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Summary of the Doctoral thesis

Inverze a hloubkový rozsah dipólových elektromagnetických indukčních měření v geofyzice

Inversion and Depth Range of Dipole Electromagnetic Induction Measurements in Geophysics

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Abstrakt

Geofyzikální metody elektromagnetické indukce se v podstatě skládají z vysílače, který produkuje magnetické pole, a souboru přijímačů, které měří primární magnetické pole z vysílače, složené se sekundárním magnetickým polem indukovaným pod povrchem. Zařízení pracující na relativně nízkých frekvencích a s krátkou vzdáleností mezi vysílačem a přijímači se obvykle nazývají konduktometry a pracují při nízkých indukčních číslech. Hloubkový dosah u takovéhoto zařízení závisí především na vzdálenosti mezi vysílačem a přijímačem, na orientaci magnetických dipólů a na výšce, ve které se přístroj nachází od země, tak aby bylo možné provést hloubkové sondování změnou těchto parametrů v jediném místě měření. Lze provádět série těchto multikonfiguračních měření, dvojrozměrných nebo dokonce trojrozměrných průzkumů a následně je invertovat tak, aby se vytvořil obraz pod povrchem země.

Přímou úlohu a inverzi multikonfiguračních dat elektromagnetické indukce lze provádět pomocí úplného nelineárního řešení Maxwellových rovnic nebo pomocí lineární aproximace s nízkým indukčním číslem. Zde jsou studovány chyby pozorované při použití této lineární aproximace za účelem ověření její platnosti a je zavedena metodika k překonání těchto chyb za účelem získání spolehlivějších hodnot zdánlivé vodivosti. Přímá úloha využívající aproximaci s nízkou indukčním číslem využívá kumulativních funkcí odezvy, které byly původně určeny pro přístroje pracující na povrchu země. Zde jsou zavedeny nové analytické relativní a kumulativní funkce odezvy s přihlédnutím k výšce, ve které se přístroj nachází od země. Vliv této výšky na hloubkový dosah je studován analyticky.

Inverze geofyzikálních dat je jedním z největších problémů v aplikované geofyzice vzhledem k tomu, že počet neznámých parametrů pod povrchem je mnohem větší než počet pozorovaných dat. Kromě toho jsou data kontaminována šumy, a proto může mít obrácená úloha obrovské množství řešení, která by vedla k dobré shodě mezi pozorovanými a modelovanými daty. U elektrických a elektromagnetických metod může být fakt, že řešení nejsou jednoznačná, způsoben například principem ekvivalence u jednorozměrných modelů země, kterému se zde podrobně věnujeme. Zvláštní pozornost je věnována rozdílu v závažnosti tohoto problému při použití zdánlivé vodivosti nebo reálné a imaginární části elektromagnetického pole jako pozorovaných dat.

Je zde představen kvazi-dvourozměrný inverzní postup, který lze také extrapolovat na trojrozměrný. Základní postup se skládá z následujících kroků: nalezení bodu na profilu, který se nachází v místě nejpodobnějším jednorozměrnému prostředí; odhad počátečního jednorozměrného modelu pro zvolený bod průzkumu za použití lineární inverzní metody s použitím Moore-Penrosovy pseudoinverze; použití metody nelineární proměnné metriky k inverzi s pomocí tlumené metody nejmenších čtverců, kde dříve získaná počáteční jednorozměrná hodnota je použita jako a priori informace k získání realističtějšího jednorozměrného modelu pro původně vybraný bod, jaký lze získat úplným řešením Maxwellovy rovnice; použití dříve získaného jednorozměrného obráceného modelu jako apriorní informace o sousedním bodě; tyto nově získané inverze jsou použity jako apriorní informace pro své další sousedy a tak dále.

Nakonec byla zavedená inverzní procedura testována na několika dvojrozměrných syntetických a reálných datech. Výsledky inverzí byly srovnány s inverzí elektrických odporových tomografických dat shromážděných ve stejných sekcích. Jsou diskutovány rozdíly zjištěné mezi těmito dvěma inverzemi pomocí srovnávání s využitím syntetických a reálných dat. Také je studován vliv stínění elektrického pole, kdy jsou na syntetickém příkladě pozorovány velké rozdíly mezi inverzí stejnosměrných a indukčních dat.

