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Tem-fast: a useful tool for hydro-geologists and environmental engineers

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Abstract
Time Domain Electromagnetic (TDEM) methods have proven to be efficacious in many studies involving environmental and engineering problems, producing better results than the traditional galvanic techniques. In fact, the major advantage of this method is that the soundings can be performed in a relatively short time and in a small place. TDEM sounding appears to be particularly useful for discriminating between layers having low resistivity, but interpretative limitations arise when intermediate and deep resistive layers occur. So the method appears complementary to the traditional electrical soundings. This method has been experimentally tested in well characterised test sites where geophysical investigations (reflection seismic, SEV, IP, gravimetry) and drillings, as well as chemical and isotopic analyses had already been conducted. The results confirm that the method is practical, economic and perfectly reliable, not only at large depths, but also in shallow research, using fast acquisition devices working in the range from 4 μs to some ms.

Key words *electromagnetic soundings – hydrogeology – environment – resistivity measurements*

1. Introduction

Developed in Russia in the early eighties for studying deep structures, since 1985 the TDEM has found wide application in many geological, engineering and environmental fields and today represents a very interesting method for investigating some electrical parameters of the subsoil. Much has been published on the TDEM, including applications in hydrogeological research (Fittermann and Stewart, 1986; Christensen and Sorensen, 1994; Meju, 1995; Sorensen, 1996), and for studying the specific problem of salt water intrusion (Christensen and Auken, 1992; Yuhr and Benson, 1995; Richards *et al.*, 1995; Goldmann *et al.*, 1996; Hoekstra *et al.*, 1996). Other workers (Nabighian and Macnae, 1991; Meju, 1994a,b, 1996; Auken, 1995; Christensen, 1997; Sorensen, 1998) have studied various aspects of the application, processing and interpretation of TDEM soundings and its use in combination with other geophysical techniques.

Here we examine the main advantages and disadvantages of TDEM in particular of the fast version, with respect to other techniques.

2. Basic concepts of TDEM soundings

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 by a motor generator, is

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injected into a square (usually single turn) loop of wire laid on the ground and directly connected to the transmitter. The transmitter current 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. A voltage pulse is recorded in a receiver loop (coincident or inside the transmitter loop) during the period of current off.

In the coincident loop configuration, the desired depth of exploration is approximately equal to the side length of the loop. Generally the loop side varies from a few meters to hundreds of meters. A single or multi turn receiver coil, located at the centre of the transmitter loop or coincident with the transmitter loop, is connected to the receiver through a short length cable.

The process of abruptly reducing the transmitter current to zero induces, in accord with 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 as shown in fig. 2.

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

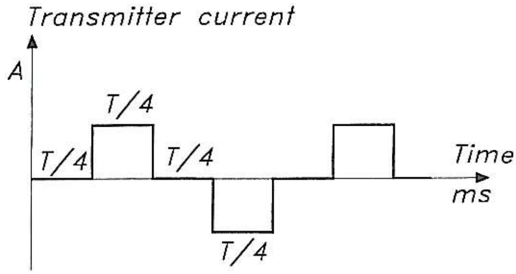

Fig. 1. Transmitter current waveform.

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

In TDEM , the transient electric field reaches a maximum at the diffusion depth (dd) which is what the skin depth δ is to FDEM.

In the TEM the diffusion depth is directly proportional to $\sqrt{t}$ and precisely

$$dd = \sqrt{\frac{2t}{\sigma\mu}}.$$

Making measurements of the voltage produced by 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 successively greater depths, which process forms the basis of

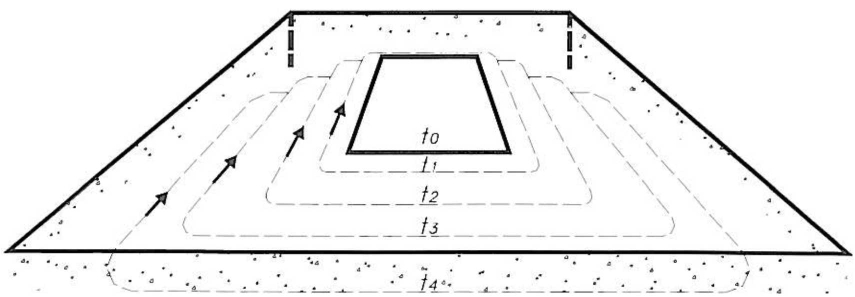

Fig. 2. Current flowing into the ground.

