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The Evolution of Induced Polarization Method in Engineering Investigations

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Abstract

The Induced Polarisation (IP) method extends the resistivity method by making an additional measurement of the ability of the ground to store electrical charge. Originally developed for mineral exploration, it is now finding new applications in the fields of environmental and engineering geophysics. IP instruments measure both the conductive and capacitive properties of the subsurface using either time domain or frequency domain techniques. The low frequency capacitance of rocks and soils is primarily a function of the surface chemical properties of the sample. In non-metallic samples the IP response is an indicator of surface area and charge density of the material. IP measurements are therefore sensitive to clay content as well as mineralogy and pore fluid composition. IP methods have been used to estimate the hydraulic properties of rocks and soils as well as to map subsurface contamination. The method is also sensitive to subsurface metals. Recent advances from laboratory investigations, new instrumentation and software development have advance the study of the use of IP in Engineering Investigations. In this review, we summarize these recent advances and discuss how the IP method can be applied to engineering problems. Applied research in engineering applications of the IP method should prove lucrative and be encouraged.

Keywords: Induced Polarisation, Engineering, Soil, Capacitance, Mineralogy

Introduction

This paper presents an overview of the Induced Polarization geophysical method. Unlike other electrical methods, IP has seen relatively little use in engineering investigations. This is unfortunate, as the IP method provides unique structural information not easily obtainable from other geophysical methods. We summarize the history of the IP method, introduce the basic theory describing the IP response and outline the important aspects of data acquisition and interpretation. Known and potential engineering applications of the method are identified. Strengths and weaknesses of the method are also evaluated. We summarize by defining the state-of-the-art as applied to engineering investigations.

In 1927 C. Schlumberger made the first observations of the low-frequency polarizability of earth materials that resulted from the injection of an electric current. The measurement of this “induced” polarization and its interpretation in terms of variability in subsurface properties constitutes the Induced Polarization (IP) method. As with other geophysical methods, the Second World War accelerated development of the IP method as potential military applications were identified. Bleil (1953) first demonstrated the viability of the technique in subsurface exploration. He showed that polarization due to the presence of disseminated mineral deposits was measurable and interpretable in terms of subsurface properties. Bleil’s work stimulated great interest in the IP method as a tool for mineral exploration. This use of the technique flourished in the 1960's and 1970's, accompanied by technological advances, improved understanding of the sources of the polarization and new methods of data interpretation (Pelton et al., 1978; 1983). Today the use of the IP method in mineral exploration is well established, and it is beginning to find wider application in environmental and engineering problems (Ward et al., 1995). The earth polarization originally observed by Schlumberger, was actually not caused by metallic minerals. Throughout the 1950's-1970's researchers in the field of IP investigated the significance of this small polarization in the absence of significant metal concentrations. Laboratory and field investigations identified a relationship between clay content and the magnitude of the IP response (Marshall and Madden, 1959; Ogilvy and Kuzmina, 1972). On the basis of this response, electrochemical models to describe this clay-induced polarization were formulated and the term "membrane polarization" applied (Marshall and Madden, 1959). Environmental and engineering applications of the IP method were identified, including the determination of variability in clay content (Vacquier et al., 1957; Bodmer et al., 1968; Ogilvy and Kuzmina, 1972; Iliceto et al., 1982) and the discrimination of clayey units from saline aquifers (Roy and Elliot, 1980; Seara and Granda, 1987). The widespread use of the IP method in engineering investigations has been limited by an incomplete understanding of the relationship between measured IP parameters and subsurface lithological and fluid properties. Confusion results from the nature of the IP parameters determined using IP instrumentation.

Laboratory studies of low frequency electrical properties of earth materials have helped to identify the physical and electrochemical significance of the IP response (Gateau et al., 1980; Vinegar and Waxman, 1984; Olhoeft, 1979; 1980; 1985; Borner and Schon, 1991; Frye et al., 1998; Sturrock et al., 1998). Outdated equipment designed for mineral exploration, and slow development of IP interpretation software, also limited use of IP in near-surface investigation. These limitations have been overcome in the last decade with design of new data acquisition systems and IP modeling algorithms. Improved understanding of the IP response, combined with new data acquisition/processing tools, now permit effective use of this method in engineering studies.

