Characterization of Frequency-Dependent Magnetic Susceptibility in UXO Electromagnetic Geophysics

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Summary

Soils at many locations that have their origin in volcanic parent material and have undergone extensive weathering often exhibit strong frequency-dependent magnetic susceptibilities. The presence of such susceptibility has a profound effect on electromagnetic induction data acquired in such environments. Their transient electromagnetic response is characterized by a $t^{-1}$ decay that is strong enough to mask UXO responses. In a field study and associated laboratory work on characterizing the frequency-dependent magnetic susceptibility and its influence on transient electromagnetic data, we collected soil samples on the surface and in soil pits from the Island of Kaho’olawe, Hawaii, and measured their frequency dependent magnetic susceptibilities. We present the details of the field investigation, confirm previous theoretical work with field and laboratory measurements, characterize the susceptibility with a Cole-Cole model, and investigate the response specific to the measured susceptibility.

Introduction

Common practice for processing and inverting geophysical data for unexploded ordnance (UXO) detection assumes there is no influence from local geology or simply ignores its presence. Recent studies show that soils with frequency-dependent magnetic susceptibility render electromagnetic induction (EMI) data noisy and may mask the response of buried metallic objects (Ware, 2001). Soils with such susceptibility will produce a delayed electromagnetic response when subjected to an applied magnetic field such as that generated by EMI instruments. This phenomenon is referred to as viscous remanent magnetization (VRM). The delayed response is a result of a slow and varied rotation of the magnetic domains within ferromagnetic and ferrimagnetic materials. The time-domain response of VRM soil will exhibit a $t^{-1}$ decay and it can be strong enough to mask the exponential response associated with buried metallic bodies (UXO).

Remediation efforts conducted on the Island of Kaho’olawe, Hawaii, encountered VRM in the soils when EMI and magnetic geophysical methods were employed to aid in the detection of UXO. Cargile et al. (2004) reports that 61,261 anomalies were dug at the Kaho’olawe site, where approximately 70% of the anomalies were caused by non-hazardous metal objects and 27% were caused by geology. This high percentage of geological anomalies illustrates the importance of developing an understanding of the influence of magnetic soils on EMI data in UXO detection.

Field Work and Laboratory Measurements

Field work was conducted at the Navy QA Grid 2E on Kaho’olawe and consisted of collecting soil samples from the surface as well as from four soil pits, and acquiring EM61-MK2 time-domain electromagnetic (TDEM) geophysical data. The locations of the four soil pits relative to the Grid 2E are shown on Figure 1.

Figure 1 – Site condition at the QA 2E grid on Kaho’olawe Island and the locations of four soil pits relative to the grid.

Multi-frequency magnetic susceptibility measurements were made at the Institute for Rock Magnetism (IRM) at the University of Minnesota in Minneapolis on a Lakeshore AC Susceptometer (LACS). The LACS is capable of measuring the complex magnetic susceptibility at 32 frequencies from 10Hz to 10kHz. Figure 2 shows the resulting laboratory measurements conducted with the LACS on two soil samples, one from Soil Pit A (A2) and one from Soil Pit B (B3). This data confirms the theoretical model put forth by Pasion et al. (2002): the measured real component of the susceptibility decreases nearly linearly with increasing logarithmic frequency while the imaginary component is a relatively constant negative value.
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Figure 2 – Complex magnetic susceptibility measurements conducted on two soil samples from Kaho‘olawe. Lines with the x-marker represent the real component and the diamond-marker show the measured imaginary component. The markers indicate the frequencies where measurements were made.

Figures 3 and 4 show the change in magnitude of the measured susceptibilities versus depth for Soil Pits A and B. The measured data indicate little or no frequency dependence and an almost constant magnitude in Soil Pit A, while frequency dependence and variations in the magnitude are clearly visible in Soil Pit B. This figure also shows how the frequency dependence changes with depth for soil samples collected from Soil Pit B, with higher frequency dependence at the surface that decreases with depth. The identified soil horizons, taken from Li et al. (2005), are also listed on Figures 3 and 4. Note the Bw/Cox layer, located approximately 1.1 meters below the ground surface, is identified at the bottom of Soil Pit B but exists at the surface at Soil Pit A. This indicates that the development of VRM in the soils is tied to the extent of the weathering (maturity) of the soils (Van Dam et al., 2008). The maturity of the soils is evident in the photographs of Figures 3 and 4. The soils from Soil Pit A are light brown and comprised of coarse grained sediments and small pebbles. Soil Pit B, located approximately 40 meters to the northeast, offers a stark contrast with predominately reddish-brown fine-grained sediments. Van Dam et al. (2008) established through laboratory measurements of the temperature dependent susceptibility ($\chi_T$) that the VRM and high susceptibilities at Kaho‘olawe are completely due to secondary, or neoformed, minerals.