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

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 distortion in measurement, the *early time gates*, located where the transient is changing rapidly with time, are very narrow, whereas the *later gates*, in which the amplitude of the transient decay becomes smaller, are much broader to enhance the signal-to-noise ratio. Only the transients that occur when the transmitter current has just been shut off are measured.

This feature offers a very significant advantage over FDEM measurements, which are generally very sensitive to variations in T/R coils spacing, because they are made while the current is flowing.

Finally, particularly for shallower sounding, 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 the signal to noise ratio. To increase the depth the variations at a later time (to some seconds) must be recorded.

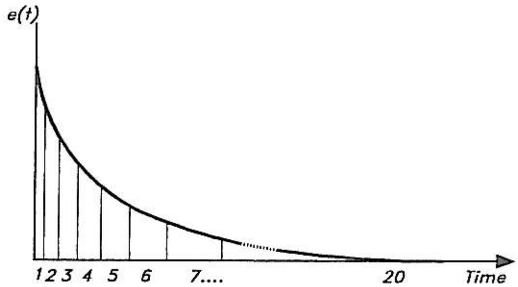

Fig. 3. Gate locations.

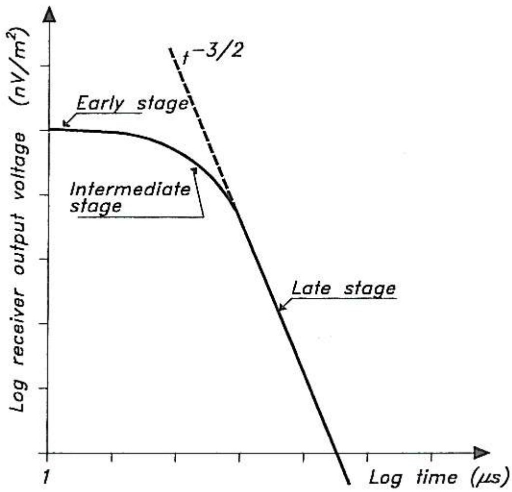

Fig. 4. Receiver output voltage *versus* time.

3. The apparent resistivity in TDEM soundings

It has seen that 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* (on log-log plot the response is a straight line) as shown in fig. 4.

The response varies quite simply with time and conductivity as

$$e(t) = \frac{k_1 M \sigma^{3/2}}{t^{5/2}} \tag{3.1}$$

where: k_1 is a constant; M is the product of T current (amps) × area (m^2); σ is the terrain conductivity (Siemens/m); t is the time (s), and $V(t)$ is the output voltage from a single turn receiver coil of 1 m^2 area.

We note that unlike the case for conventional resistivity measurement, 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 the 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

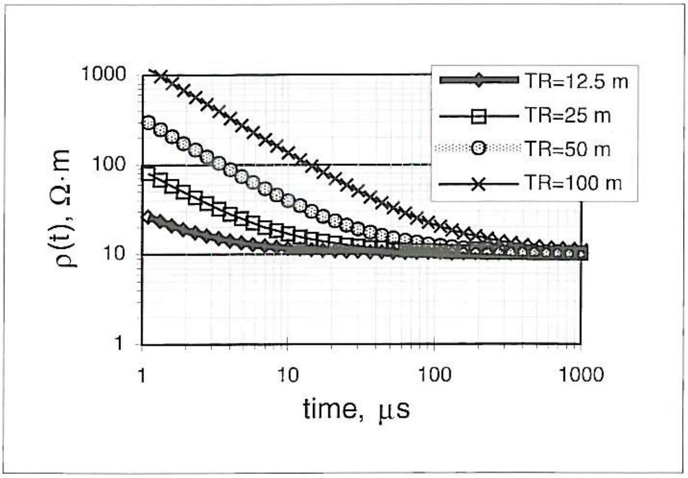

Fig. 5. Apparent resistivity *versus* time for different loop size in 10-Ω·m homogeneous half space (by courtesy of AEMR - The Netherlands).

resistive structure, we can convert the voltage curves to apparent resistivity.

