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Comparing one- and two-dimensional EMI conductivity inverse modeling procedures for characterizing a two-layered soil

Timothy Saey *, Philippe De Smedt, Samuël Delefortrie, Ellen Van De Vijver, Marc Van Meirvenne

Department of Soil Management, Ghent University, Coupure Links 653, 9000 Gent, Belgium

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A B S T R A C T

Apparent electrical conductivity (σ_a) measured with electromagnetic induction (EMI) instruments is used widely as a proxy to map lateral variations in soil properties. To account for the vertical changes in soil properties, EMI inversion techniques have been developed. Improvements in EMI sensing instrumentation allow simultaneous recording of σ_a measurements with different depth responses, facilitating 1D and 2D inversions. In this study, different inversion procedures of EMI data were evaluated on their effectiveness to characterize the depth of the interface between two contrasting soil layers, as well as their respective conductivities. A 1D-laterally constrained inversion procedure was compared with a non-constrained, robust 1D-inversion procedure. Both procedures make use of low induction number (LIN)-approximated depth response curves and provided similar results, although calibration with soil data was essential to attribute absolute values to the inversion data. Aforementioned 1D procedures were then compared to a procedure wherein the full solution of Maxwell's equations, which describe the electromagnetic signal response into the soil, is applied. All approaches rendered similar results. This shows that despite their limitations, the cumulative approximations of the EMI signal response can be used as a valuable and effective alternative to the full solution of Maxwell equations within EMI inversion procedures, especially when the measurements are mainly situated within the LIN measurement range. In a final step, 2D inversions of the EMI data were compared to 2D-inverted electrical resistivity tomography (ERT) data. The general patterns of the resulting inverted soil models were largely comparable and consistent with the observed soil information. To conclude, the different inversion procedures revealed analogous results which were largely comparable and consistent with the soil information. However absolute values could impossibly be obtained without any prior knowledge about the vertical distribution of the soil model. Therefore, the implementation of a thorough calibration based on soil observations was essential to guide the inversion results to a realistic outcome.

1. Introduction

Delineation of the spatial variation of soil properties is a crucial element for soil quality assessment, site-specific crop management and non-point source pollutant transport in the vadose zone (Corwin and Lesch, 2005). Non-invasive proximal soil sensors are able to collect detailed measurements of the soil spatial variability. The ability of such a sensor to obtain data at many more points, as compared to conventional invasive methods, means that overall spatial estimation accuracy can increase even if the accuracy of individual measurements is lower.

Proximal soil sensors based on electromagnetic induction (EMI) are widely used to characterize the near-surface soil because different layers of soil can be characterized by measured variations in electrical conductivity. In the past, different procedures were developed to estimate soil layer conductivities and thicknesses by inverting theoretical models of the measured conductivity. To implement these inversion solutions, multiple conductivity measurements are needed at each point. That is why frequency-domain electromagnetic induction instruments with different coil configurations and/or spacings were developed to simultaneously obtain the required multiple readings while traversing a field (Sudduth et al., 2013). With these instruments, the propagation of EMI radiation into the soil is described by Maxwell's equations (Reynolds, 1997), which means that the forward response is considered to be non-linear. McNeill (1980) and Wait (1962) defined the depth response functions of EMI instruments in homogeneous soils by asymptotic approximations of Maxwell's equations. Hendrickx et al. (2002) proved these approximations to be valid in heterogeneous soils. These are based on the assumption that the induction number is very small (<<1) and also assume zero instrument elevation. At low induction number (LIN), the eddy current loops induced by the primary magnetic field within the soil are considered as non-interacting (Callegary et al., 2007). The dimensionless induction number is defined as the ratio of the instrument coil separation divided by the skin depth δ. As the true conductivity increases, the skin depth decreases causing the induction

* Corresponding author.
E-mail address: Timothy.Saey@UGent.be (T. Saey).

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number to rise. This effect is enhanced with increasing spacing in-between transmitter and receiver coils. At high values of true conductivity the instrument response is no longer proportional to the true conductivity. Moreover, the true conductivity is increasingly underestimated by the instrument output with increasing coil spacing and frequency. However, it is unclear what the upper boundary of the induction number for a valid LIN approximation should be. Therefore, EMI inverted data can be biased employing the LIN approximated depth response functions (Callegary et al., 2007; Delefortrie et al., 2014).

EMI measurements return an apparent electrical conductivity (σ_a) that represents an integrated average of the electrical conductivity (σ) distribution over a certain soil volume. The reconstruction of this distribution is often difficult due to the intrinsic non-uniqueness, over-parameterization, and/or large residuals between measurements and the modeled outcome. Despite these difficulties, different procedures were developed for inverting EMI data. Monteiro Santos (2004) introduced a smooth and laterally constrained inversion algorithm based on the McNeill (1980) LIN approximation. Saey et al. (2009) inverted multiple EMI measurements one-dimensionally, also based on the LIN approximation, to map the depth of the interface between contrasting soil layers. Hendrickx et al. (2002) employed a forward model based on both the McNeill approximations and on the full solution of Maxwell's equations, to predict the vertical distribution of the soil conductivity. Recently, Mester et al. (2011) developed a novel two-layer EMI inversion algorithm that employs both the LIN approximation and the full solution to invert the simultaneous σ_a measurements recorded with different coil spacings, coil orientations, and frequencies. Regularization is commonly included in the inversion procedures, to obtain a gradual σ depth model. However, when the subsoil manifests a distinct 'layeredness', smooth inversion models are inherently less appropriate for reconstructing abrupt vertical changes in σ with depth. Monteiro Santos et al. (2010) observed relatively high misfits between the conductivity obtained after inverting data gathered from a one-dimensional forward modeling of a synthetic conductivity model and the synthetic model itself in situations where sharp vertical variations of σ are present. Such deviations are caused by the difficulty of the inversion procedure to represent these abrupt σ changes. However, this smooth inversion procedure, which integrates different consequent measurements to estimate the depth of a soil layer, introduces a more gradual variation in soil layeredness through 2D smoothness constraints between adjacent 1D models.