Abstract

Electromagnetic induction geophysical methods are, basically, composed by a transmitter which produces a magnetic field and a set of receivers which measure the primary magnetic field, from the transmitter, superimposed by secondary magnetic fields inducted in the subsurface. Equipment operating at, relatively, low frequencies and with short distances between the transmitter and the receivers are usually called conductivity meters and operate at low inductions numbers. The depth of investigation, in such kind of equipment, depends mainly on the transmitter-receiver distance, on the orientations of the magnetic dipoles and the height of the instrument from the ground, in order that a depth sounding can be done changing these parameters in a single measurement location. Making a series of these multi-configuration measurements, two-dimensional, or even three-dimensional surveys, can be performed and, subsequently, inverted in order to produce an image of the subsurface of the earth.

Forward modelling and inversion of multi-configuration electromagnetic induction data can be made using the full non-linear solution of Maxwell's equations or using the linear low induction number approximation. Here, the errors observed when using this linear approximation are studied in order to check its validity and is introduced a methodology to overcome these errors in order to obtain more reliable values of the apparent conductivity. Forward modelling using the low induction number approximation makes use of the cumulative response functions, which were originally designed for instruments operating at the surface of the earth. Here, new analytical relative and cumulative response functions are introduced, taking into account the height of the equipment from the ground. The influence of this height upon the depth of investigation is analytically studied. Here is also presented a study of the validity of the low induction number approximation.

Inversion of geophysical data is one of the greatest problems in applied geophysics, as the number of subsurface unknown parameters is much greater than the number of observed data. Besides that, the data is contaminated by noise and thus the inverse problem may have a huge number of solutions which would lead to a good fit between observed and modelled data. In electric and electromagnetic methods, the non-uniqueness of the solution can be caused, for example, by the principle of equivalence in one-dimensional earth models, which is discussed thoroughly here. Special focus is given to the difference in the order of magnitude of this problem when using, as observed data, the

apparent conductivity or the real and imaginary parts of the electromagnetic field.

Here is introduced a quasi-two-dimensional, which could also be extrapolated to three-dimensional, inversion procedure. The basic procedure is to find the point of the electromagnetic survey which is more likely to be within an one-dimensional environment; estimate an initial one-dimensional model, for the chosen point of the survey, using a linear inversion approach using the Moore-Penrose pseudo-inverse; use the non-linear variable metrics method to solve the damped least square inverse problem where the previously obtained initial one-dimensional is used as *a priori* information to obtain a more realistic one-dimensional model for the initially chosen point, as it is obtained from the full solution of Maxwell's equation; use the previously obtained one-dimensional inverted model as *a priori* information to the neighbour points and these newly obtained inversions are used as *a priori* information for their next neighbours and so on.

Finally, the introduced inversion procedure was tested for several two-dimensional synthetic and real data. The inversions results were compared with the inversion of electrical resistivity tomography data collected at the same sections. A discussion about the differences found between these two inversions, by the means of comparisons using synthetic and real data, is presented. The electric field shielding problem, where great differences between the two inversions are particularly observed, is studied by means of a synthetic example.

Contents

1 Introduction

One of the most commonly used geophysical techniques for mapping the electrical conductivity of the subsurface is by means of conductivity meters using the electromagnetic induction (EMI) principle. EMI methods can be used for a wide range of applications and notably for soil mapping, contaminant detection, characterisation of shallow aquifers, and location of buried objects or ore bodies.

In electromagnetic induction methods, electric currents are introduced within the earth by the principle of electromagnetic induction where a time varying magnetic field impinging the surface of the earth or propagating within the earth, called the primary magnetic field (H^P), induces an electric field in the subsurface, in the presence of which, electric current flows. These electric currents flowing within the earth produces by its turn, another magnetic field, called the secondary field (H^S). The sum of the primary field with the secondary field is then measured by magnetic receivers.

Most conductivity meters measure the mutual coupling ratio (Q) which is the ratio between the secondary magnetic field (H^S) and the primary magnetic field (H^P) at the receiver coil. The measured quantity Q is usually given in two components: the real part, which is in-phase with the primary field, and the imaginary part which is in quadrature (off-phase) in relation to the primary field.