As observed earlier, as time increases so too does the depth of the current loops and we can carry out resistivity sounding with depth. Since $\rho = 1/\sigma$ from eq. (3.1)

$$\rho_a(t) = \frac{k_2 M^{2/3}}{e(t)^{2/3} t^{5/3}}. \tag{3.2}$$

In the homogeneous half-space the apparent resistivity $\rho_a(t)$ against time would be as in fig. 5, equal to ρ_1 at late time but much larger than ρ_1 at the early time. For layered earth, in which $\rho_2 < \rho_1$ the measured voltage will be less than it should have been for homogeneous half space. For conductive basement the behaviour will be inverse and ρ_a becomes equal to ρ_2 at late time.

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.

4. Practical indications from theory

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

$$\frac{e(t)}{M_r} = \frac{\mu M_t}{5t}\left(\frac{\mu}{4\pi t \rho_a}\right)^{3/2}. \tag{4.1}$$

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 gives some important points about transient soundings. Because $e(t)/M_r$ is inversely proportional to time and the current diffuse downwards with time, it is more difficult to sound more deeply 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 depends upon the geo-electrical 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.

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

Opposite to DC methods, in TEM the form of apparent resistivity curves depends on the size of receiving-transmitting antenna. At early times, $\rho_a(t)$ appear overestimated the smaller the loop size (fig. 5).

5. Practical recommendations

From different uses of TDEM in many works, we can list some recommendations:

1) The maximum depth of researches is determined by the maximal time t, on which it is possible reliably to register a signal $E(t)/I$ and not exceed 3 times the loop side.

2) The TDEM effectively works in sections with high conductivity: the layers, for example, with $\rho = 1$ and $\rho = 1.5\ \Omega \cdot \mathrm{m}$ are reliably stratified.

3) It is practically impossible to distinguish layers with very high resistivity.

4) The application of «super-small» antennas (less than 10-15 m) for stratification of layers at small depths is possible only at low resistivity rocks.

5) At high levels of resistivity it is necessary to use large sizes antennas.

6) The most favourable range of specific resistivity for stratification of rocks lies within the limits of $10\ \Omega \cdot \mathrm{m} < \rho < 300\ \Omega \cdot \mathrm{m}$.

7) The mean resolution is about 1/10 of the loop side.

For optimum sizing of the antenna it should be remembered that large antennas increase the limiting depth of the investigation, but they do not allow the subsurface horizons to be defined.

Estimations of depths h, for which reliable interpretation of the results is possible, using coinciding antennas with the side TR = REC = L, usually fall within the range: $h_{min} > L/10$ and $h_{max} < 3L$.

6. 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 the 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 contain 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 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.

An example of SPM effect for different loop size on high resistivity rocks is shown in fig. 6.

IP effects are produced in:

– Thin well-conducting horizon of surface clay deposits with $\rho < 20\text{-}40\ \Omega \cdot \mathrm{m}$, bedding on a fairly resistive layer with $\rho > 300\text{-}500\ \Omega \cdot \mathrm{m}$. 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.

An example of IP effect for two loop sizes are shown in fig. 7.

