

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 subsidences are due to tunnel erosion, popularly called "soil pipe". It generally begins as a tiny flute hole in the ground but may cause significant environmental implications when uncontrolled. Varieties of damage resulting from soil subsidence have been reported in several regions within Anambra State, Nigeria. Therefore, the study examines 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 in each of the study areas, each with a traverse length of 100 m and a spacing of 5 m. The results indicated that the study areas had developed a void-like vertical structure of approximately 2 m and 0.5 m in depth from the profile's top. The Karous-Hjelt filtering indicated low conductivity (0.01–0.5 S/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 resulting in earth materials' natural wear and transportation 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], and [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 the Karst region, where the soils are thickly patched [11]. It occurs in areas with high seasonal contrast and rainfall variability [7] and usually begins 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 surface and subsurface erosion [14]. It begins in many ways, but the most common is the action of rainfall [7], [8], and [15]. Here, percolating water carrying finer silt and clay particles forms passageways that create pipes [16], [5], which are mainly a few millimetres to a few centimetres in size but can grow to a metre or more in diameter [12], [13]. They may lie very close to the earth's surface or extend several metres 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 the collapse of the subsurface roof and tunnel roofs has largely been reported from various parts of the state [19], [22], and [23]. 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, lives and properties have been lost, and people's means of livelihood have been cut short. Finances have also been sunk into the control of this soil subsidence to reclaim the road, people's property, and valuable farmland by community and government members using the filling-up method [24], but little progress has been recorded. Therefore, it becomes urgent to look for an alternative scientific method.

In order to estimate the extent to which soil piping has built up without carrying out a major excavation process that will require heavy types of machinery 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 a 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 to deduce the characteristics of soil pipes found in Awka, Anambra State.

Study Area

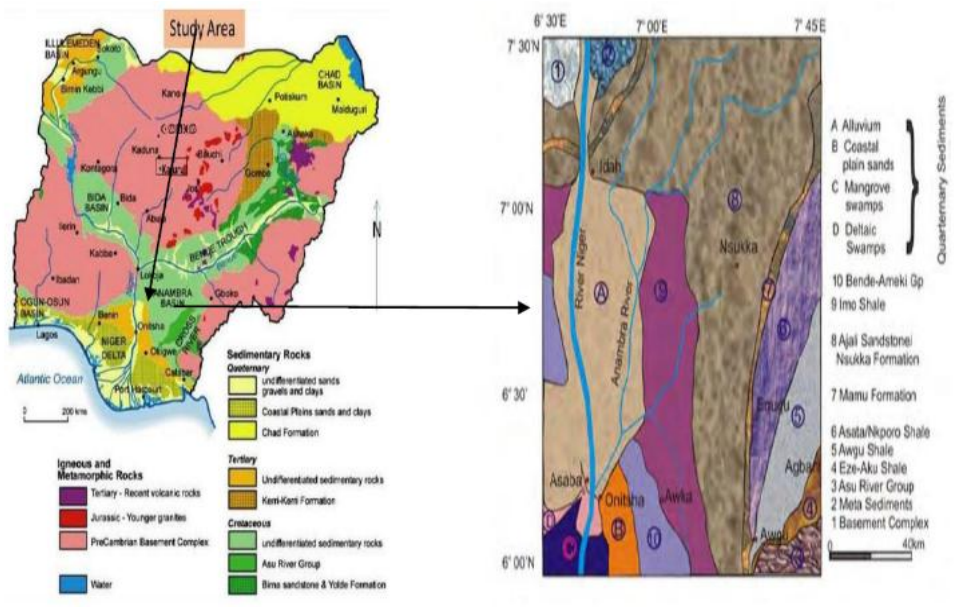
The study area is Awka, the capital of Anambra State, Nigeria, and it is bounded by latitude (6.15 N and 6.31667 N) and longitude (7.18333 E and 7.2 E). The population of this state was 4,177,821 as of the 2006 census, with an area of approximately 1,870 sq mi, or 4,844 km². Some parts of the state are densely populated; the estimated density is 1500 to 2000 persons per square kilometre [37], [38].