Theory/Concepts

In simple terms, the IP response reflects the degree to which the subsurface is able to store electrical charge, analogous to a capacitor (Sumner, 1978). This polarization occurs at the interface between [1] a metal and a fluid (electrode polarization), and [2] a non-metal (e.g. silica or clay minerals) and a fluid (traditionally called membrane polarization). Polarization results from a redistribution of ions along such interfaces following application of an electric current (Fig. 1). Upon current termination, ions relax to the equilibrium condition. This diffusion-controlled relaxation is equivalent to a residual current flow (as observed during discharge of a capacitor) and is the source of the subsurface IP response. The IP method measures the magnitude of this polarization. In contrast, the resistivity method measures the magnitude of conduction provided by both electrolytic and surface conduction (enhanced in the presence of clay minerals). Electrode polarization generally produces a larger IP response than membrane polarization. Both types of polarization may provide useful subsurface information on engineering properties. A simple equivalent circuit model for electrical current flow in rocks is presented in Fig. 2. The basic model incorporates a purely conductive (predominantly electrolytic) flow pathway (σ_{bulk}) in parallel with a frequency dependent complex-conductivity element (σ^*_{surf}). This complex surface-conductivity incorporates surface conduction and the diffusion-controlled electrochemical polarization depicted in Fig.1.

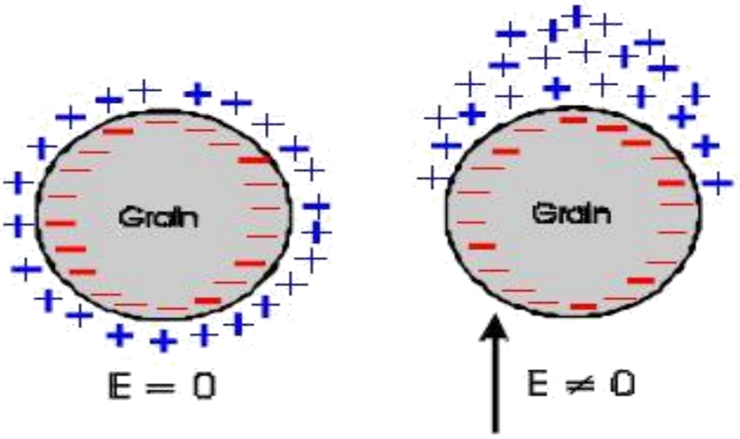

Figure 1: [a] Equilibrium ion distribution [b] polarization following application of an electric field. Residual current flow occurs as ions relax to equilibrium following removal of electric field

The complex surface conductivity response of rocks and soils is dependent upon the microgeometry, bulk fluid composition and surface chemistry. Efforts to understand the electrochemical control on the IP response are reported in Angoran and Madden (1977) and Keevil and Ward (1982). In the presence of metals, ó*surf is dependent upon metal concentration, metal distribution and metal type. In the absence of metals ó*surf is related to specific surface area, surface charge density and cation exchange capacity (CEC) (Vinegar and Waxman, 1984; Borner and Schon, 1991; Klien and Sill, 1982). In both cases, since ó*$_{surf}$ is also a function of fluid chemistry, IP interpretation in terms of structural properties can be complicated (Frye et al., 1999). However, the concurrent measurement of earth resistivity reduces ambiguity in interpretation, as it is primarily dependent upon fluid chemistry. The fundamental value of the IP method relates to its first-order dependence on important structural properties not easily resolved from other geophysical measurements.

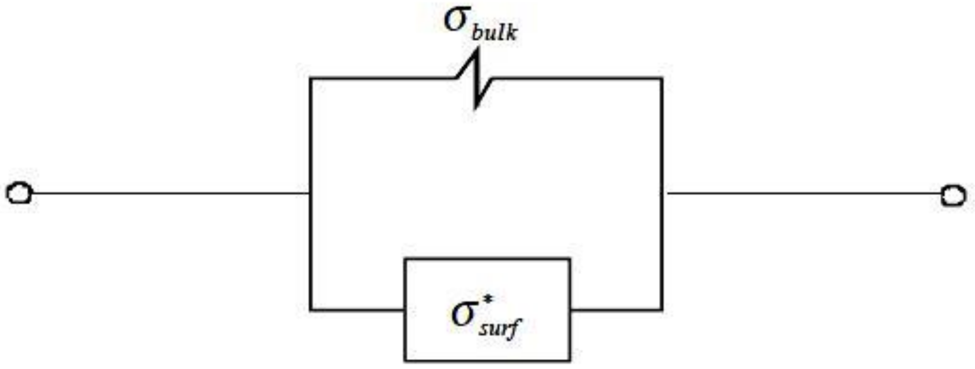

Figure 2: Equivalent circuit model for electrical current flow in rocks and sediments. sbulk is a Bulk (volume) conduction term and s*surf is a complex surface conduction term

