TDEM: A USEFUL TOOL FOR IDENTIFYING AND MONITORING THE FRESH-SALTWATER INTERFACE

Giovanni BARROCU & Gaetano RANIERI
Department of Territorial Engineering
Faculty of Engineering - University of Cagliari, Italy
E-mail: barrocu@unica.it - granieri@unica.it

Abstract

One of the main problems in studying saltwater intrusion processes is the temporal and spatial monitoring of the fresh-saltwater interface. In the past geophysical methods have been used to study its evolutionary trend. Time Domain Electromagnetic (TDEM) methods have proven to be most efficacious, producing better results than the traditional galvanic techniques. In fact, the major advantage of this method is that deep soundings can be performed in a relatively short time. TDEM sounding appears to be particularly useful for discriminating between layers having low resistivity and consequently for monitoring salt water intrusion and diffusion, as well as artificial recharge procedures. However, interpretative limitations related to the principle of equivalence arise when intermediate resistive layers occur, together with problems of induced polarisation (IP) and superparamagnetism (SPM) associated with the presence of highly resistive layers at the base of the stratigraphic sequence. This method has been experimentally tested in well characterised test sites where geophysical investigations (reflection seismics, SEV, IP, gravimetry), drillings, as well as chemical and isotopic analyses of the water had already been conducted. The results confirm that the method is practical, economic and perfectly reliable, especially at large depths (down to 100 m) and in the fast acquisition version, using windows from 4 μs to some ms.

Introduction

Developed in Russia in the early eighties for studying deep structures, since 1985 the TDEM has found wide application in geological, engineering and environmental spheres and today represents a potentially promising method for investigating electrical parameters of the subsoil.

Much has been published on the TDEM, including applications in hydrogeological research (Sorensen K.I., 1996; Fittermann D.V. and Stewart M.T., 1986; Christensen N.B. and Sorensen K.I., 1994; Meju M.A., 1995), and for studying the specific problem of salt water intrusion (Yuhr L. and Benson R.C., 1995; Hoekstra P. and al. 1996; Richards R.T. and al. 1995; Goldmann M., 1996).

Other workers (Nabighian M.N. and Mcnae J.C., 1991; Auken E., 1995; Sorensen K.I., 1998; Christensen N.B., 1997; Meju M.A., 1994,1994) have studied various aspects of the application, processing and interpretation of TDEM soundings and its use in combination with other geophysical techniques.

A variety of geophysical methods has been adopted in saltwater intrusion investigations. Conventional DC resistivity techniques have long been used to characterise shallow aquifers, gravity and magnetic methods have been applied to reconstruct deep aquifers and the bedrock. Barbieri G. et al., 1986 applied the I.P. method to describe the temporal evolution of saltwater intrusion. Other applications have involved electromagnetic and seismic methods.

Here we examine the main advantages and disadvantages of TDEM with respect to other techniques.

A typical TDEM array consists of a transmitter loop and a receiver coil. A very strong current (from 1 to 20 A), produced by a battery or motor generator, is injected into a square (usually single turn) loop of grounded wire and connected directly to the transmitter. The transmitter current, though still periodic, is a modified symmetrical square wave, as shown in Fig. 1.

After every second quarter-period the transmitter current is abruptly reduced to zero for one quarter period, whereupon it flows in the opposite direction. In a receiver loop (coincident or inside the transmitter loop) when the current is switched off a voltage pulse is recorded. In the coincident loop configuration, the length of the loop side is approximately equal to the desired depth of penetration. Generally the loop side varies from a few to hundreds of meters. A single or multi turn receiver coil, placed in the middle of the transmitter loop or coincident with the transmitter loop, is connected to the receiver by means of a short cable.

As shown by Mc Neill J.D., 1996, the principles of TDEM resistivity sounding are relatively easily understood.

The process of abruptly reducing the transmitter current to zero induces, according to Faraday's law, a short duration voltage pulse in the ground, which causes a loop of current to flow in the immediate vicinity of the transmitter wire (see Fig.2).