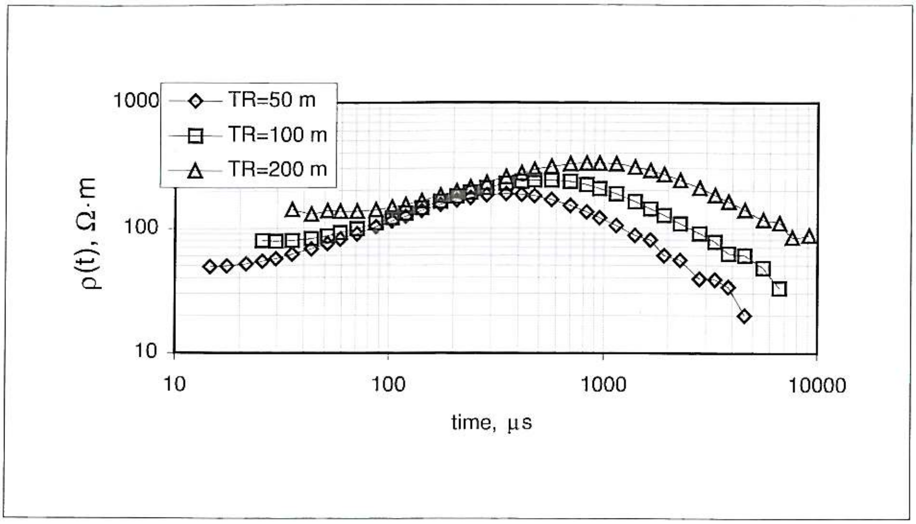

Fig. 6. SPM effect on very high resistivity rocks, for different loop size (by courtesy of AEMR - The Netherlands).

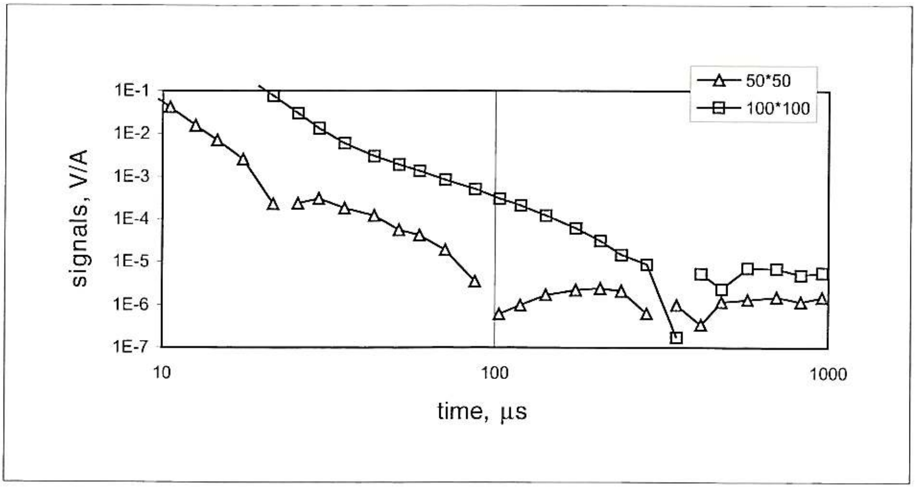

Fig. 7. IP effects (by courtesy of AEMR - The Netherlands).

7. Sources of noise

Other sources of noise for TEM soundings include:

– *Circuit noise* (depending of the goodness of device).

– *Radiated and induced noise by radio and radar transmitters and also from thunderstorm lightning* (that can be extensive on summer days and due to the electrical noise from lightning strikes). It can be reduced increasing the staking or discontinuing the survey.