IP instrumentation varies in the way the IP response is measured. Conventional measures of the polarization include the phase angle (f), chargeability (M) and percentage frequency effect (PFE). Phase angle and PFE are measured with instruments that operate in the frequency domain, whereas chargeability is measured with instruments that operate in the time domain. The most common measurement is the chargeability, defined as (e.g. Ward, 1990),

$$\mathrm{M} = \frac{\int_{t_s}^{t_f} V_s dt}{V_p} \frac{1}{\Delta t} \quad (1)$$

Where V_S is a residual voltage integrated over a time window defined between times t_S and t_f after termination of an applied current, V_p is the measured voltage at some time during application of the current and Δt equals the length of the time window of integration. Units of chargeability are typically quoted as millivolts per volt (MV/V). Figure 3 shows the time domain IP waveform recorded and measured properties used in the calculation of M. In the frequency domain, an equivalent measure of IP effect is the percentage frequency effect (PFE) defined as,

$$\mathrm{PFE} = \frac{\sigma(\omega_1) - \sigma(\omega_0)}{\sigma(\omega_0)} \times 100 \quad (2)$$

Where $\sigma(\omega_1)$ and $\sigma(\omega_0)$ are conductivity measured at frequencies ù_1 and ù_2 ($\text{ù}_1 > \text{ù}_0$). The presence of a frequency dependent conductivity is analogous to residual current flow following termination of an impressed current due to a polarizable earth. A final measure of the IP effect used in some instrumentation is the phase angle Ø,

$$\phi = \tan^{-1}\left(\frac{\sigma''}{\sigma'}\right) \cong \frac{\sigma''}{\sigma'}, \quad (3)$$

Where σ’’ is the imaginary component of complex conductivity and s’ is the real component of complex conductivity.

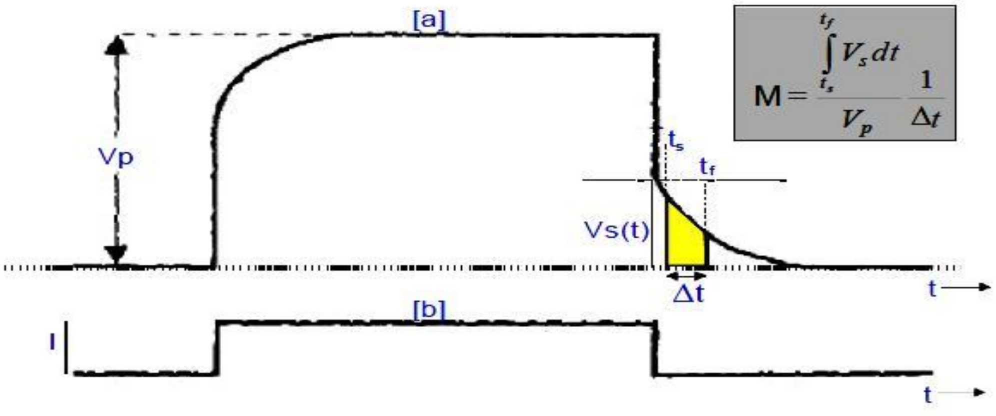

Figure 3: [a] Time domain IP signal received showing measured parameters and calculation of chargeability

M [b] Current waveform: Square-wave is generated at low frequency (~ 1Hz) and polarity is continually switched. The phase angle is related to volumetric (bulk) and surface conduction/polarization mechanisms. The bulk conductivity is purely a real term whereas the surface conductivity contains imaginary (σ_{surf} '') and real (σ_{surf}') components. The magnitude of surface polarization is given by σ_{surf}'' and the magnitude of surface conduction is given by σ_{surf}'.

From Fig. 2, ∅ defines the strength of the polarization process relative to ohmic conduction (primarily through the electrolytic pore fluid),

$$\phi = \frac{\sigma''_{surf}}{\sigma'_{bulk} + \sigma'_{surf}} \qquad (4)$$

In many instances bulk conductivity is greater than surface conductivity such that,

$$\phi \cong \frac{\sigma''_{surf}}{\sigma'_{bulk}} \qquad (5)$$

Pelton et al. (1978) defined the chargeability M in terms of two parallel conduction paths, which in terms of our model are bulk conductivity (σ'$_{bulk}$) and surface conductivity (σ'$_{surf}$). In the case that the bulk conductivity is much greater than the surface conductivity, the chargeability is proportional to the ratio of the surface conductivity to the bulk conductivity effects,

$$M \propto \frac{\sigma'_{surf}}{\sigma'_{bulk} + \sigma'_{surf}} \cong \frac{\sigma'_{surf}}{\sigma'_{bulk}} \qquad (6)$$

