Observed Linear and Non-linear IP Effects - A Summary of Joint Italy-South Africa Bilateral Projects 2007-2014

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Observed Linear and Non-linear IP Effects - A Summary of Joint Italy-South Africa Bilateral Projects 2007-2014

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SUMMARY

Among the several types of induced polarization effects, electro-osmosis and membrane polarization by constrictivity of pores my result in non-linear behaviour, i.e. chargeability is not constant with supplied dc current. A new model, based on the second Fick's equation succeeded in predicting, on laboratory samples, this behaviour. In fact, The non-linear behaviour was shown to correlate well with Pore Size Distribution (PSD) of laboratory tested samples whose PSD distribution was measured experimentally using a mercury injection capillary pressure test method. The model predicts also the non-linearity of the electrical resistivity for sufficiently high current densities. In this paper, we show that non-linear behaviour of resistivity and chargeability vs. supplied current density can be met in field measurements, provided they are carefully planned. In a site located in Northern Apennines, where a saturated sandstone outcrops, different values of resistivity and chargeability were obtained at different supplied electric current whose achieved results agree with the forward model. Moreover, the non-linearity can also perturb TEM data as being affected by this IP effect, as the model predicts a dependence of non-linearity also on the current supply length. An example of anomalous TEM data collected in Northern Apennines is also presented and discussed.

Introduction

The effect of Induced Polarization (IP) occurs in the rocks due to distribution of ions in the pores when continuous electrical current is applied. There are several types of induced polarization effects observed in geophysical surveys and laboratory measurements on samples. These are electrolytic polarization, Maxwell-Wagner effect, electro-osmosis and membrane polarization. We will concentrate on the latter two. It is known that two important conclusions have been accepted by all geophysicists, namely: 1. Processes of IP at time on and time off are the same. 2. There is a linear dependence between applied electrical current and IP amplitude. However, these assumptions are not universal: linearity or non-linearity of IP depends on the type of polarization. The electro-osmosis polarization arises as a result of the transport of the electrolyte through the porous rock when a gradient in the electrical field is applied. Mathematical modelling of a little known model of IP referred to as "induced polarization caused by constrictivity of pores" was developed by Zadorozhnaya and Hauger, (2009), Zadorozhnaya and Maré (2011). It was shown that this effect is non-linear at least for high current density. The aim of this paper is to show the influence of different kinds of IP effects on field and laboratory geoelectric and geoelectromagnetic measurements obtained results.

Theory

Membrane polarization occurs in all types of porous, water-saturated rocks if surface areas and transfer numbers are different for connected pores. The duration of the polarization process depends on two parameters: pore radii of connected capillaries and transfer numbers. During the polarization process all contacts between pores of different transfer numbers will be blocked and the electrical current will flow through the remaining canals. Two phenomena control the amplitude of potential difference at time-on: 1. Successive blockage of pores increases the resistivity of involved rock volumes and results in increased potential difference between two measuring electrodes (the "overvoltage" effect). 2. Excess concentration of electrolyte at the boundaries between pores with different radii provides an additional potential.
The amplitude of the potential difference (voltage) of such rocks, in response to an electric current flow, not only depends on solutions filling pore spaces, porosity and tortuosity of pore channels, but also on ion mobility, diffusion coefficient, and difference of transfer numbers. During time-on a voltage occurs due to flowing current and to excess concentration at the contacts among pores. However during the time-off only the potential due to excess of concentration is involved in the diffusion process which tends to level the ion concentration along the pores. Hence the well-known fact results that the measured chargeability depends (increases with) the porosity. Blockage of pores and excess/loss ions at the pores in contact control this physical parameter.
However the relationship between resistivity and porosity is very complicated. Mathematical modelling and laboratory measurements both confirmed that membrane IP effect diminishes with increasing fluid filling pores salinity and does not exist at high frequencies when an alternating electrical current is fed (Figure 1). As a result the resistivity measured by direct and alternating current is different. The new algorithm is based on Fick's second law as the Authors showed that the well-known Marshall and Madden's equations Nos. 37 and 38 (1959) are only correct to a certain point (see Hallbauer *et al*., in press). Many tests on laboratory samples show the correctness of the approach. The model links the specific dependence of resistivity and chargeability of a sample on the injected current to its Pre Sze Distribution (PSD): it is able to predict the PSD from measurements that are current and time dependent. Predicted PSD was found to be in good agreement with mercury injection capillary pressure test results.
Therefore the most proper definition of the membrane IP effect is: "Membrane IP is the successive blockage of inter-pore connections due to the excess distribution of ions during current flow".