For a qualitative analysis of the observed data, derived from Q, the most commonly used information are the apparent conductivity and the depth of investigation. Apparent conductivity is, by definition, the conductivity of a homogeneous subsurface which would lead to the same value of the measured ratio Q. The most common way to obtain the apparent conductivity is by using the, so-called, Low Induction Number (LIN) approximation, described in McNeill [1], in which a linear relationship between the measured off-phase component of Q is used to calculate the apparent conductivity.

The depth of investigation (DOI) of conductivity meters operating in the LIN zone depends mainly on the transmitter-receiver distance (s), on the orientations of the dipoles and the height of the instrument from the ground. Changing these configuration parameters is possible to make a depth sounding at each point of measurement. For a more quantitative analysis of the observed data, inversion techniques must be used.

2 Aims of the study

The main goal of this thesis is to quantitatively characterize 2-D media by means of geophysical inversion of multi-configuration EMI data. The multi-configuration EMI data may be obtained by means of different distances between the transmitter and receiver coils, the orientation of the dipoles and the height of the dipoles from the ground.

Other results were obtained in order to achieve this main goal:

- A discussion about the validity of the LIN approximation was published in [2]. This paper also proposes a methodology to overcome these errors in order to obtain more reliable values of the apparent conductivity.
- The introduction of new generalized response functions, where the height of the equipment from the ground is taken into account, which were published in [3]. It includes also a study about the depth of investigation of EMI equipment operating at low induction numbers and introduces analytical equations derived from the generalized cumulative response functions.
- A study of the principle of equivalence in EMI methods with special focus on the difference in the order of magnitude of the problem when the apparent conductivity or the real and imaginary parts of Q are used as observed data.
- The introduction of a new iterative approximate methodology to solve even-determined linear systems, where the number of layers is equal to the number of measurements, which was published in [4].
- Discussion about the differences usually found between inversion of EMI and electrical resistivity tomography data by means of comparisons using synthetic and real data. The electric field shielding problem, where great differences between the two inversions are particularly observed, is studied by means of a synthetic example.
- A discussion about the validity, necessity and usefulness of techniques, derived from electrical resistivity tomography (ERT) data inversion, for calibration or correction of the collected apparent conductivities values before EMI inversion.

3 Materials and methods

The usually measured quantity by EMI equipment is the mutual coupling ratio (Q). The electromagnetic forward modelling based in the full solution of

Maxwell's equations for vertical and horizontal dipole (VCP) source-receiver combinations with an inter-coil separation s over an 1-D layered earth with N layers over an infinite half-space with conductivity σ_{N+1}, is given by Keller and Frischknecht [5] in terms of the mutual coupling ratio (Q) at the receiver coil as:

$$Q^V(s) = \frac{H^S}{H^P} = -s^3 \int_0^\infty R_0(\lambda) J_0(s\lambda) \lambda^2 e^{-2\lambda h} d\lambda \tag{1}$$

and

$$Q^H(s) = \frac{H^S}{H^P} = -s^2 \int_0^\infty R_0(\lambda) J_1(s\lambda) \lambda e^{-2\lambda h} d\lambda \tag{2}$$

where J_0 and J_1 are the first kind zero-order and first-order Bessel functions, λ is the radial wave number, h is the height of the dipoles from the ground and $R_0(\lambda)$ is called the reflection factor which depends on the thicknesses and the electrical conductivities of each layer and is calculated at the interface between the air and the first layer. It can be obtained recursively beginning from the bottom layer N observing that there are no upcoming waves from the lower half-space, so $R_{N+1} = 0$ and:

$$R_n(\lambda) = \frac{(\Gamma_n - \Gamma_{n+1})/(\Gamma_n + \Gamma_{n+1}) + R_{n+1} e^{-2\Gamma_{n+1} d_{n+1}}}{1 + (\Gamma_n - \Gamma_{n+1})/(\Gamma_n + \Gamma_{n+1}) R_{n+1} e^{-2\Gamma_{n+1} d_{n+1}}} \tag{3}$$

where $\Gamma_n = \sqrt{\lambda^2 + i\omega\mu_0\sigma_n}$, d_n and σ_n are the thickness and the electrical conductivity of the nth layer. $R_0(\lambda)$ is obtained assuming layer 0 as the air with $\sigma_0 = 0$. The integrals in equations 1 and 2, the Hankel transforms of functions $\lambda^2 R_0 e^{-2\lambda h}$ and $\lambda R_0 e^{-2\lambda h}$, respectively, can be calculated by linear filtering. Here we used the Guptasarma and Singh filters [6] with 120 elements for the Hankel J_0 transform and 140 elements for the Hankel J_1 transform. The above equations are, again, valid only for constant values of ϵ and μ and for the quasi-static approximation.