Figure 5 shows EM61-MK2 data collected at the Navy QA Grid 2E on Kaho‘olawe, which typify the impact the Kaho‘olawe geology has on EMI data. The response from the soils would easily mask the response from any buried metallic objects. In this example a very strong gradient of nearly 500 milliVolts (mV) exists across this 30 meter by 30 meter grid. The calculated difference at two measured susceptibilities (200Hz and 2kHz) is shown in Figure 6. These data give another indication that the EM61 is mapping the variations in the frequency dependence and magnitude of the magnetic susceptibility.

Representation of Frequency Dependence Susceptibility

Pasion et al (2002) proposed a theoretical model to describe the impact of soils with VRM on TDEM data. Soils with VRM will exhibit a real component that decreases linearly with increasing frequency and a constant negative imaginary component. This theoretical model for VRM results in 1D forward models that exhibit a decay curve with a $f^{-1}$ slope for soils with a frequency dependent
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susceptibility and a decay curve with a slope of $t^{3/2}$ for soils with a static susceptibility.

where $\chi_0$ are the real magnetic susceptibilities as the frequency ($\omega$) goes to zero, respectively. The $\tau$ parameter is the relaxation time constant, and the $\alpha$ parameter describes the breadth of frequency distribution with limits of $0<\alpha<1$. An $\alpha = 0$ indicates a single Debye relaxation while an $\alpha = 1$ represents an infinitely broad distribution of relaxation times (Olhoeft and Strangway, 1974).

We have carried out a nonlinear least squares fit to extract the parameters $\alpha$, $\tau$, and $\chi_0$ from the multi-frequency susceptibility measurements. The data misfit between the measured complex susceptibility values and those predicted by the Cole-Cole model is minimized using a downhill simplex method (DSM) (Nelder and Mead, 1965). The DSM provides a straightforward technique to minimize the data misfit function given by:

$$\phi_2 = \sum_{i=1}^{N} \left| \chi_i - \chi_i^{\text{pre}} \right|^2$$

where $\chi_i$ is the observed data, $\chi_i^{\text{pre}}$ is the predicted data, and $N=20$ is the number of frequencies at which we measured the complex susceptibility. Figure 7 shows the resulting fit for soil sample B1.

1D Forward Model of VRM Response

The recovered Cole-Cole parameters may now be used to build a forward model that represents an accurate depiction of the frequency dependent properties of the soils identified at Soil Pit B. The forward model is created using the EM1DTMFWD software produced by the Geophysical Inversion Facility at the University of British Columbia.
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Figure 8 shows two forward models, a single layer model over a half-space and a five layer model over a half-space. The models presented in Figure 8 are built from the soil horizons identified in Soil Pit B. The recovered Cole-Cole parameters for each soil sample were averaged together within each soil horizon – for example, soil samples B7, B8, and B9 were averaged together to get the parameters for the 4th layer in the model. Table 1 lists the parameters used for each layer. The resulting decay curve is displayed in Figure 8 as the red line. The black lines show a $t^{-1}$ slope (solid) and a $t^{-5/2}$ slope (dashed).

As expected, the single layer model, with a 5cm thickness over a half space, has lower amplitude at later time. This is a result of the smaller susceptibility of the half space located at 5cm below the ground surface. The 1D forward models show that a thin layer at the surface (blue line), in this case 5cm thick, with VRM will produce a $t^{-1}$ slope in the decay curve at late time. The five layer model produces almost the exact same decay curve except for the increase in amplitude at late time. These data show how susceptible TDEM data are to a thin layer of soils with VRM. These results are based on a 1D forward model and do not take into account the spatial variability of the susceptibility, VRM, or the volumetric measurement of the typical TDEM system.

![Graph](image)

**Table 1** – Layer properties for the forward models shown in Figure 9. A $\chi_\infty = 1E-6$ was used for Layer 6 and a $\sigma = 0.1$ S/m for all layers.

<table>
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<tr>
<th>Layer #</th>
<th>$\chi_0$</th>
<th>$\tau$</th>
<th>$\alpha$</th>
<th>Thickness (m)</th>
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<td>3.50E-05</td>
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</table>

Conclusions

The work presented here confirms the theoretical model proposed by Pasion et al. (2002) for VRM. The laboratory susceptibility measurements have confirmed that the magnetic susceptibility has a real component that decreases linearly with increasing frequency and an imaginary component that has a constant negative value. Furthermore, TDEM data collected over soils with VRM exhibit a $t^{-1}$ decay with time.

We have represented the complex susceptibility by a Cole-Cole model and obtained the relevant parameters through a nonlinear least squares fit between the laboratory magnetic susceptibility measurements and the Cole-Cole model. Use of the recovered Cole-Cole parameters in the 1D forward indicates that, under a 1D assumption, even a thin layer (~5cm) at the surface with VRM can significantly impact TDEM data in UXO clearance. Therefore, any UXO detection and discrimination work carried out in such an environment must take into account the effect of the magnetic soil.

Acknowledgements

This work is supported by SERDP through project MM-1414. The authors would like to thank Bruce Harrison, Sean Walker, Rich Krahenbuhl, Kris MacLennan. We’d also like to thank the members of the Center for Gravity, Electrical, and Magnetic Studies at the Colorado School of Mines. The authors also thank Mike Jackson at IRM for use of the LACS.
EDITED REFERENCES
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