Example 1: ERT and IP data

These facts open the perspective for new hydrogeophysical applications in the field. To show the possible portability of the above results from the laboratory to field practice using electrical resistivity tomography (ERT) and IP methods, a cooperative research project between the above Institutions was written and applied to the respective Governments. In this frame, based on detailed geologic maps, several sites were selected in the Northern Apennines (Italy), where saturated sandstone rocks either outcropping or lied at very shallow depths. Water saturation was ensured by the presence of springs of fresh water, often exploited for drinking use. Besides the careful selection of the candidate sites, collection of field data was also carefully planned. A commercially available geo-resistivity meter was purposely used, to verify that the expected behaviour could be acquired using current technology. The SAS4000 by ABEM was selected, because it is a current generator, which allows fixing current for a whole dataset, thus allowing acquisition of each datasets at a specific current. Time of switch on-switch off was purposely kept at 1 s, so as to mimic the usual choice in IP field data acquisition.

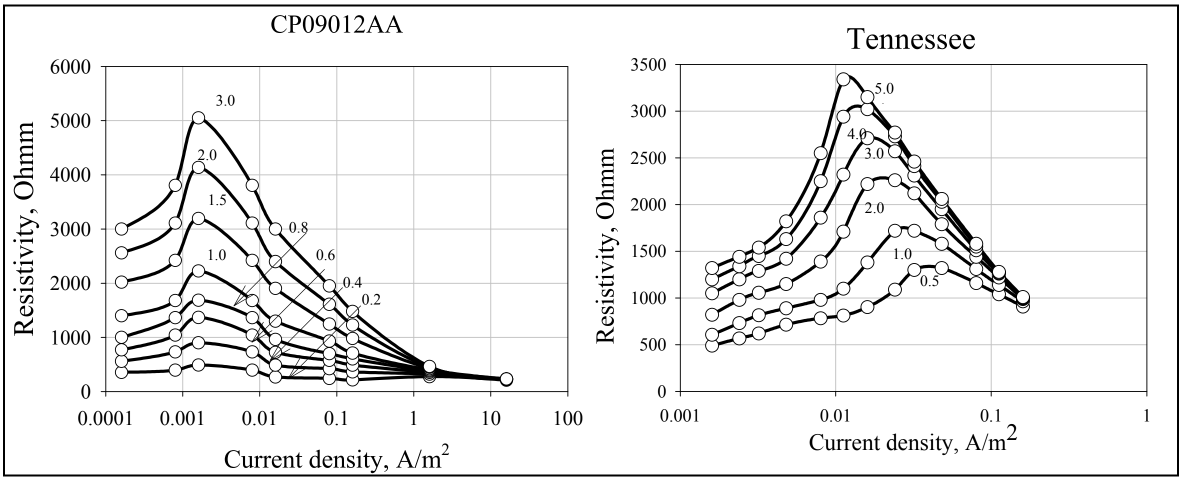

Figure 1 *Resistivity has direct relationship with current density if the latter is small and reverse relationship if current density is larger: circles: laboratory measurement data, curve: theoretical fitting data. Numbers on the curves indicate time of current flow (in seconds).*

In one of those sites we got data of both resistivity and chargeability fairly depending on the injected current. We arranged two orthogonal ERT profiles, acquiring two datasets per profile at two injected current strengths differing by one order of magnitude, keeping the cycle time constant at 1 s. The obtained results can be summarized as follows, which are in excellent agreement with the proposed model:

1. A fair increase in estimated resistivity with increasing current within those volumes that can reasonably be associated to the saturated sandstone bodies (Figure 2);
2. A strong decrease in chargeability with increasing current, which extends also over other volumes (besides sandstone) of the subsurface; this last finding should be investigated further (Figure 3).

While the authors guarantee that data are available to anybody interested, they are aware that field evidence should be enriched both by investigating other potentially suitable sites (there are many available in the Northern Apennines) and by investigating the effects of longer current on and off time cycles, although this practice could be more time consuming. We want to highlight that the presented data should not be intended as a warning against the well consolidated geoelectrical and IP methods, which would be a misunderstood consequence of the proof that non-linear phenomena can take place. Rather it is the exploration of new, and potentially powerful features of these methods in hydrogeophysics as, acquiring data (i.e. apparent resistivity and apparent chargeability) in a suitable way to highlight possible non-linearity, quantitative information about pore size distribution (PSD) can be achieved, which extends the characterisation of the hydrodynamic properties of an aquifer well beyond the estimation of its effective porosity. The relative difficulty we met to observe the reported phenomenon suggests that specific strategies of data acquisition have to be planned and, to some extent, specifically designed georesistivity-meters should be employed.