In fact, immediately after the transmitter current is turned off, the current loop passes into the ground immediately below the transmitter and, on account of the finite resistivity of the ground, the current amplitude immediately starts to decay. Similarly the decaying current induces a voltage pulse which causes more current to flow at a greater distance from the transmitter loop, and also at greater depth (Mc Neill J.D, 1996).

The deeper current flow also decays due to finite resistivity of the ground, inducing even deeper current flow and so forth.

To determine the voltage produced by the decaying magnetic field at the receiver coil at successively later times, measurements are made of the current flow and thus also of the electrical resistivity of the earth at increasingly greater depths, and it is this process that forms the basis of resistivity

Basic concepts of TDEM soundings

sounding in the time domain. The output voltage of the receiver loop is shown in fig.3.

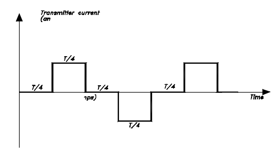


Fig.1- Transmitter current waveform

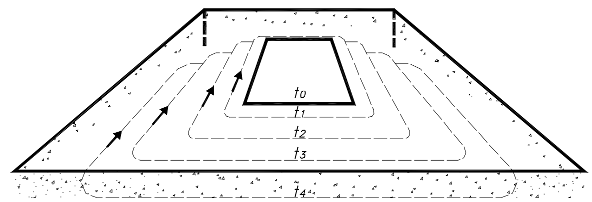


Fig. 2 - Current flowing in the ground.

The decay characteristic of the voltage in the receiver is determined for a number of time gates, each measuring and recording the amplitude of decaying voltage. The time gating differs with time. In fact, to minimise measurement distortions, the **early time gates**, which are located where the transient changes rapidly with time, are very narrow, whereas the **later gates**, where the amplitude of the transient decay diminishes, are much broader to enhance the signal-to-noise ratio.

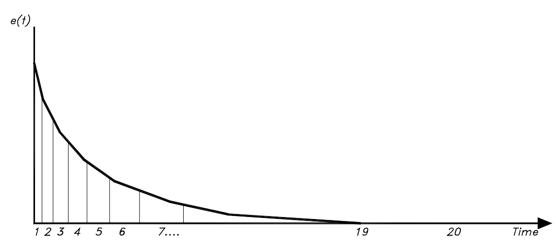


Fig.3 – Gate locations

Only the (two) transients that occur when the transmitter current has just been shut off are measured.

Lastly, particularly for sounding at shallower depths, where it is not necessary to measure the transient characteristics out to very late time, the period is typically of the order of one millisecond or less, which means that in a total measurement time of a few seconds, measurements can be made and stacked on several thousand transient responses to improve signal-to-noise ratio. To increase depth the variations must be recorded at a later time (by some seconds).

Apparent resistivity in TDEM soundings

The voltage response can be divided into an **early stage** (where the response is constant with time), an **intermediate stage** (response shape continually varying with time) and a **late stage** (response is a straight line on log-log plot).

The response varies quite simply with time and conductivity as :

$$V(t) = \frac{k_1 M \sigma^{3/2}}{t^{5/2}} \qquad (1)$$

where k_1 = a constant

M = product of T current (amps) x area (m^2)

σ = terrain conductivity (Siemens/m)

t = time (seconds)

and V(t) = output voltage from a single turn receiver coil of 1 m^2 area.

Note that unlike conventional resistivity measurements, where the measured voltage varies linearly with terrain resistivity, for TDEM the measured voltage, V(t) varies as $\sigma^{3/2}$, so the TDEM is intrinsically more sensitive to small variations in conductivity than conventional resistivity soundings.

It can also be shown for layered earth, that the shape of the induced curves is very similar. To make the curves more representative of the resistive structure, we can convert the voltage curves to apparent resistivity.

As observed earlier as time increases, so too does the depth to the current loops and we can carry out resistivity sounding with depth.

Since ρ=1/σ, from equation (1)

$$\rho_a(t) = \frac{k_2 M^{2/3}}{e(t)^{2/3} t^{5/3}} \qquad (2)$$

Summing up, except for the early time descending branch and the intermediate anomalous region described above, the sounding behaviour of TDEM is analogous to conventional DC resistivity if we let the passage of time achieve the increasing depth of exploration rather than increasing inter-electrode spacing . However, at very late time there is no signal and no asymptote to the bedrock resistivity in the curve can be observed.