The study was conducted at two sites in the centre of Awka town in Awka South Local Government Area, the capital of Anambra State, Nigeria (Figure 1). The first site (Awka Site I) is close to Paul University, Awka, with a geographical coordinate of 6.22320N and 7.08240E. The piping hole of about 5 cm in diameter is visible, and it has done major damage to the constructed road by creating double sinkholes (soil subsidence), which are about 60 cm in diameter. The second site (Awka Site II) is located along the popular Jerome Udorji Secretariat Complex with a geographical coordinate of 6.22200N and 7.08190E. The piping hole on this site has existed for about 10 years, creating multiple holes of an average diameter of 10 cm and a visible sinkhole with a diameter of about 200 cm [39].

Geology and Lithostratigraphy of Study Area

The study area forms part of the Anambra sedimentary basin in southeastern Nigeria. The Anambra Basin, shown in Figure (2), covers about 40,000 sq. km [36]. The 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. Figure 2 shows the geologic map of southern Anambra [40].

The soils of Anambra State particularly have groundwater reservoirs that severely contribute to ecological problems in the region. The coastal plain sands mainly typify them 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, referred to as aquifers, with pore water pressures that become threatening when overlying structures carry uncompromising loads. Stormwater run-offs easily erode the lateritic and sandy soils [36].



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

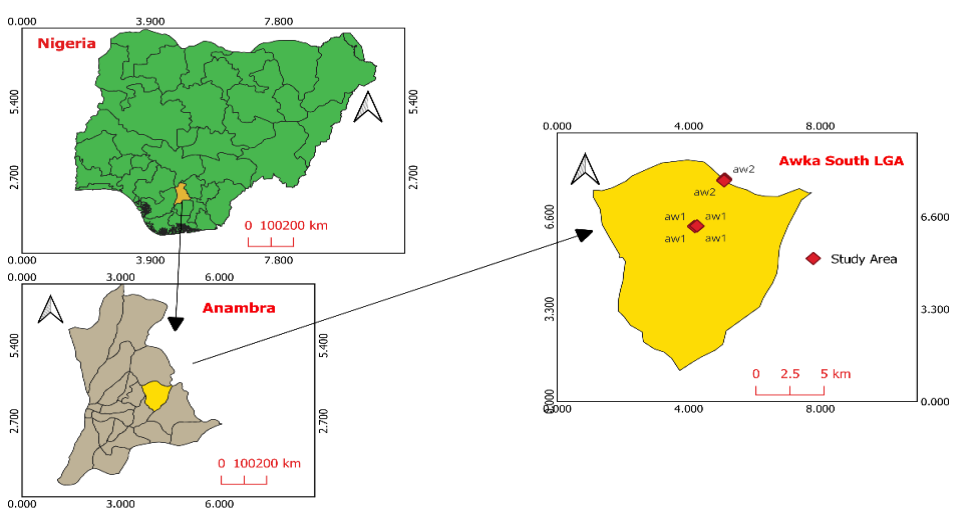


Figure 2. Map showing the surveyed state and LGA

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 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 and secondary fields 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 (1800) 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 900 [32], [33].

For the analyses of VLF-EM data, RAMAG and KHfilt software [29] and [34] are used to find the characteristics of the cross-sectional depth 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 polarisation ellipse are used to calculate the real and imaginary responses. The tilt angle (θ) 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].

$$\tan(2\theta) = \pm \frac{2(H_z/H_x)\cos\Delta\theta}{(H_z/H_x)^2} \quad (1)$$

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

Where H_z and H_x are the amplitude of the phase difference, $\Delta\theta = \theta_z - \theta_x$, and in which θ_z is the phase of H_z and θ_x is the phase of H_x and $H_i = |H_z e^{i\Delta\theta} \sin\theta + H_x \cos\theta|$ (2)

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

$$\text{Real} = 100 \tan\theta \quad (3)$$

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

$$\text{Imaginary} = 100e \quad (5)$$

The tangent of the tilt angle approximates the ratio of the real component of the vertical secondary magnetic field to the horizontal primary magnetic field. The ellipticity approximates the ratio of the quadrature component of the vertical secondary magnetic field to the horizontal primary field [33]. These quantities are called the real (= $\tan \alpha \times 100\%$) and imaginary (= $e \times 100\%$) anomalies, respectively, normally expressed as percentages. Only the in-phase and out-phase 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 lengths of 100 m and 5 m spacing were surveyed (Figures 3 and 4).

On each profile, the in-phase and out-phase 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 where the reading was collected were recorded. Each profile was oriented in the NW-SE direction to follow the stress formation of the study area. It was done to reduce complications due to anisotropic effects associated with the study area.