A direct proportionality between ∅ and M has been experimentally and theoretically established (see for example, Seigel, 1959; Marshall and Madden, 1959; Madden and Cantwell, 1967; Wait, 1984; Vinegar and Waxman, 1984). Equations 5 and 6 show that both phase and chargeability are a function of bulk conduction and surface polarization. These parameters measure the magnitude of surface polarization relative to the magnitude of bulk conduction. Consequently M and ∅ are dependent on changes in fluid conductivity. This is significant in data processing (as discussed in Section 6) and interpretation (as discussed in Section 7).

Survey Design/Data Acquisition

IP data acquisition is very similar to resistivity data acquisition. All IP instruments also record electrical resistivity concurrently. However, much smaller voltages are measured in the IP method, requiring additional consideration during data acquisition. Figure 4 illustrates generic

components of an IP survey. Depending on the instrumentation (discussed in Section 5) the transmitter and receiver may either be separate units or consolidated into one module. A current is injected into the earth via a current dipole of metal electrodes. Voltage is simultaneously recorded on n channels. The number of channels will depend on the complexity of the instrumentation. Ideally, voltage electrodes are non-polarizing porous pots. These consist of a metal in equilibrium with a saturated salt solution of the same metal. This metal-fluid junction has low impedance and minimizes electrode polarization at the electrode, which constitutes noise in an IP survey. Pre-amplifiers with high input impedance and low output impedance may be used to condition the voltage signal by eliminating capacative coupling between the subsurface and the wires. These pre-amplifiers are especially important when surveying across resistive ground.

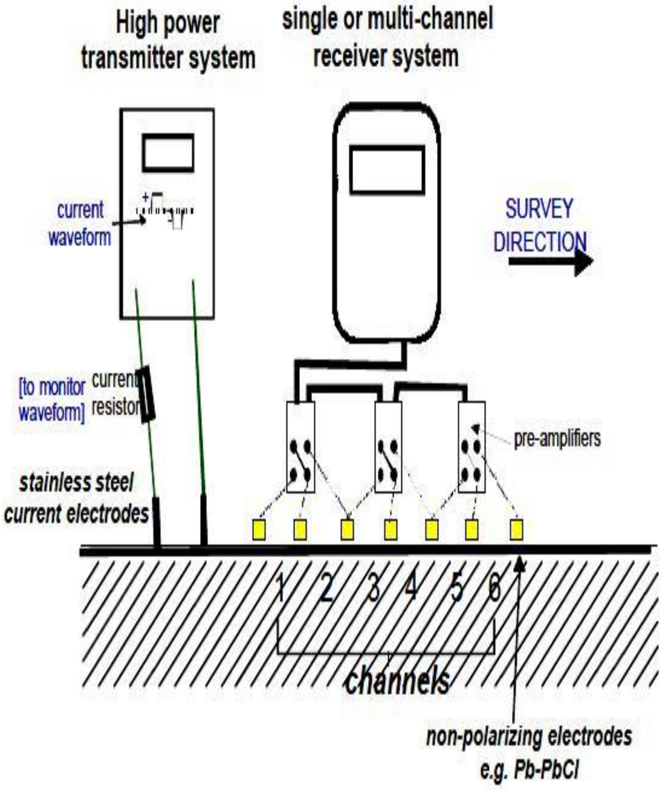

Figure 4: Main components of a field IP survey. Transmitter and receiver may be separate (as shown) or integrated into one unit

A 2D dataset is constructed by lateral movement of a linear electrode array across the ground surface. The survey is simply extended to 3D by using a grid of electrodes. Numerous conventional electrode arrays have been defined for resistivity surveying. The arrays differ in sensitivity to vertical structure, sensitivity to lateral structure and ease of implementation in the field. The dipole-dipole array is typically favored in IP surveys (Sumner, 1978). Data acquisition is simplified with this array as lateral/vertical information is obtained on n channels (using porous pots) without needing to move the current dipole pair (using metal stakes). The dipole-dipole array also minimizes electromagnetic coupling that can occur between current dipole wires and voltage dipole wires. These wires are coupled via the subsurface and can result in a spurious chargeability unrelated to any change in subsurface material.

Coupling increases with length of wires and ground conductivity, and will be a problem for large separations between voltage and current dipoles in conductive ground. As with resistivity surveying, depth of investigation increases with distance between current and voltage dipoles. Hence voltage dipoles further away from the current dipole sense chargeability structure at greater depth.