A very important dimensionless parameter in EMI methods is the induction number (B) defined by $B = s/\delta$ where the skin depth (δ) is a well-known characteristic of a homogeneous half-space defined as the depth in the half-space at which the amplitude of a generated primary field has been attenuated to $1/e$ of its amplitude at the surface. If $B \ll 1$, Q_V and Q_H can be approximated, for a homogeneous medium, by means of the first term of a Taylor expansions, to an expression depending only on the conductivity. It means that when the instrument operates at very low induction numbers, we can obtain the value of the conductivity of the homogeneous half-space as:

$$\sigma = \frac{4}{\omega\mu_0 s^2} \Im\left(\frac{H^S}{H^P}\right). \tag{4}$$

This is the so-called *Low Induction Number* (LIN) approximation. Most electromagnetic induction equipment displays the results of measurements in terms of apparent conductivity using this approximation.

A study of the errors of the LIN approximation for the configurations of several available instruments was made [2]. In average, to obtain an error less than 5%, the induction number should be at least smaller than 0.05 for the case when the equipment is used over the ground. For the cases where the equipment is used at the height of one meter from the ground the error is never smaller than 20%. An iterative method for overcoming these errors and obtain a more precise value of apparent conductivity, using the Newton-Raphson method to find the zero of the function $f = |\Im(Q_{measured}) - \Im(Q_{calculated})|$, which use the conductivity obtained by the LIN approximation as the starting value, was also introduced. The method is easily implemented and leads to much smaller errors compared with the LIN approximation.

Following McNeill [1], a low induction number approach can also be used to forward model the apparent conductivity, using the so-called cumulative response functions R_V and R_H, as follows:

$$\sigma_a = \sum_{i=0}^{N} \sigma_{i+1}[R_{V|H}(z_i) - R_{V|H}(z_{i+1})] \tag{5}$$

where z_i is the depth of the bottom of the layer i. Note that $z_0 = 0$, which leads to $R_{V|H}(z_0) = 1$, and $R_{V|H}(z_{N+1}) = 0$ as $z_{N+1} = \infty$. The cumulative and relative response functions given in [1] were obtained for the case when the equipment is operated at the ground level. Comparing these well-known expressions with numerically obtained response functions using equations 1 and 2 for the case when the equipment is operated at some height h from the ground, new generalised analytical relative and cumulative response functions which take into account the height (h) from the ground were introduced [3]. The generalised relative response functions are given by:

$$\Phi_V(z, h, s) = \sqrt{4(h/s)^2 + 1}\frac{4(z + h/s)}{(4(z + h/s)^2 + 1)^{3/2}}, \tag{6}$$

and

$$\Phi_H(z, h, s) = \left(2 - \frac{4(z + h/s)}{(4(z + h/s)^2 + 1)^{1/2}}\right)\frac{1}{\sqrt{4(h/s)^2 + 1} - 2(h/s)}. \tag{7}$$

The generalised cumulative response functions are given by:

$$R_V(z, h, s) = \frac{\sqrt{4(h/s)^2 + 1}}{\sqrt{4(z + h/s)^2 + 1}} \tag{8}$$

and

$$R_H(z,h,s) = \frac{\sqrt{4(z+h/s)^2+1} - 2(z+h/s)}{\sqrt{(4(h/s)^2+1} - 2h/s} \tag{9}$$

Analysing the introduced generalised equations, we can show that when an EMI equipment operating in the vertical dipole mode is raised above the ground, the influence of near-surface material increases until the height equals the half of the inter-coil distance and then it starts to decrease. It can also be shown that the depth of investigation for the vertical dipole mode also varies with height: it decreases until the height equals the half of the inter-coil distance multiplied by the value of the cumulative response function used to define it, and then increases with increasing height.

