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Characterizing Buried Metallic Objects in Porous Media from Attenuation Fluctuations

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ABSTRACT

Study of attenuation characteristics of electromagnetic signals passing through porous media is becoming increasingly relevant in providing important insights into the physical properties of the medium and objects that are buried therein. Laboratory experiments have been carried out in this work to determine the relationship between Q-factor of the electromagnetic signal passing through buried metals and the porosity of the surrounding sediments. Sediments were obtained from Erinle River in Ilobu, Southwestern Nigeria and Iron, Silver and Copper plates of similar dimensions were buried inside box-filled sediment in succession. Electromagnetic signal was passed through metals, sediments and sediments with buried metals while lissajous figures generated at different frequencies were analyzed to assess the impacts of buried objects. Results showed that Q-factor decreased as the porosity of riverbed sediments increased. Of the metals buried inside the sediments, Iron had the most attenuating effect while Silver plates had the least, except at frequency 400 Hz where Copper had the least and at 600 Hz where there were some overlaps between Silver and Copper. Q-factor increased, for all metals and at all signal frequencies, up to a maximum value at the porosity of 0.24 and thereafter decreased. Knowledge of Q-factor from attenuated signals is therefore, a useful way to characterize and identify buried materials.

Key words: Q-factor, attenuation, buried metals, porous media, riverbed sediments

INTRODUCTION

Sub-surface buried objects such as pipes, cables, canisters, landmines and archaeological artifacts and the surrounding environment constitute a scientifically complex system with variable characteristics. As a consequence, the detection and recognition of these objects may be extremely difficult (Santulli, 2009). Analysis of sand reservoirs and aquifers through geophysical methods was discussed by Eiken and David (2000). Muller and Gurevich (2005) studied how elastic waves in inhomogeneous porous media are related and the impacts of wave-driven fluid flow. Detection of buried metals is usually done using geophysical methods that ensure improved depths of exploration and object characterization as opposed to conventional metal detection methods. Electromagnetic method of survey which is usually based on the differences in attenuation as electromagnetic field propagates through materials, has been established as a quick and useful way of detecting buried conductive bodies. Alternating current passing through a coil that is held through a prescribed direction produces an alternating magnetic field which induces current in any electrical conductors that are nearby. Any induced current creates its own magnetic field which is measured by a search coil that is connected to a meter of voltage. Electromagnetic survey does not require electrical ground contact and thus helps to determine effective conductivity of underground material beneath the instrument transmitter and receiver coils. In most cases, an airborne electromagnetic survey is followed up by ground electromagnetic work.

Q-factor increases with stress, so the ratio of P-wave to S-wave Q-factor QP/QS gives a good correlation to porosity and permeability (Mohiuddin *et al.*, 2001). The main factor controlling the Q-factor is cation order/disorder while grain size is of secondary importance. Q-factor depends on not only grain size but also the porosity in the grains (Choi *et al.*, 2003). Biella *et al.* (1983) investigated some hydro-geophysical properties of unconsolidated porous media and found that Q-factor decreases though porosity in the grains increases. High frequency waves are related to the porosity of sandstones through the presence of clay and lime mud (Best *et al.*, 1994; Best and Mccann, 1995). Need to develop fast, reasonably accurate and affordable preliminary means of identifying buried mines and other objects is becoming increasingly necessary, especially for developing countries that have experienced various forms of violence. In addition, Q-factor in relation to porosity has been widely investigated, but its direct use on characterizing buried metals has received only very little attention.

The study was therefore aimed at establishing the effects of Q-factor on porosity of riverbed sediments by analyzing attenuation fluctuations in different metallic objects. It was also to assess impacts of buried metals on attenuation fluctuations in riverbed sands, with a view to having preliminary insights into material characterization and identification of such metals in porous media.