New IP systems are designed for automated data acquisition on a grid of electrodes. These systems automatically switch electrodes used for current injection and voltage recording to rapidly build up a large number of measurements. Non-polarizing electrodes are not suitable for current injection and hence cannot be used in this manner. To overcome this, equipment suppliers may promote use of high quality metal (such as a high-grade stainless steel), both for current injection and voltage measurement. However, polarization at the metal-earth interface potentially complicates IP interpretation. As an alternative, manual, or only semi-automated, measurements can be made, in which current is injected using metal stakes and voltage is recorded using non-polarizing electrodes. The continuous exchange of metal stakes with non-polarizing electrodes will significantly impact survey time (Ward et al., 1995).

Equipment Used

IP instrumentation was originally developed for use in mineral exploration, which requires a high power transmitter to ensure that measurable voltage decay-curves are recorded at large electrode separations required to obtain electrical information from depth. Power is typically provided by a 1-2 Kw generator, and currents up to 10 Amperes may be injected into conductive ground. Such systems are manufactured by Phoenix Geophysics (Canada), Zonge Geophysics (USA) and IRIS Instruments (France). Following renewed interest in the IP method for engineering and environmental studies, equipment specifically designed for measuring the electrical properties of the near surface is now available. Such instrumentation is similar to modern multi-electrode resistivity meters marketed for automated 2D or 3D data acquisition. Most calculate the time-domain chargeability M (Equation 1) as the measure of subsurface polarization. The power output is typically less than 250 W, to keep the systems compact, light and easily portable. Examples of such systems are marketed by IRIS Instruments (France), ABEM Geophysics (Sweden) and Geometrics (USA).

Power output is the primary consideration when evaluating IP equipment (Ward et al., 1995). The magnitude of the voltage decay recorded after current shut-off is directly proportional to the magnitude of the primary voltage during current injection and hence to power output. With a low power output the small decay voltage may fall below the background noise level. As signal strength decreases with increasing electrode spacing, the depth of IP exploration is dependent upon power output. This is also a factor limiting resistivity surveys at depth. It is a greater limitation in IP surveys as the measured decay voltages are typically a factor of 100 less than the primary voltage recorded in a resistivity measurement. Some manufacturers may claim that a lower power can be compensated for by high voltage resolution on the receiver unit. However, only additional power at the transmitter can improve the signal-to-noise ratio. A high-resolution receiver may simply provide an accurate measure of background noise.

Discussion

It is important to emphasize that all IP instruments also record the resistivity magnitude $|\rho|$ (the reciprocal being the conductivity magnitude |s|) in addition to the IP response (chargeability, PFE or phase). The resistivity is an important parameter in the interpretation of IP data. Processing of IP data is complicated by the lack of a consistent definition of M between instruments and surveys. As defined in Equation 5, M varies depending on the time (t) at which Vs is measured. McLaughlin (1967) emphasized the need for a standardized measure of M between instruments and surveys. However, equipment manufacturers and users still adopt different calculations of M from measured parameters (Vs and t). In any given survey the same definition of M must be adopted for all measurements. Then spatial or temporal changes in M will solely reflect changes in the subsurface. Comparison of IP measurements between different surveys will only be meaningful if the definition of M is consistent between surveys. A useful step in data processing is to normalize the chargeability by the resistivity measured concurrently (Frye et al., 1998; Slater et al., 2000). This is helpful, as M is the magnitude of surface conduction s'surf relative to bulk conduction σ'_{bulk} i.e. M is sensitive to changes in s' bulk as well as σ'_{surf} (Equation 6). The normalized chargeabilty Mn is defined as,

$$M_n = \frac{M}{|\rho|} = M|\sigma| \quad (7)$$

From Equation 6, given that $|\sigma|$ @ σ'bulk,

$$M_n \cong \sigma'_{surf} \quad (8)$$

i.e. M_n is a direct measure of surface conduction, which is proportional to polarization. As changes in resistivity are directly determined from the resistivity measurement, the dependence of M on resistivity may complicate IP interpretation. Plotting M_n in addition to M can help separate IP responses due to changes in bulk conduction from responses due to changes in lithology. Incorrect interpretation of subsurface materials may have resulted from poor appreciation of the dependence of chargeability on resistivity.