Practical indications from theory

The voltage induced in the receiver coil is the product of the receiver coil Moment $\mathbf{M_r}$ (area times the number of turns) multiplied by the time derivative of the vertical magnetic flux density:

$$\frac{V(t)}{M_r} = \frac{\mu M_t}{5t}\left(\frac{\mu}{4\pi t \rho_a}\right)^{3/2} \qquad (3)$$

Where μ is the magnetic permeability and M_t is the transmitter loop moment =L^2 I, with L length of the side .

The equation describes some major points concerning transient soundings. Because V(t)/Mr is inversely proportional to time and the current diffuses downwards with time, it is more difficult to sound at greater depths unless the transmitter moment is increased. To increase the transmitter moment, we can increase the transmitter current or the loop area or the wire turns or both.

The depth of investigation is dependent upon the geolectrical section: with two-layered sections with the same first-layer resistivity , we can sound more deeply with the same current in the section with the more conductive basement.

In investigations at shallow depths, it is very important to measure the voltage in the early and intermediate stages.

Early stage measuring is rather delicate and complex, but in latter years several devices have been developed for measuring during a short time after the transmitter current is cut-off. Soundings obtained with this instrument are called TEM-FAST and are a very useful tool for hydrologists for studying the shallower subsoil .

By contrast to DC methods, in TDEM sounding the form of apparent resistivity curves depends on the size of receiving-transmitting antenna. At early times ρ(t) appears to be overestimated the smaller the loop size is.

Practical recommendations

Based on the experience gained from using TDEM sounding in many different applications, some practical recommendations are summarised below:

1. The maximum depth of investigation is determined by the maximal time **t**, in which it is possible to reliably register a signal **V(t)/I** and not exceed the loop side by 3 times;
2. the TDEM technique performs effectively in sections with high conductivity: the layers, for example, with ρ = 1 and ρ = 1.5 Ohm m are reliably stratified;
3. it is practically impossible to distinguish layers with very high resistivity;
4. super-small antennas (less than 10-15 meters) for stratifying layers at shallow depths can only be used for rocks with low resistivity;
5. at high levels of resistivity it is necessary to use large antennas;
6. the most favourable range of specific resistivity for stratification of rock is 10 Ohm m < ρ < 300 Ohm m;
7. mean resolution is about 1/10 of the loop side.

For optimum sizing of the antenna it should be remembered that large antennas increase limiting depth of the investigation, but they do not allow to stratify subsurface horizons. Estimations of depths h, for which reliable interpretation of the results is possible, at use of coincide antennas with the side TR=REC=L usually fall within the range:

$h_{min} > L/10$ and $h_{max} < 3L$.

Recently, vertical and lateral resolution problems of TDEM soundings have been studied on the Poetto beach in Cagliari (Deidda G.P. and Ranieri G., 2000). Figure 4 shows a 66 m long apparent resistivity pseudo-section, reconstructed from 23 soundings performed using a 6.25m loop side with 3 m spacing. The profile was carried out parallel to the coast line, 50 m far . The layered section, with the very low resistivity contrast indicated, demonstrates the possibility of discriminating low resistivity from very low resistivity. The layered increased resistivities towards the surface show different salt content (salt water zone, diffusion zone, brackish water zone, fresh water zone)

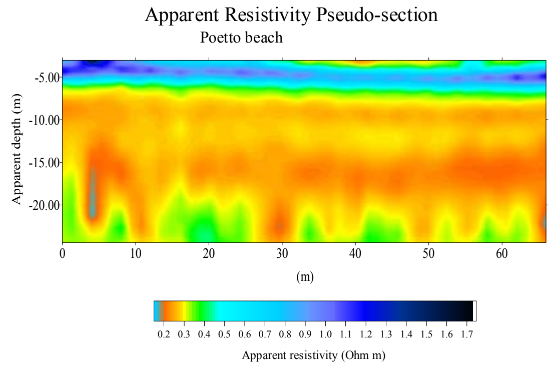


Fig.4 – Apparent resistivity pseudosection showing different conductive layers

Natural phenomena affecting TEM measurements

In practice, two physical phenomena exist that can essentially effect the efficiency of geological interpretation of TDEM soundings. Both these phenomena are associated with frequency dispersion of electromagnetic properties of rocks:

- *Superparamagnetic effect (**SPM** effect)*
- *Induced polarisation effect(**IP** effect)*

However, depending on the desired outcome, both effects can be considered either "harmful" (noise), or "useful", as they containing further information on the structure being investigated.