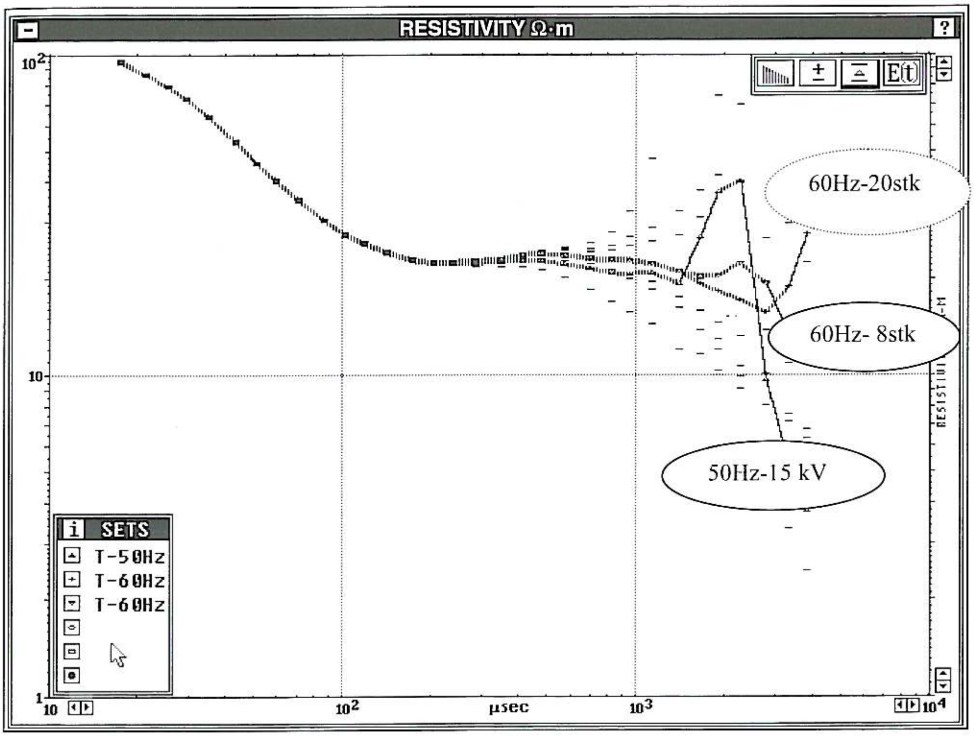

Fig. 8. Effect of an electrical power line with different acquisition (by courtesy of AEMR - The Netherland).

– *Presence of magnetic field produced by 50/60 Hz power lines.* The remedy is to reduce the receiver gain so that overload does not occur. In this case the measurement of the transient will be less accurate since the available dynamic range is not being fully utilised. Another alternative is to move the measurement array further from the power line. An example of noise due to an electric power line is reported in fig. 8, the power line shows an oscillating response. In fig. 9a,b the effect of a 15 000 Volt line is reported. As shown in fig. 9a where $E(t)$ and in fig. 9b where $\rho_a(h)$ are reported, the effect diminishes at about three times the loop size.

– *Presence of nearby metallic structures.* The response from metallic structures can be very large compared with the response from the ground. Metallic object responses such as those from buried metallic trash, or pipes, can also present a problem (fig. 10). The remedy is to use two loops shifted by some metres. Application of another instrument such as a metal detector or ground conductivity meter to quickly survey the site for pipes can often prove useful.

8. Data reduction and interpretation

Before the interpretation the field data $E(t)/I$ must be transformed. The first step is to transform $E(t)$ data into $\rho_a(t)$ data calculated using normalizing at all stages of a transient for uniform half-space. Successively the data are transformed in $\rho_a(h)$ using the formula like

$$\rho^*(t) = \rho_*(t);\ h(t) = \sqrt{(t\rho_*(t)/\mu_0)}$$

where $\rho_*(t)$ is apparent resistivity in normalisation on all stages of process, $\rho^*(t)$ is the trans-