A new iterative quick method for one-dimensional linear inversion of multi-configuration EMI data, solving even-determined systems, which can be created using equation 5 for different configurations, where the number of layers is equal to the number of measurements, is introduced [4]. The methodology makes use of the generalised cumulative response functions.

The main objective of this thesis is to introduce a new methodology of non-linear quasi-2D inversion. The quasi-2D inversion consists, basically, of 1-D inversions at each multi-configuration measurement point where, starting from a point at which the medium is most likely to be one-dimensional, the remaining 1-D inversions use the parameters, obtained from the 1-D inversions of its neighbour points, as *a priori* information for which a weight is given, within the objective function, so that a lateral continuity is fulfilled. The quasi-2D inversion follows these steps:

1. Choose the point of the profile that is more likely to be within a 1-D environment. It is done by calculating a 7-points moving coefficient of variation of the apparent conductivity and picking the point in which it is minimal, which means that the conductivities near this point have the minimum variation along the profile.

2. Estimate an initial model at this point by setting the number of layers to 4 and make a grid search for the thicknesses of the layers. The search is made from 0.5 to 4 m. For each point of the grid we solve the linear inverse problem for the conductivities of the layers using the Moore-Penrose pseudo-inverse. The final inverted 1-D model is chosen as the set of thicknesses which minimizes the squared differences (L2-Norm) between the observed apparent conductivities and the predicted apparent conductivities obtained from the linear forward modelling using the parameters of each grid point.

3. Using the initial guess model found in step 2 as an *a priori* model $\vec{m_p}$ we use the Variable Metrics method to solve the damped least square problem: $min(||\vec{d_{obs}} - G(\vec{m})||_2^2 + \alpha||\vec{m} - \vec{m_p}||_2^2)$, where $G(\vec{m})$ is the non-linear full solution of Maxwell's equations (equations 1 and 2), α is the regularization parameter and $\vec{d_{obs}}$ are the observed apparent conductivities. The parameter α is chosen, from a direct search, as the one for which the data part of the objective function is closest to the model part $(||\vec{d} - G(\vec{m})||_2^2 \approx ||\vec{m} - \vec{m_p}||_2^2)$. With this procedure we get a more precise 1-D model as it is obtained from the full solution of Maxwell's equation.

4. Using the inverted 1-D model obtained in step 3 at the chosen point (step 1) as an *a priori* model we use the same procedure described in step 3 to obtain the inverted model at the two neighbour points (to the right and to the left of the chosen point in step 1). The parameters for these points are then used as the *a priori* model for the next neighbour points and so on.

4 Results and discussion

Several tests were made, six using synthetic models and three using real field data, to evaluate the performance of the proposed quasi-2D inversion methodology. The analysis of the results from synthetic data examples shows that the inversions, in most cases, lead to quite good estimations of the subsurface. The greatest found issues come from the non-uniqueness character of the inverse problem derived mostly from the principle of equivalence. These problems can only be solved with the inclusion of some *a priori* geological information taken, for example, from lithological profiles made, from samples extracted from boreholes or from geophysical well-logging.

The principle of equivalence in EMI methods is thoroughly studied with special focus on the difference in the order of magnitude of the problem when the apparent conductivity or the real and imaginary parts of the mutual coupling ratio, Q, are used as observed data. It was concluded that if we have a n-layered earth-model we would need $2n$ - 1 measurements of apparent conductivity to obtain a single point solution, but we would only need n measurements of the mutual coupling ratio (H^S/H^P) to obtain a single point solution.

The analysis of the EMI inversion results from real data showed a good agreement with what was expected to be obtained, based on general geological information of the studied areas. The results are also compared with inversion results of electrical resistivity tomography (ERT) surveys performed on the same locations. Analysis of both inversion results showed a general similarity between the inverted sections. The differences between EMI and ERT inversions were also studied by the means of synthetic and real data examples. It could be concluded that if a calibration (correction) of the collected EMI data, using the forward modelled EMI data, obtained from the ERT inverted model is performed, the results of the inversion of the *calibrated* (corrected) data can be, in some cases, even worse than the results from the uncorrected data. This may indicate that the calibration of EMI data, using ERT inverted data, may not be always useful as both data cannot be directly correlated.