Results

Figures 4a–4h illustrate the outcome of the VLF-EM geophysical survey, which utilised Fraser filtering for the current density data response and pseudo-sections of Karous-Hjelt filtering to visualise the current density data against subsurface depth. This survey aimed 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 exactly 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 separated by 5 meters, except for Profile 4, which had a different orientation due to space restrictions.

The pseudo-section for Karous-Hjelt filtering has revealed an uneven distribution of conductivities in the subsurface. Different shades of blue represent the various conductivity zones and distinguish distinctive zones in the subsurface. The light blue colour represents the intermediate conductivity of the clay zone, while the sandy zone is represented by the not-too-light blue colour, indicating low conductivity. The dark blue colour represents eroded structures, such as fractured or anomalous zones resulting from very low conductivity.

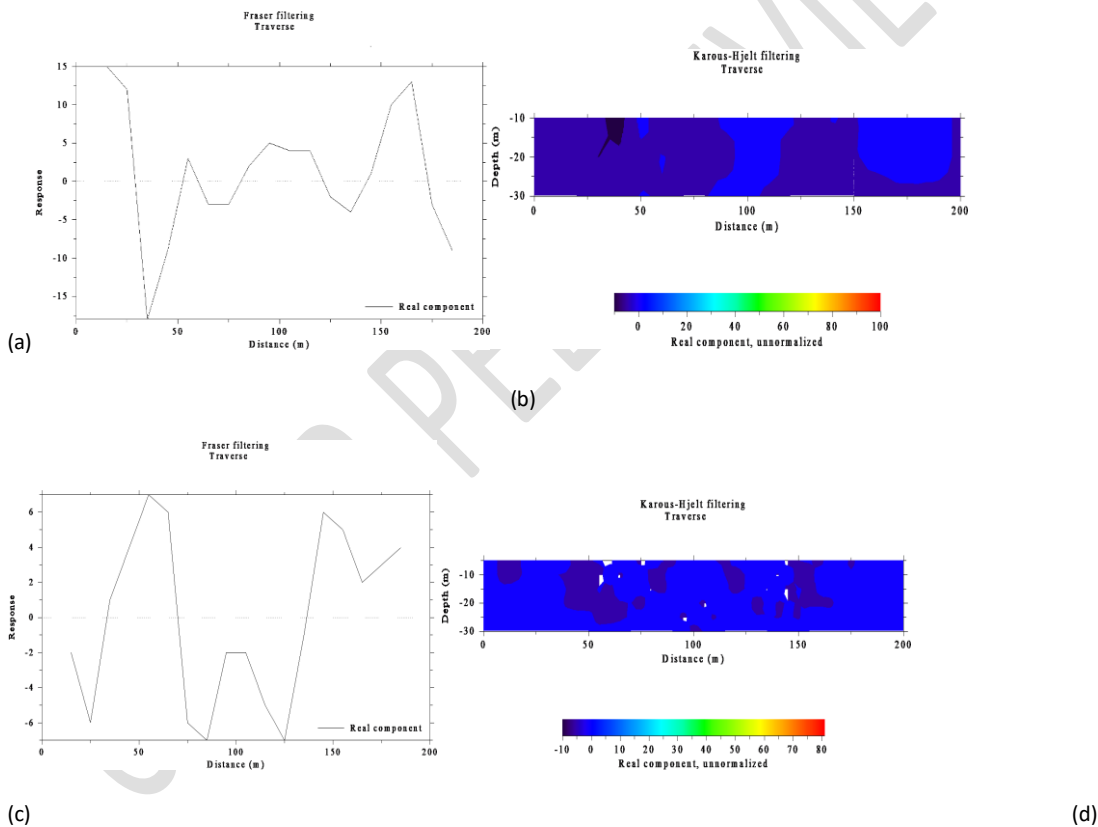


Figure 3a-3d. A graph of Fraser filtering (a and c) and Pseudosection of Karous-Hjelt filtering (b and d) for Awka site 1