THEORETICAL BACKGROUND

Porosity of a medium is the amount of void space in a given volume of the medium. It is a dimensionless quantity which is usually expressed either as a decimal fraction or as a percentage taking value between 0 and 1 or 0 and 100% (Schlumberger, 2010; Slutsker *et al.*, 2002; Calo *et al.*, 2001; Rodrigues *et al.*, 2002). It is denoted by:

$$\text{Porosity} = \frac{\text{Pore volume}}{\text{Bulk volume}} \tag{1}$$

Phase difference is calculated from measurements made from lissajous figures, using the formula:

$$\text{Sin}\theta = \frac{a}{b} \tag{2}$$

where, θ is the phase angle (is phase difference in radian). ‘a’ is the minor axis and ‘b’ is the major axis of the lissajous figures. Lissajous curves can be seen on oscilloscopes and are the result of combining two trigonometric curves at right angles (Bourne, 2009; Thomas, 2011).

Phase delay is the ratio of the phase difference (radians) of a sinusoidal signal (ϕ) in transmission through a system to the angular frequency (radians/second) of the signal (Smith, 2007).

$$\text{Phase delay} = \frac{\phi}{2\pi f} \tag{3}$$

Q-factor is defined as fractional loss of energy per cycle (McCann and Sothcott, 2009; Tancer and Treited, 2005; Haase and Stewart, 2004). It is calculated by:

$$Q = -\frac{\pi R}{\ln\left(\frac{A}{A_0}\right)\lambda} \tag{4}$$

Where:

$$\lambda = 2\pi A \sin\phi \tag{5}$$

and 'R' is the distance travelled by the wave (i.e., thickness of the porous medium). 'A' is the amplitude of the output signal after passing through the porous medium. A_0 is the amplitude of the input signal and λ is the wavelength of the signal passing through the sample as calculated from Eq. 5.

MATERIALS AND METHODS

Materials used in this study were Riverbed sediments, Iron plate, Silver plate and Copper plate, Square box made of turfnor and aluminum plate, Signal Generator of 3 MHZ and a Double channel oscilloscope of 20 MHZ.

Study location: Ilobu in Irepodun Local Government in the central part of Osun State, South Western Nigeria falls within the basement complex region of the country. The south western Nigeria consists of Lagos, Ogun, Oyo, Osun, Ondo and Ekiti states in the south west geographical zone of Nigeria. It lies between longitude 2°31' and 6°00' E and latitude 6°21' and 8°37' N (Agboola, 1979) with a total land area of 77, 818 km^2. The south west is bounded in the East by Edo and Delta States, in the North by Kwara and Kogi States, in the west by the Republic of Benin and in the south by the Gulf of Guinea. The climate of southwest Nigeria is tropical in nature and it is characterized by wet and dry seasons where temperature ranges between 21 and 34°C and the annual rainfall ranges between 1500 and 3000 mm. The wet season is associated with the southwest monsoon wind from the Atlantic Ocean while the dry season is associated with the northeast trade wind from the Sahara desert. The Southwest Nigeria's vegetation is made up of fresh water swamp and mangrove forest at the belt.

The studied area is of latitude 7.8333° and longitude 4.44833° of Osun state. Erinle river has some tributaries like Elentere river in the northern part, Awesin river in the western part and Owala river in the eastern part of the town. This river flows to Osun river at Osogbo and Ede towns in Osun State.

Riverbed sediments were collected from Erinle River, washed, dried and heated to 150°C to remove some moisture contents. Sediments were separated into 300, 212, 150, 75 and 60 μm sizes with the use of standard sieves in order to mix and achieve ten samples with different porosities tagged A to J. Ten samples were prepared from the sediments as shown on Table 1. Iron, Silver and Copper were cut into plates of uniform dimensions 1 by 0.5 cm and thickness 5.092 mm.

Determination of porosity: In this study, bulk volume was determined using volumetric approach. This was done by measuring 10 mL of the sample using a 20 mL measuring cylinder. The cylinder was tapped with a solid object to ensure compactions of the sample in it. Matrix volume was

Table 1: Samples A to J with determined values of porosity

Sample	Porosity
A	0.16
B	0.18
C	0.20
D	0.22
E	0.24
F	0.26
G	0.28
H	0.30
I	0.40
J	0.44

determined using a similar cylinder of 20 mL size filled to 9 mL mark by water. The measured sample was then poured into the water and the volume of the mixture in the cylinder was recorded for each sample. The porosity for each sample was thus determined as shown on Table 1.