Here it is presented two of the studied examples. One for synthetic data and the other for real data. The synthetic model example is a three-layered earth model with a conductive middle layer. The first layer has a constant thickness of 1.5 m and conductivity of 5 mS/m. The thickness of the second layer increases from 1.5 m in the borders to 4 m in the centre of the profile and its conductivity is 20 mS/m. The bottom layer has the same conductivity of the first layer. The Synthetic model is shown in Figure 1.

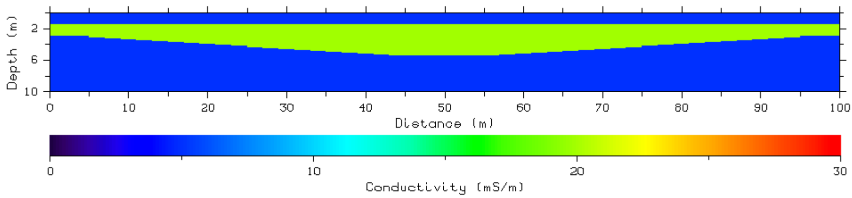

Figure 1: Original model of a 3-layered earth with a resistive middle layer and descending bottom layer.

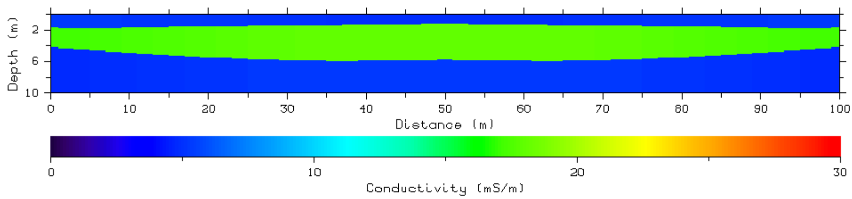

Figure 2: Inversion result from 9-configurations synthetic EM data from Example 4.

Figure 2 shows the results of the quasi-2D inversion applied to the stitched synthetic 1-D EM data obtained from the synthetic model while Figure 3 shows the results of the quasi-2D inversion applied to the synthetic EM data with the addition of 5% noise.

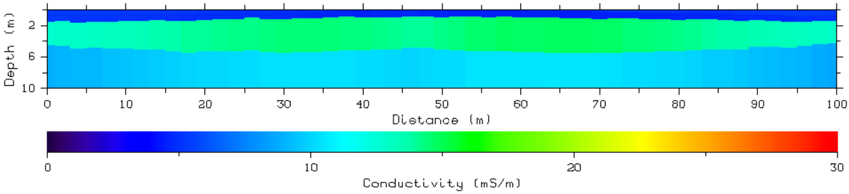

Figure 3: Inversion result from 9-configurations synthetic EM data from Example 3 with 5% white noise added.

The inversion of the noiseless data clearly shows the presence of the conductive middle layer and its decreasing thickness from the centre to the borders. The conductivities of the three layers were very well estimated as it was the thickness of the top layer. The main pitfall is that the thickness of the middle layer was a bit overestimated in the borders and consequently the dip was underestimated. The inversion of the noisy data did not show significant differences from the noiseless data in terms of the geometry of the layers but the conductivity contrast between the two bottom layers was not so evident.

The real data example was made on a crop field over alluvial sediments near Bystřice, in the Benešov district, Czech Republic. The expected subsurface was to be of the contact between the alluvial gravel, sand and clay sediments, close to a small river and the Splavský dam, with the outcropping crystalline basement.

The EM measurements were made along a 200 m profile, with distance between stations of 2 m, with the GF Instruments CMD-Explorer with 6 different dipoles configurations. The profile starts downhill to the East where the sediment layer is expected to be thicker. An electrical resistivity tomography (ERT) survey with 96 electrodes, using a Wenner-Schlumberger array with minimum electrode distance of 2 m, was also made along the same profile of the EM data in order to compare the inversion results from the two methods. The collected ERT data was inverted using the *DC2dInvRes* software [7].

