystalline rock are devoid drained soil, and many of them constitute of 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 profile 1 and profile 3.

conclusion

Results from the study show that subsurface low conductivity zones (-10 - 0.5Mhos) existing both within and surrounding the piping zones, suggest the presence of subsurface cavities. This observation is supported by the alignments between 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 on 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 10m vertically downward and horizontally greater than 0.5m on average

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