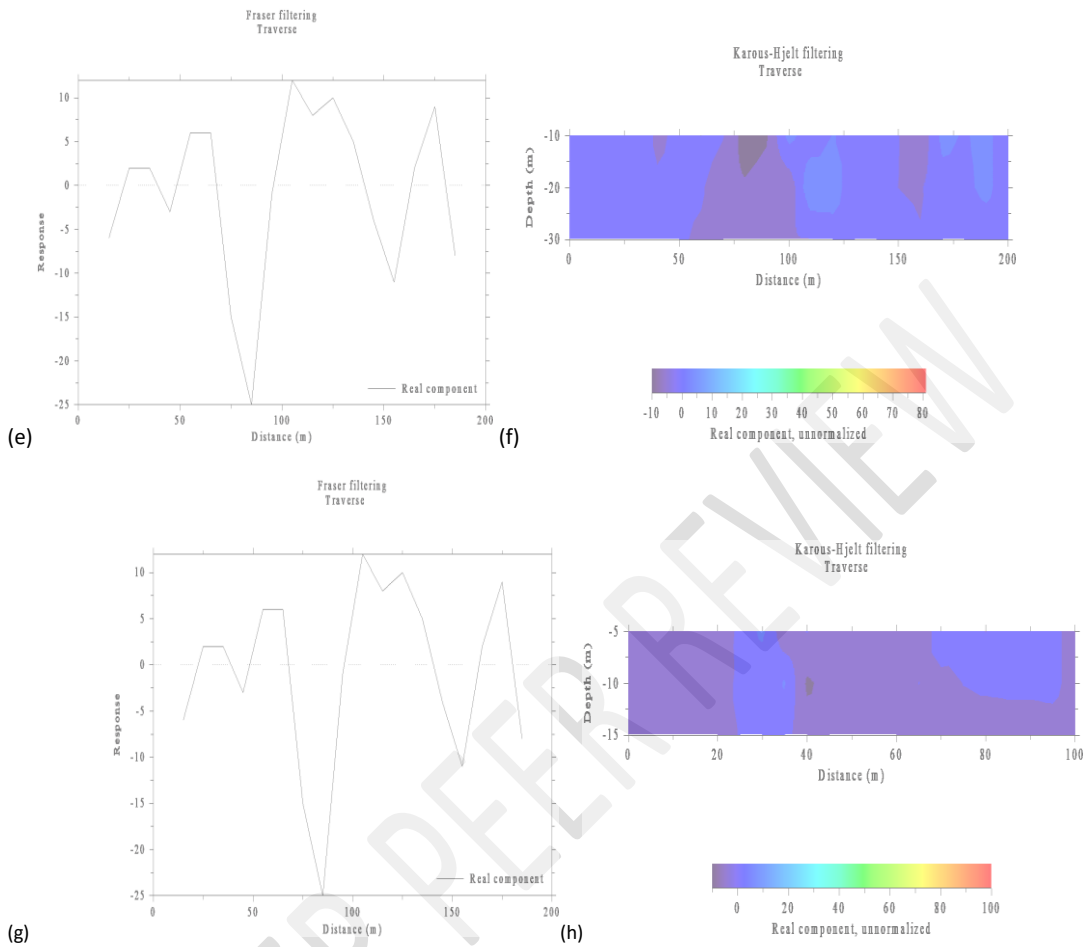


Figure 3e-3h. A graph of Fraser filtering (e and g) and Pseudosection of Karous-Hjelt filtering (f and h) for Awka site 2

For the Fraser filtering in Figure 4, areas on the graph with a maximum negative anomaly amplitude are considered zones in the subsurface with layers of shallow overburden (eroded) and are likely to reveal major fractures, which may contain air in this case. The areas in Profile 1 (Figure 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 (figure 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 90 m for profile 3 (figure 4e). Profile 4 (Figure 4g) has two specific areas for maximum negative anomaly amplitudes located at a response mark of 25 and 10 within a profile length of 80 m. 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. The depth of this layer is approximately 15 m (Figure 4b). For

Profile 3 (Figure 4d), it could be observed to have penetrated a depth of 10 m in between profile lengths of 75 m and 80 m. No evidence exists of this low-conductive zone in Profile 2 (Figure 4f), while a brief dot is observed in Profile 4 (Figure 4h).

Discussion

For ease of comparison, soil pipes are mainly void spaces beneath the earth's surface or areas 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], and [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, while areas with moderate to high conductivity are interpreted as crystalline rocks since the crystalline rocks are devoid of drained soil, and many of them constitute saline pore spaces [34, 35]. It implies that the affected areas or areas with prevalent soil piping in the subsurface are within Profiles 1 and 3.

Conclusion

Results from the study show that subsurface low conductivity zones (-10–0.5 Mhos) existing 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 data also reveals that 80% of the pseudo-section starts from the profile top, indicating the trend of downward piping formation. Subsurface voids in the study areas may have extended 10 m vertically downward and horizontally greater than 0.5 m on average.

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