The final step in data processing is to iteratively model and solve (invert) for an estimate of the multidimensional chargeability distribution below the survey grid (Fig. 5). Modern forward and inverse modeling of IP data is performed similar to 2D or 3D inversion of resistivity data (Oldenburg and Li, 1994; Ramirez et al., 1999). In a multi-electrode survey a large number of measurements are acquired on a 2D or 3D grid. Electrodes may be placed in boreholes, where available. The objective of the inversion is to find an estimate of the 2D (or 3D) chargeability structure that provides theoretical data closely matching measured data. An estimate of resistivity structure is obtained concurrently. The inverse modeling usually incorporates a smoothness-constraint such that the model solution is a smooth rendition of the true chargeability structure. The forward calculation of theoretical data is usually performed using a finite difference or finite element approach. It is important to appreciate that the solution is non-unique and that other distributions of chargeability may also fit the measured data well. The fundamental way to improve confidence in interpretation is to obtain control data, for example from geologic logs of boreholes. A good modeling/inversion algorithm will allow for incorporation of such ground-truth data as a constraint on the inversion result.

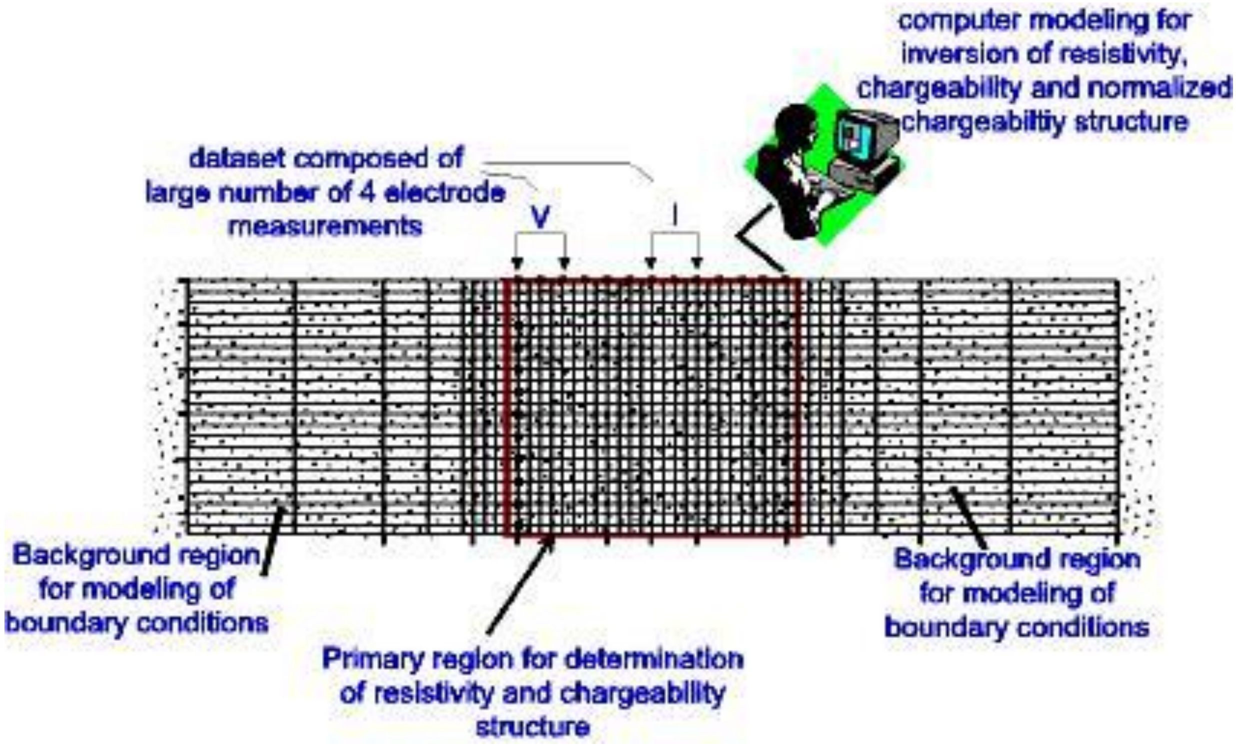

Figure 5: Inversion of IP data for determination of subsurface resistivity and chargeability distribution. A finite difference or finite element grid is used in the modeling. A large number of resistivity and chargeability measurements are used to recover an estimate of the 2D [in this case] electrical structure. Note: electrodes can be placed in boreholes, if available.

In the absence of metals, IP interpretation involves definition of variability in electrochemical processes related to (1) the surface area of materials, and (2) the surface charge density or cation exchange capacity. One potential use of IP in engineering investigations is lithological discrimination. Clays disseminated in unconsolidated sands and silts increase the surface area and surface charge density relative to clean sands/silts. The result is an enhanced IP effect in such shaly sediments. However, highly compacted clays often exhibit a low IP effect (Vanhala, 1997). Small but measurable IP effects are typically recorded for clean sands and gravels.