Box fabrication: A square box made up of turfnor and aluminum plates was fabricated. The turfnor was cut into a square shape of dimension 4×4×1 cm and a square hole was drilled in it. Two plates of aluminum of dimension 4×4 cm and thickness 1mm were cut. One side of turfnor was sealed with aluminum plate. The other side of turfnor was opened but when filled with samples, the second aluminum plate served as lid.

Experimental procedure: The square box was initially filled with sediments of pre-determined porosities and sealed. Uniform distribution and packing was achieved by applying a gentle knock on all sides of the box until it was completely filled. The box was thereafter sealed and connected to a signal generator and an oscilloscope. Two sinusoidal waves of the same frequency, but different amplitudes were passed from a signal generator, one directly to the oscilloscope while the other through the porous medium. This was to establish eddy current in the sample in order to generate secondary signal. The two signals arriving at the oscilloscope are similar to two perpendicular signals of different amplitude and phase difference. These signals interact forming lissajous figures which were analyzed at frequencies 200, 400, 600, 1000, 2000, 3000, 4000, 5000 and 6000 Hz. The procedure was repeated for sediments with buried iron plate, silver plate and copper plate as well as for metal plates alone. Metals of exactly same dimensions (1×½ cm×0.596 mm) were buried using similar orientations and at same centre positions in the sediments. Q-factor was obtained from the measurement by using Eq. 4 and was measured at pre-determined porosities for sediments only, as well as for sediments having buried metals. Similar experiment was performed for metal plates only without any sediments and Q-factor was measured five times for each metal plate and averaged.

RESULTS AND DISCUSSION

Porosity increased in marginal steps across samples A, B, C, D, E, F and G as shown in Table 1. Porosity was however substantially higher in samples H, I and J compared with other samples. Table 2 shows the results of Q-factor ranges as obtained from the analysis on the oscilloscope at frequencies 200, 1000 and 6000 Hz to investigate behavior at lower, medium and higher frequencies. At 200 Hz frequency, Q-factor of ordinary metals (without sediments) increased in the order of Iron to Silver to Copper and decreased in the same order at higher frequencies of

1000 and 6000 Hz. Presence of sediments decreased Q-factor in the three metals considered at all frequencies. Iron in sediments, silver in sediments and copper in sediments were investigated at frequencies 400, 600, 3000, 4000 and 5000 Hz, respectively to study effects at varying frequencies. Q-factor increased slightly, for metals buried in sediments, with porosity up to a maximum porosity value of 0.24, after which it decreased as shown in Fig. 1. A sharp increase in Q-factor was however observed for copper with sediments up to a value of 5.9 after which a sharp fall occurred to a value of 4.3 at porosity of 0.45. A similar but less pronounced trend was observed in Fig. 2. At high frequencies of 3000, 4000 and 5000 Hz, difference between Q-factor of Iron with sediments and other metals with sediments widened considerable as shown in Fig. 3-5, respectively.

Table 2: Results of Q-factor range for different measurements

	Q-factor range ($\times 10^{-3}$)		
Sample	Frequency 200 Hz	Frequency 1000 Hz	Frequency 6000 Hz
Sediments (Sands)	4.89-5.25	5.70-8.00	6.51-8.53
Sediments with iron plate	4.02-5.57	7.17-8.80	5.72-8.47
Iron plate	5.80-0.00	9.00-0.00	8.40-0.00
Sediments with silver plate	5.0-6.500	5.30-6.80	5.00-6.30
Silver plate	6.6-0.000	7.00-0.00	6.50-0.00
Sediments with copper plate	5.4-6.700	6.13-6.85	5.50-6.10
Copper plate	6.8-0.000	6.90-0.00	6.20-0.00