It is well-known that 2D- or 3D-inversion procedures can better reproduce actual soil variations compared to 1D inversions, as the latter cannot determine the thickness and conductivity of all soil layers unequivocally (Bongiovanni et al., 2008). Nevertheless, 1D methods can be more effectively applied to soil sensing data because inverting in 3D or even in 2D increases the complexity and calculation effort. Furthermore, restrictions and boundary conditions can be easily implemented within 1D-inversion procedures as constraints to work towards a realistic outcome. Subsequently, these procedures can be implemented on a larger scale, improving the non-invasive characterization of large areas at a high resolution both laterally and with depth (Gaffney et al., 2012; Saey et al., 2013).

The aim of this paper is to compare the application of a 1D-laterally constrained smooth inversion technique by Monteiro Santos (2004) with the non-constrained 1D-inversion procedure by Saey et al. (2008, 2009) to predict the depth to the interface within a two-layered subsoil, and to reconstruct the vertical σ distribution. The LIN approximated cumulative depth responses as a basis for inversion procedures, will be compared to the use of the full solution of Maxwell's equations. Both procedures will then be evaluated based on the results from soil auger observations. Additionally, the results from a 2D-inversion routine will be compared to electrical resistivity tomography (ERT) results along a transect to provide a qualitative measure of the success of a 2D-EMI inversion routine.

2. Materials and methods

2.1. Study site

A study site (central coordinates 50°47′58″N, 3°24′41″E) was selected within the Belgian loess belt. It comprises an arable area of 2.0 ha and is situated on a south-east facing hill slope (Fig. 1). Plowing occurs up to 0.35 m depth. Its subsoil consists of Eocene marine clayey deposits, covered by a Quaternary loess layer with a thickness ranging between a few decimeters to some meters. The thickness of the loess cover varies with position in the landscape (Saey et al., 2008). On this site, which deposits constitute at wo-layered soil with a large textural contrast between both layers (the average difference in clay content is 21%, see Saey et al. (2008)), soil auger observations allow calibration and validation of the 1D inversions. Apart from this site, two EMI and ERT profiles were collected at a 500 m distance from the study site (with similar soil configuration).

2.2. Multi-receiver EMI instrument

We employed the DUALEM-21S instrument (DUALEM, Milton, Canada), which consists of one transmitter coil and four receiver coils at spacings of 1, 1.1, 2 and 2.1 m and works at a frequency of 9 kHz. The 1 and 2 m transmitter–receiver pairs form a horizontal coplanar dipole mode (HCP-1 and HCP-2), while the 1.1 and 2.1 m pairs form a perpendicular dipole mode (PRP-1 and PRP-2). The depth response pattern of the signal depends on both the transmitter–receiver spacing and on their respective orientation. The cumulative σ_a response (relative to 1) from the subsurface volume above a depth z (in m) was given by McNeill (1980) for the horizontal coplanar ($R_{HCP,s}(z)$) dipole mode. Dualem Inc. (2007) developed the equation of the cumulative response for the perpendicular dipole mode ($R_{PRP}(z)$) based on Wait (1962):

$$R_{HCP\text{-}s}(z) = 1 - \left(4 \cdot \frac{z^2}{s^2} + 1\right)^{-0.5} \quad (1)$$

$$R_{PRP\text{-}s}(z) = 2\frac{z}{s}\left(4\frac{z^2}{s^2} + 1\right)^{-0.5} \quad (2)$$

with s being the transmitter–receiver spacing.

The depth of exploration (DOE) differs for the different coil configurations: PRP-1: 0.5 m, PRP-2: 1.0 m, HCP-1: 1.5 m and HCP-2: 3.2 m. These are the depths at which 70% of the cumulative response of the coil configuration is reached. With this definition, 30% of the response still originates from soil material below the DOE. Therefore, highly contrasting electrical features below the DOE can influence the σ_a measurements substantially.

Our EMI sensor was pulled in a polyethylene sled by an all-terrain vehicle at a speed of about 5–8 km h^{-1}, crossing the field at parallel lines spaced 2.0 m. Within the lines, the measurement interval was approximately 0.25 m.

2.3. Smooth 1-D inversion

EM4Soil is a software package (EMTOMO, 2013) for inverting σ_a data (Triantafilis and Monteiro Santos, 2013). The applied procedure was first presented by Monteiro Santos (2004) and employed the non-linear smoothness-constrained inversion algorithm by Sasaki (1989). The soil model used within the inversion process consists of a number of blocks whose distribution and size depend on the measurement locations, and on the number of intercoil spacings from the EMI instrument. Either the depth response functions from Eqs. (1) and (2) are used within the forward model to calculate the σ_a response from the soil model or the full solution of Maxwell's equation can be