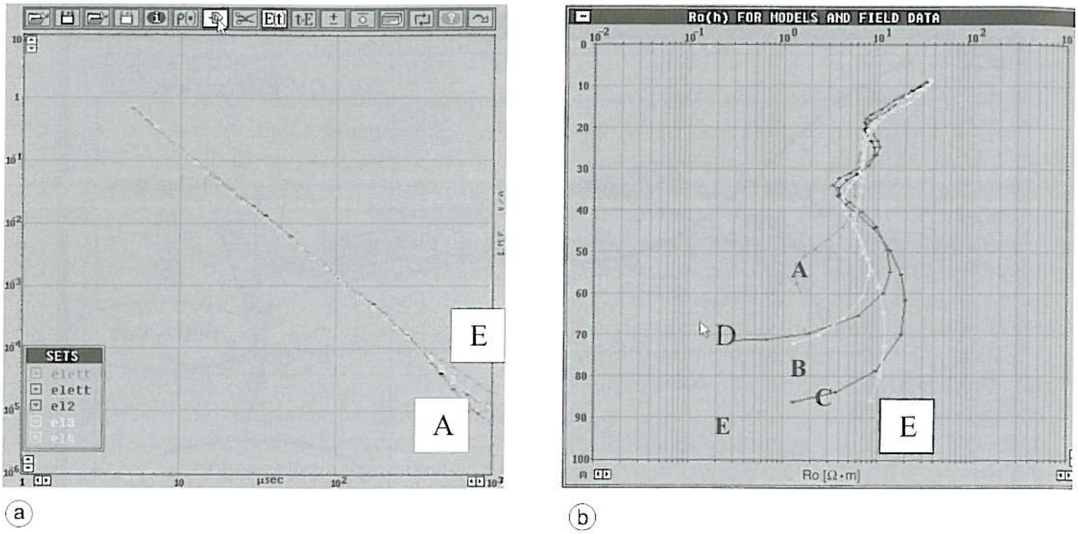

Fig. 9a,b. Effect of a 15 000 V power line in a 25 m loop at different distance. As shown in fig. 9a, where $E(t)$ and in fig. 9b where $\rho_a(h)$ are reported, the effect extinguishes at a distance three times the loop size. The different curves are obtained for different distance of the center from the power line. A = 0 m; B = 12.5 m; C = 25 m; D = 37.5 m; E = 50 m and 100 m.

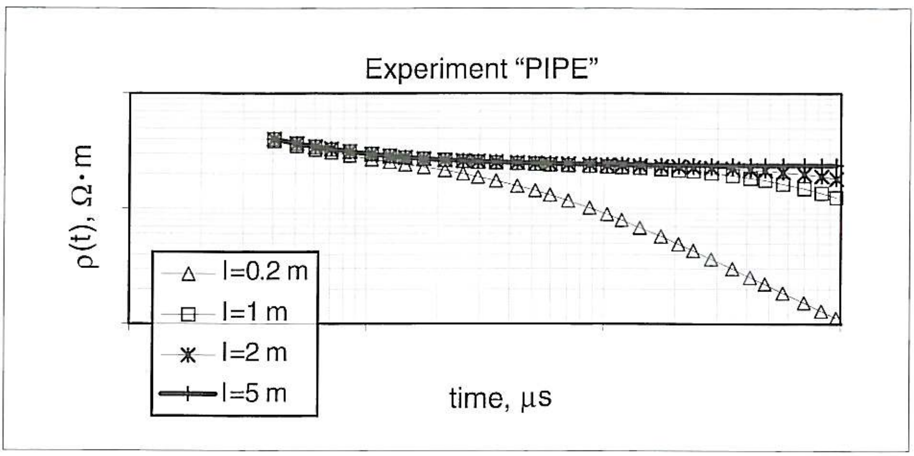

Fig. 10. Effect of a metallic pipe in a sounding on a homogeneous half space. At a distance l = 5 m the effect is null (by courtesy of AEMR - The Netherland).

formed apparent resistivity, $h(t)$ is the apparent depth, μ_0 is the magnetic permeability of vacuum.