Studies of SPM effects using TEM-FAST in various parts of the world have shown the following:

- The most intensive SPM effects exist in areas of effusive and volcanic sedimentary rocks. Surface clay formations covering parent rocks are the most superparamagnetic.
- SPM effects are produced in conditions of long term permafrost and are usually located on the edges of zones of thawing frozen rocks.

- Significant SPM effects are observed on glaciers or very resistive rocks.

IP effects are produced in

- Thin well-conducting horizon of surface clay deposits with ρ<20-40 Ohm m, bedding on fairly resistive layer with ρ>300-500 Ohm m. The late stage will be deformed.
- Glaciers and permafrost rocks.
- Surface deposits severely polluted with industrial waste, (including petroleum pollution)
- Crustal erosion in crystal rocks and fault zones

Noise Sources

Other sources of noise for TDEM soundings include :

- circuit noise (depending on the goodness of the device).
- radiated and induced noise by radio and radar transmitters and also by lightning;
- presence of magnetic field produced by 50/60 Hz power lines.
- presence of nearby metallic structures.

Data reduction and interpretation

Apparent resistivity curves have been numerically calculated for a variety of layered soils , particularly in Russia where the technique was developed. The field data are compared with a selection of curves, from which the actual geo-electric section is determined. More recently the advent of fast computer inversion programs allows the field transient data to be automatically inverted to a layered earth geometry in a matter of minutes. Like all electrical sounding techniques, TDEM interpretation also suffers to a greater or lesser extent from equivalence. In many cases the automatic inversion program giving the real thickness and resistivities of the different layers is not always usefully applied.

When the layers have very similar resistivity it is more convenient to transform the voltage data into apparent resistivity versus depth. Godio et al. 1999 show that in many cases it is more reliable to transform only the V(t)/I versus time data into ρa versus h data. Figures 5,6 and 7 show the apparent resistivity pseudo-sections obtained in the area of Capoterra (south-west Sardinia), for a profile perpendicular to the coast line and two profiles parallel and perpendicular to salt works. The apparent resistivity sections describe saltwater intrusion more accurately than the true resistivity sections, which are very irregular (and unnatural) on account of the equivalence effect in the interpretation.

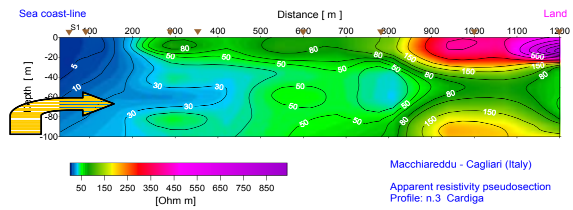


fig.5- Apparent resistivity pseudosection showing the salt water intrusion far from the coastal line.

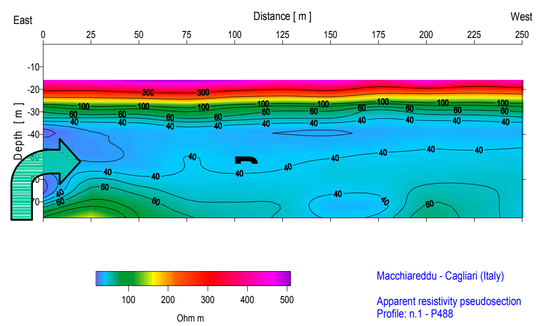


Fig. 6- Apparent resistivity pseudosection in a profile perpendicular to salt-works showing salt water intrusion and the "spray" effect

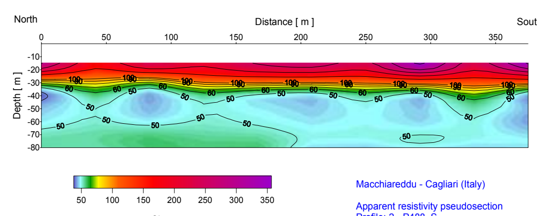


Fig.7- Apparent resistivity pseudosection in a profile parallel to salt-works.