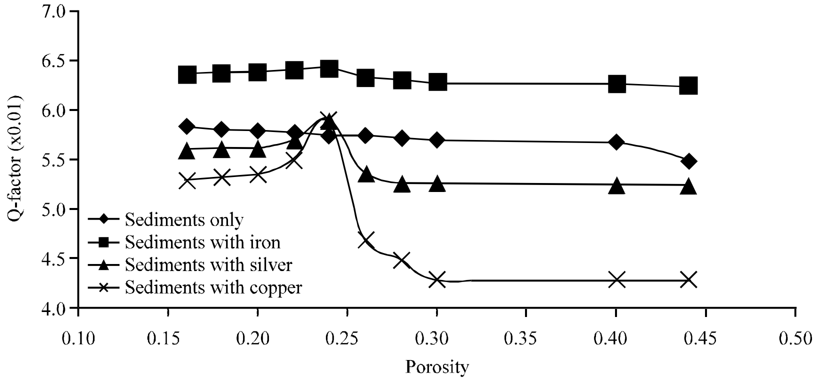

Fig. 1: Relationship between Q-factor and porosity of samples A to J at frequency 400 Hz

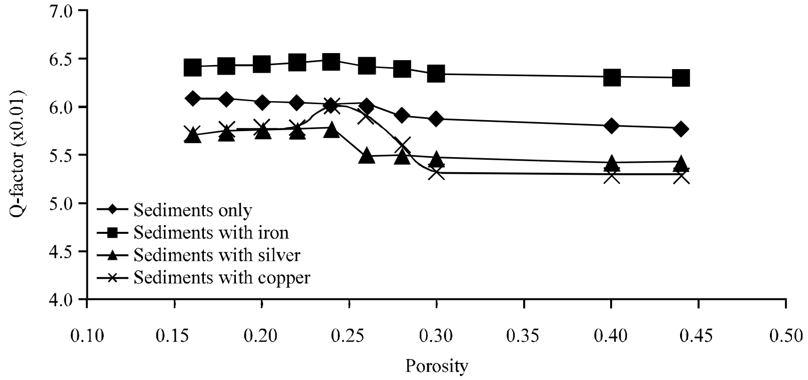

Fig. 2: Relationship between Q-factor and porosity of samples A to J at frequency 600 Hz

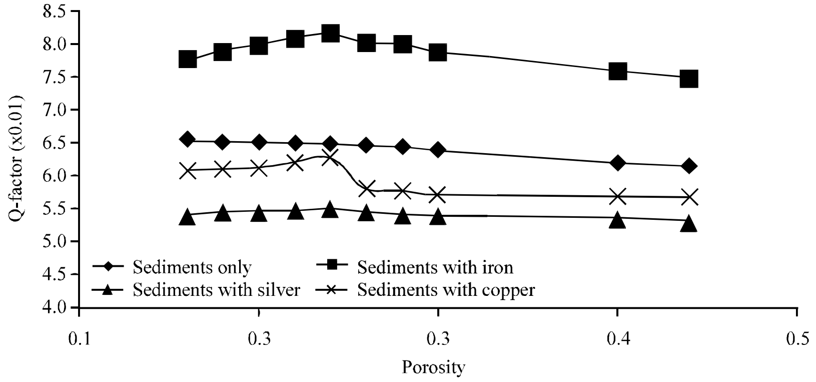

Fig. 3: Relationship between Q-factor and porosity of samples A to J at frequency 3000 Hz

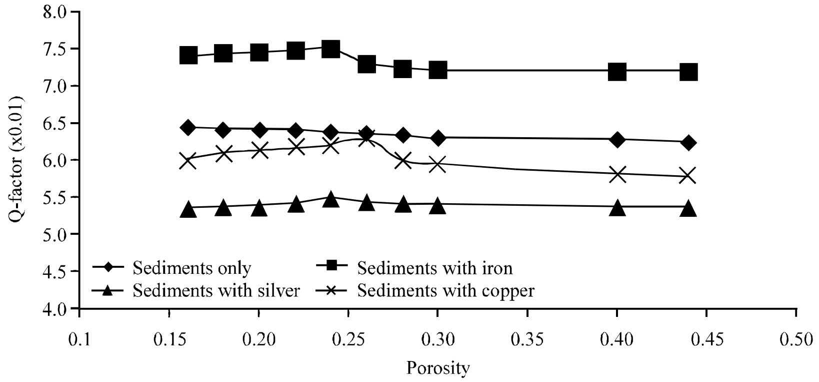

Fig. 4: Relationship between Q-factor and porosity of samples A to J at frequency 4000 Hz