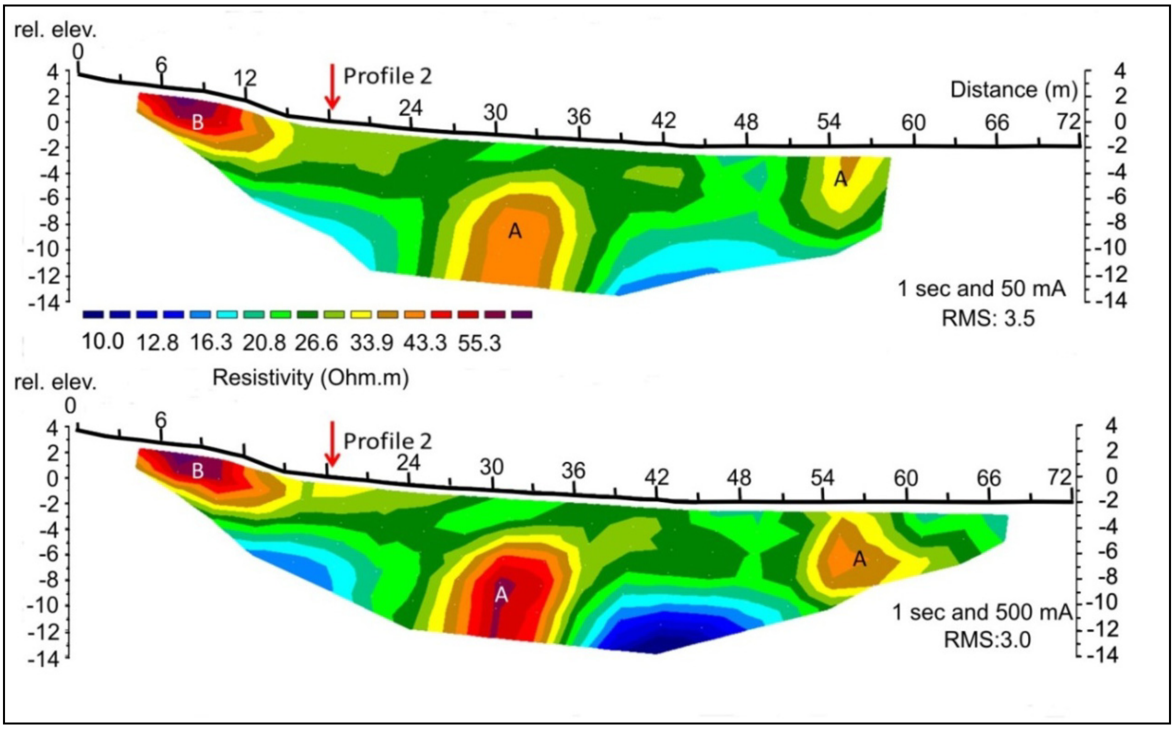

Figure 2 Resistivity model sections of Profile 1. Upper window: section obtained at 50 mA of supplied current; lower window: section obtained using a supplied current of 500 mA.