Resistivity is also used to determine the geometry of clay units. However, this application of the resistivity method is complicated by the fact that measured $|\rho|$ (or its reciprocal $|\sigma|$) is dependent upon both (1) electrolyte conductivity and (2) surface conductivity due to the presence of clays.

Considering our simple electrical model, $|\sigma| \cong \sigma'$ (as $\sigma'' << \sigma'$) and,

$$\sigma' = \sigma'_{bulk} + \sigma'_{surf} \cong |\sigma| \qquad (9)$$

Where σ_{bulk} is the volumetric (primarily electrolytic) conduction term and σ'_{surf} is the surface conduction term which will be enhanced in the presence of clays. Hence changes in resistivity may reflect changes in electrolytic conduction (primarily due to a change in salinity) or changes in clay content/mineralogy. This complicates resistivity interpretation in terms of lithology. In contrast, normalized chargeability is only a measure of surface conduction, as given in Equation 8. The IP method is hence a valuable method for lithological discrimination. As an example, Figure 6 shows how sand-clay materials of varying fluid chemistry (in which the clay is disseminated throughout the sand) can be characterized on the basis of IP and resistivity measurements. Examples of the use of IP for lithological characterization are given in a companion paper (Slater, Binley and Kemna, this volume).

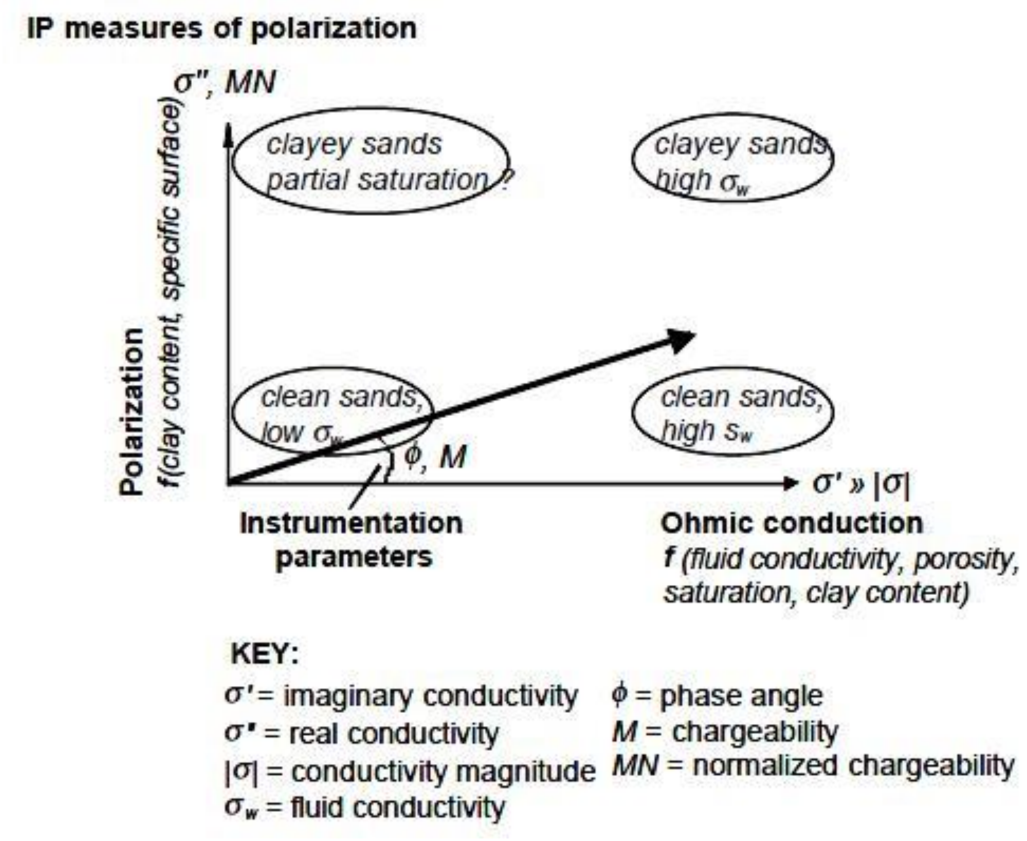

Figure 6: Plot of normalized chargeability (MN) against conductivity (|σ|) showing discrimination of clayey samples from clean sands (clay disseminated in sand)