Q-factor of ordinary sediments decreased with porosity irrespective of the applied frequency of electromagnetic signal, though not remarkably. This implies that at any frequency, the fractional loss of energy per cycle in a material medium is inversely proportional to the rate at which the material is porous. Q-factor decreases though the grain size and porosity in the grain increases in line with the earlier findings of Choi *et al.* (2003). As metals were buried within sediments, Q-factor increased to a maximum value, for all metals and at all frequencies, at the porosity of 0.24 and then decreased afterwards. This agrees with previous literature that Q-factor does not have a good correlation with either porosity or permeability (Assefa *et al.*, 1999). Iron had the most pronounced attenuating effect at all frequencies while silver plates had the least except at frequencies 400 where copper was the least and at 600 Hz where there were some overlaps. The observed behavior could be as a result of the ferromagnetic nature of Iron i.e., having strong positive susceptibility to external magnetic field and diamagnetic nature of silver and copper. Consistency of the effects of various parameters was observed to improve with frequencies as Fig. 3-5 displayed more consistent trends as opposed to Fig. 1 and 2. At lower frequencies there were indications of irregularity of patterns especially with respect to Silver and Copper plates, but this soon gave way at higher frequencies in all cases investigated.

Table 2 presents the Q-factor range which indicates the variation of Q-factor at different signal frequencies and at different ranges of porosities for metals only, sediments only, as well as sediments with buried metals at frequencies 200, 1000 and 6000 Hz. Similar trends were also

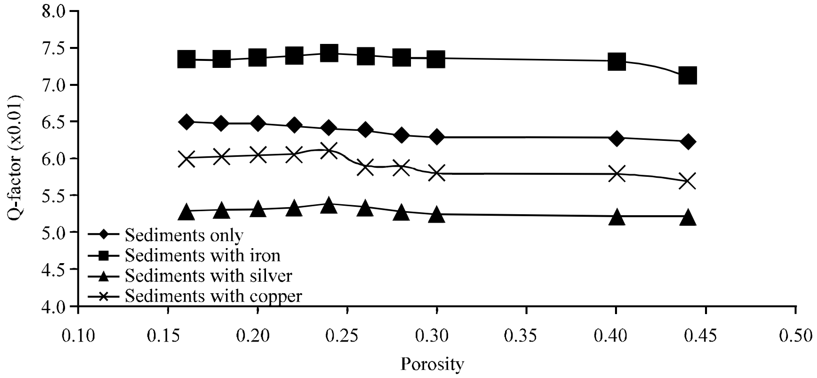

Fig. 5: Relationship between Q-factor and porosity of samples A to J at frequency 5000 Hz

observed as riverbed sediment was found to have resisted the passage of the signal through it but at some point as the frequency increased, the energy loss in the signal reduced. That is, Q-factor decreases as porosity increases and this is because the material medium has become more permeable to the passing signal. Q-factor increased in all cases from 200-1000 Hz and reduced at 6000 Hz. As the energy loss in the signal increases, porosity increases up to a particular frequency 1000 Hz and then decreased afterwards. Quan and Harris (1997) stated that high frequency component of the seismic signals is attenuated more rapidly than the low frequency component as the wave propagated.

CONCLUSION

This study presents the laboratory investigations of the effects of Q-factor of electromagnetic signals passing through a porous media with buried metals on porosity of surrounding medium. Porosity of Erinle riverbed sands was determined using volumetric method. Electromagnetic signal were made to pass through the samples to generate lissajous figures at frequencies 200, 400, 600, 1000, 2000, 3000, 4000, 5000 and 6000 Hz. Iron, Silver and Copper plates, in turns, were buried inside Erinle riverbed sediments and Q-factor was determined from generated lissajous figures. Results showed that Q-factor decreased as the porosity of riverbed sediments increased but when metallic plates were buried in the sediments, Q-factor initially increased with, for all metals and at all signal frequencies, up to a maximum value of 0.24 and thereafter decreased. Buried metallic plates caused attenuation with iron plates having the most pronounced effects and silver plates having the least except at frequencies 400 where copper was the least and at 600 Hz where there were some overlaps. Attenuation characteristics of electromagnetic signals passing through porous media therefore have the potentials to provide insights into the physical properties of the medium as well as that of the buried objects.

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