Numerically calculated apparent resistivity curves for a variety of layered earth have been produced, particularly in Russia where the technique was developed. The field data would be compared with a selection of curves, from which the actual geo-electric section would be determined. More recently the advent of fast computer inversion programs allows the field transient

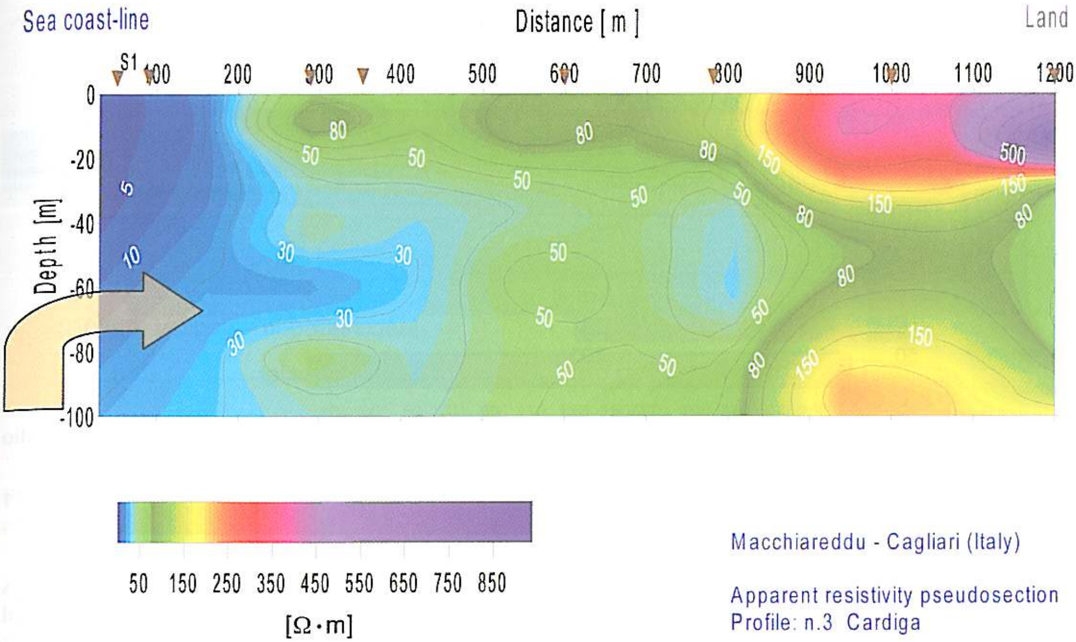

Fig. 11. Apparent resistivity pseudosection perpendicular to the coast line, showing the salt water intrusion to 800 m from the sea (after Godio *et al.*, 1999).

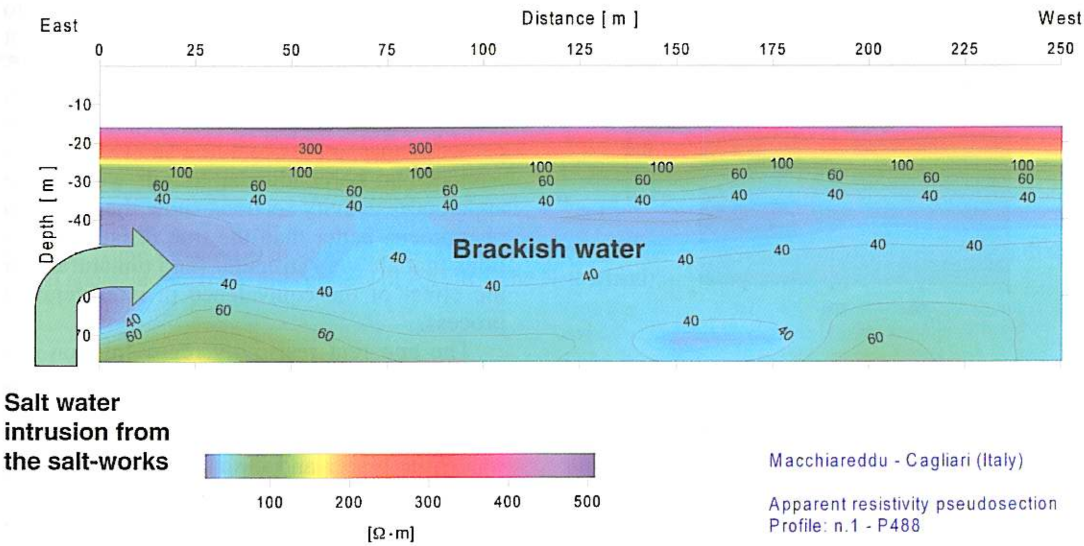

Fig. 12. Apparent resistivity pseudosection perpendicular to salt-works showing salt water intrusion and the «spray» effect (after Godio *et al.*, 1999).