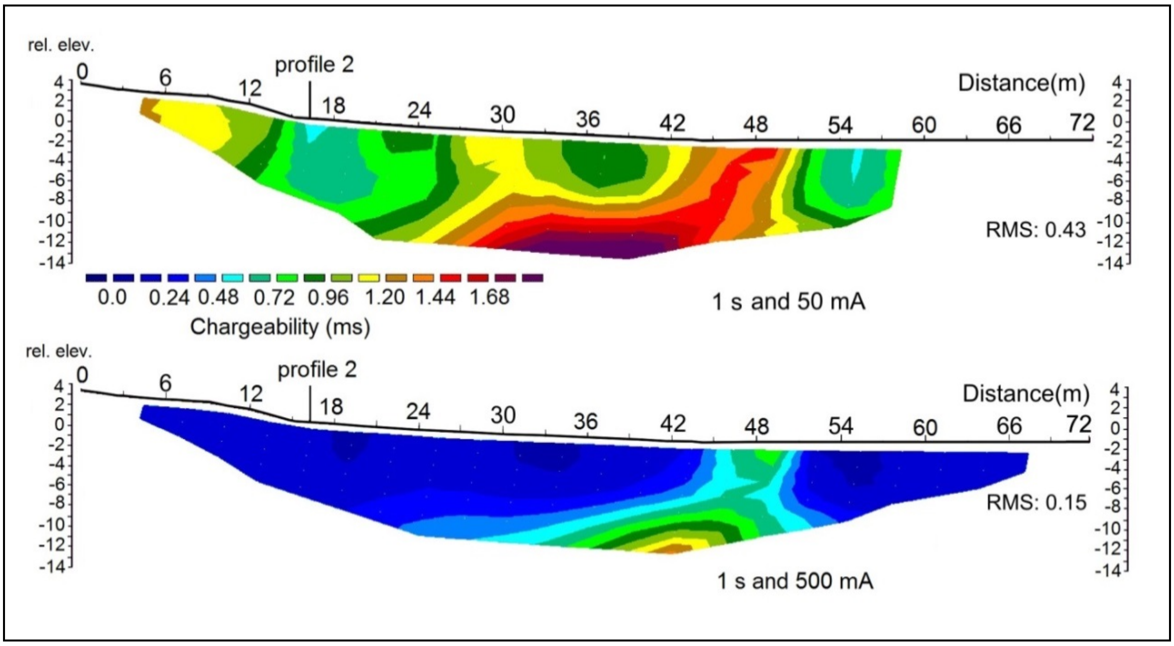

Figure 3 *Chargeability model sections of profile 1. Above: section obtained at 50 mA of supplied current; below: section obtained using a supplied current of 500 mA.*

Example 2: TEM data

The applied geophysics group at the University of Ferrara recorded in 2012 a new type of time domain EM (TEM) signals. The relaxation curves were affected by IP effect but shape of TEM signals depend on current pulse length. This is a new phenomenon related to a non-linearity of the IP effects.

In Figure 4 we show two of the 6 TEM soundings acquired by the Italian team in a site located in the Northern Apennines, above a thick clay formation intercalated by a layer of coarser sediments, with laterally variable thickness and texture. Obtained decay curves were acquired using the Zonge TEM equipment, at three different frequencies, i.e. 32, 8 and 4 Hz. Both soundings are fairly affected by IP, but while in TEM 4 the IP effect is invariant with frequency, in TEM 3 the decay curve at 32 Hz is strongly different from the others at the times where IP arises. Using a 1D modelling which includes the IP effect based on the well-known Cole-Cole formula, TEM 4 and TEM 3 at 32 Hz give a model compatible with known subsurface geology, while TEM 3 model at 4 and 8 Hz gives unrealistically low resistivities. Integrating the modelling with a relaxation time inherent to the above considerations about electro-osmosis and membrane polarization by pore constrictivity, allowed to get for these “anomalous” decay curves a consistent resistivity model.

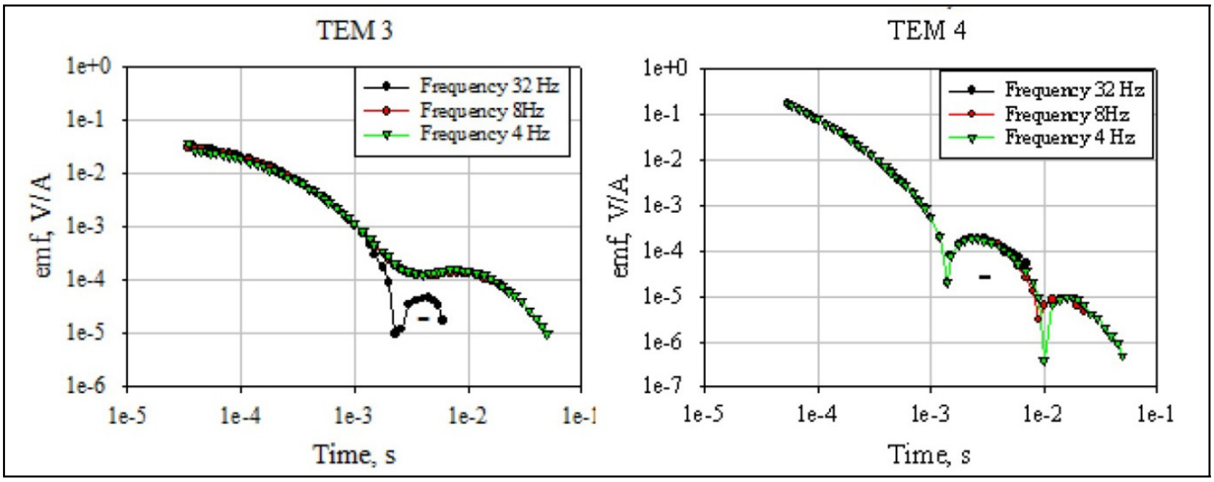

Figure 4 *Decay curves of TEM soundings 1-6 (continuous line: best-fitting 1D model).*

Conclusions

Linearity of the IP effect is dependent on the type of polarization. Amplitude of the membrane IP effect depends on pore space structure of rocks as well as on the density of electrical current. Low density of electrical current provides the linear IP effect which is usually experienced in IP method. Increasing current density inverts this law: the membrane effect becomes non-linear. However, modelling this effect resulted to be a good way to estimate PSD. To obtain more informative data the specific strategies of data acquisition have to be planned and, to some extent, specifically designed georesistivity-meters should be employed if not newly designed.

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