A measurable IP response often exists even in the absence of clay minerals, and results from charge redistribution on a mineral/fluid interface. Borner and Schon (1991) determined a strong linear relationship between σ''surf and the Specific Surface to Porosity Ratio (Spor). Frye et al. (1999) showed the direct proportionality between σ''surf and Mn. Consequently, Mn is also linearly proportional to Spor. Using this information, it may be possible to determine saturated hydraulic conductivity [Ksat] from IP measurements (Weller and Borner, 1995; Borner et al., 1996; Sturrock et al., 1998; 1999). The complimentary information obtained from resistivity and IP measurements is used in an empirical formulation based on the Kozeny-Carmen equation (Borner et al., 1996),

$$K_{sat} = \frac{0.00001}{FS^{c}_{por[el]}} \quad (10)$$

Where $S^{c}_{por[el]}$ is the electrically determined S_{por}, c is a constant and F is the formation factor,

$$F = \frac{\sigma_w}{\sigma_{bulk}} \quad (11)$$

obtained from the resistivity measurement and knowledge of the fluid conductivity ($\sigma\omega$). Borner et al. (1996) used this approach to obtain 1D sections of variation in Ksat in unconsolidated sediments. The value of this interpretation of IP data is promising but requires further investigation. Another potential use of the IP method is hydrocarbon detection. The surface polarization is significantly modified by clay polymerization at a clay-organic interface (Olhoeft, 1985). The change in polarization magnitude caused by the presence of a hydrocarbon appears to depend upon both clay mineralogy and hydrocarbon type (Olhoeft, 1985; Vanhala et al., 1992; Borner et al., 1993). Field studies have also shown that the electrical response of hydrocarbon contaminant varies with time (Sauck et al, 1998). Given these complexities, further laboratory work is required to fully understand the value of the IP method for hydrocarbon detection. However, controlled field studies have shown that IP imaging of a hydrocarbon contaminant (in this case perchloroethelyne) is feasible (Daily et al., 1998). Future use of the IP method for detection/monitoring of hydrocarbon contaminants at gasoline storage facilities is likely.

We consider the primary strength of the IP method the unique sensitivity to surface conduction/polarization and hence lithological variability. Given the availability of new multi-electrode equipment, IP should be an excellent tool for 2D or 3D mapping of the geometry of alternating clay/sand units. Resistivity data are obtained concurrently and provide supplementary information on variability in fluid chemistry, simplifying IP interpretation. With new instrumentation the survey procedure can be automated for rapid data acquisition. Exact survey times will depend on the instrument. As an approximate estimate, a 2D section along a 150 m traverse would take less than 1 hour using a 5 m electrode spacing (including layout and uptake of instrumentation).

The IP method suffers from the same weaknesses as the resistivity method. It is a direct contact method and requires good electric contact with the ground. A resistive surface (e.g. bedrock or pavement) can make measurements difficult. Long cables are required to transmit signals between electrodes and the transmitter/receiver unit.

In this paper we primarily deal with IP interpretation for polarization processes not related to subsurface metal concentration (electrode polarization). However, it is important to appreciate the significance of electrode polarization in the presence of buried metals. This may provide valuable subsurface information on the location/state of buried foundations. For example, in-situ evaluation of the integrity (corrosion) of metal foundations might be possible using IP. However, electrode polarization may also seriously hinder IP surveys aimed at investigating subsurface lithology. Variability in the IP response to changing amounts of clay could easily be lost in larger magnitude responses caused by a subsurface arrangement of buried metal objects. The sensitivity to subsurface metals should hence be considered both a potential strength and potential weakness of the IP method, depending on the particular application

.

Conclusion

The IP method provides unique lithological information that is not easily determined from other available geophysical methods. However, appreciation of the significance of conventional IP parameters recorded by the instrumentation is vital to ensure a meaningful interpretation of subsurface structure.These parameters are heavily dependent on fluid chemistry and normalization is required to obtain a true measure of the magnitude of polarization.

In the absence of metals, the polarization is primarily dependent upon surface area and mineralogy.

Consequently, the IP method is an excellent indicator of clay content. However, even materials with insignificant clay mineralogy exhibit polarization. Recent work suggests that the dependence of polarization on surface area of such materials may hold the key to electrical determination of hydraulic conductivity. Polarization also occurs in the presence of metals in contact with a fluid. Although this may limit effectiveness of IP in determining lithology, it also indicates that other engineering applications of the IP method may exist (e.g. evaluating integrity of metal foundations). Given the unique information potentially obtainable from IP, we anticipate the increased use of the IP method as a tool in engineering studies.

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