Advantages of TDEM

TDEM geo-electric sounding offers significant advantages over conventional DC resistivity sounding, namely:

- improved operating speed (it is possible to perform about 30 soundings per day, in a very confined space, while in conventional DC soundings the AB line can be over 2 km long when the surface layers are highly conductive for sounding down to 100 m)

- improved lateral resolution;
- improved resolution of conductive electrical equivalence;
- simple to inject current into a resistive surface layer
- possibility of using the instrument in urban areas;
- great synergy with other geophysical methods

The latter point has been clearly demonstrated by Deidda G.P. et al. (2000). The TDEM can be conveniently integrated with the seismic reflection method to provide a more complete interpretation of the geological section. In fact the seismic data, though they provide a very good description in terms of geometry and elastic characteristic of a layered subsoil, are unable to identify salt water and fresh water content. The two sections obtained by superposing TEM FAST results and TEM results on the seismic reflection, show excellent agreement of most of the interfaces obtained via TDEM and seismics. And allow to assign to the different layers recognised by seismics, electrical resistivities indicating the salt contents of those layers. In the sections saltwater intrusion effects have been observed along what are probably fresh water canals and aquifers, laterally confined by clay beds, at a depth of over 100 m (figg. 8a,b and 9a,b).

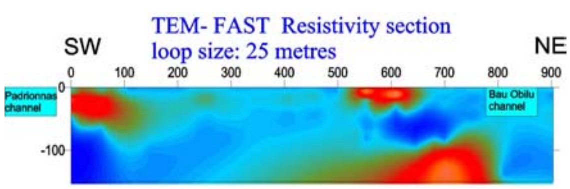
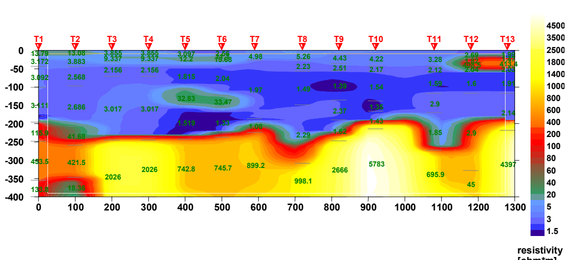


Fig.8a,b- Resistivity section obtained respectively from a TEM FAST survey and a TEM survey.



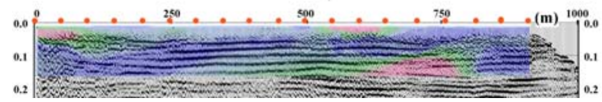


Fig. 9a – Superposition of TEM FAST results and HR reflection seismic section

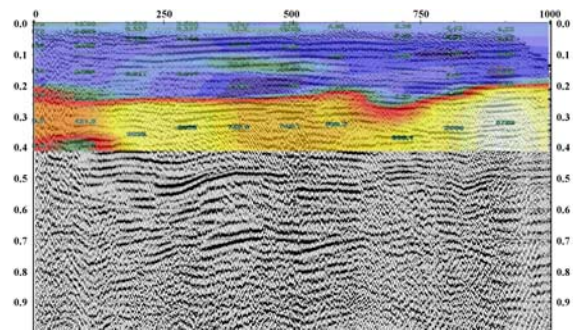


Fig. 9b – Superposition of TEM results and seismic section

The disadvantages of TDEM soundings are:

- they do not perform well in highly resistive soils
- the interpretation programs are limited to 1D or 2D structures
- the equipment is rather expensive

Conclusions

The TDEM method is a potentially useful tool for hydrogeologists, particularly for studying salt water intrusion phenomena . It can complement conventional DC resistivity methods and FDEM methods. The combination with other high resolution geophysical method such as reflection seismics and a knowledge of a given geological feature gained from a few boreholes can be very usuful for describing the subsoil and to define the aquifer geometry and groundwater quality.

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