Figure 4 shows the results of the quasi-2D inversion applied to the collected EM data and Figure 5 shows the results of ERT inversion. In both figures we can see to the left a very low resistive ($\approx 30\,\Omega$m) region within a medium resistive layer ($\approx 100\,\Omega$m) representing probably a clay lens within the alluvial sediments and a more resistive layer on the bottom. To the right this layer vanishes indicating a very shallow crystalline basement.

Changing the inversion methodology to use the real and imaginary parts of the ratio H^S/H^P, instead of the apparent conductivity as observed data,

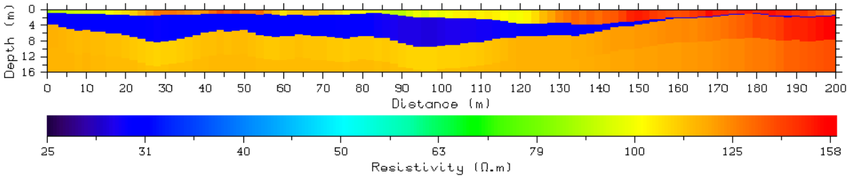

Figure 4: Inversion result from 6-configurations EM data measured in a crop field over a contact between alluvial sediments and outcropping crystalline basement, near Bystřice.

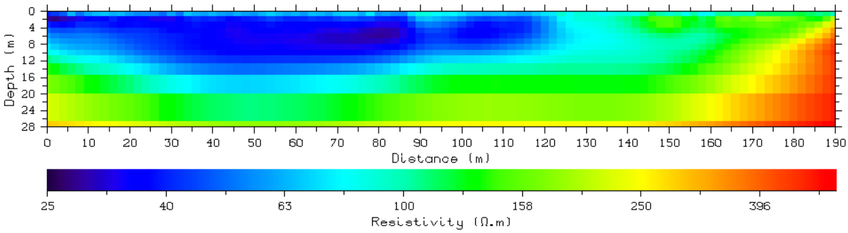

Figure 5: Inversion result from ERT data measured in a crop field over a contact between alluvial sediments and outcropping crystalline basement, near Bystřice.

showed that the results improved considerably. It points to the recommendation of the direct use of the components of Q, when they are available, as observed data instead of transforming them into apparent conductivities.

5 Conclusions

Electromagnetic data inversion is a difficult task due to, mostly, the principle of equivalence and the presence of noise. The use of *a priori* information obtained from boreholes makes the task much more reliable. The use of the real and imaginary components of the magnetic field as observed data, instead of the apparent conductivity, can be very useful to decrease the order of magnitude of the principle of equivalence and, consequently, improve the inversion results. The use of electrical resistivity tomography inverted data to calibrate electromagnetic data may not always be useful as the two methodology can lead to quite different results, due to the behaviour of the current flow within the earth when using direct or induced currents. The proposed new generalised relative and cumulative response functions are very useful for linear 1-D modelling and inversion when the electromagnetic instrument is not operated at the earth's surface; made possible to, analytically, study the behaviour of the depth of investigation with the height of the instrument from the ground and were used within a new iterative method for one-dimensional linear inversion of multi-configuration EMI data. The introduced non-linear quasi-2D inversion technique proved to be very useful for 2-D environments as it produced good results for many tested synthetic and real data examples, being able to identify, very efficiently, the subsurface structures.

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Curriculum Vitae

Personal Information

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Working experience

1994-NOW	Researcher
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1991-1994	Researcher, fellowship
	Fundação Cearense de Meteorologia e Recursos Hídricos
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1988	Mechanical Engineer
	Indústria Naval do Ceará
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Education

2014-NOW	Ph.D.
	Applied Geology
	Charles University, Faculty of Science
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1989-1991	M.Sc.
	Geophysics
	Universidade Federal da Bahia
	Salvador, Brazil.
1983-1988	Engineer
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Personal skills and competences

Languages	Portuguese, English, Spanish and a bit of Czech
IT	Fortran, Python, Android Java, PHP
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Selected Publications

Andrade, F.C.M. and Fischer, T. (2018). Generalised relative and cumulative response functions for electromagnetic induction conductivity meters operating at low induction numbers. Geophysical Prospecting 66(3):595-602 (IF:1.744).

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