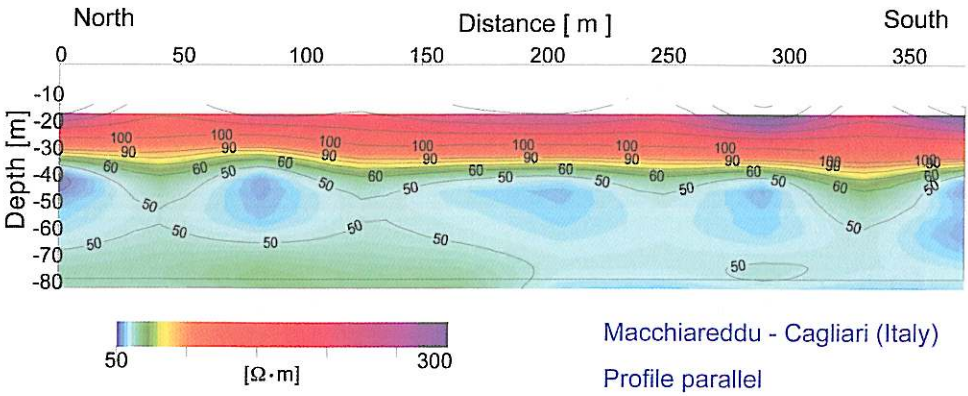

Fig. 13. Apparent resistivity pseudosection parallel to salt-works showing salt water intrusion (after Godio *et al.*, 1999).

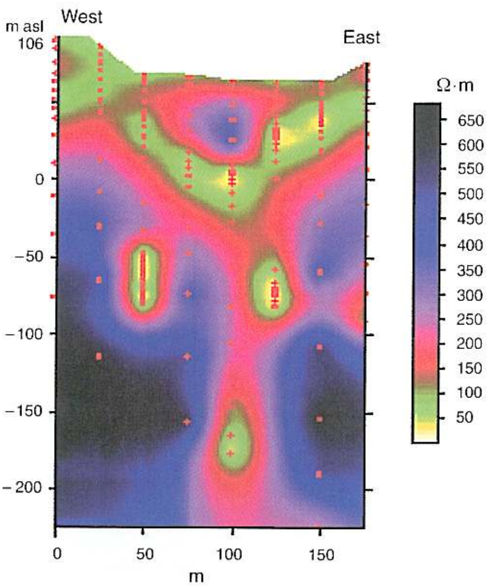

Fig. 14. Apparent resistivity pseudosection obtained in corresponding of a gold deposit and showing the vertical structure of the deposit and the superficial alteration.

data to be automatically inverted to a layered earth geometry in a matter of minutes. Like all electrical sounding techniques, the TDEM sounding interpretation also suffers to a greater or less extent from equivalence. In many cases the automatic inversion program giving the real thickness and resistivities of different layers is not always usefully applied.

When the layers have very similar resistivity it could be more useful to transform the voltage data in apparent resistivity *versus* depth. Godio *et al.* (1999), show that in many cases it is more reliable to transform only the $E(t)$ data into $\rho_a(h)$. Figures 11, 12, 13 represent the apparent resistivity pseudosections obtained in the region of Capoterra (South-Western Sardinia), respectively in correspondence with a profile perpendicular to the coast line and two profiles parallel and perpendicular to salt works. The apparent resistivity sections show the intrusion phenomena better than the true resistivity sections that are very irregular (and unnatural) for the effect of the equivalence in interpretation process.

The apparent resistivity representation can also be more useful when IP and/or SPM occur. In fig. 14 related to a mining research for gold, where the geological features are volcanic rocks, the placer and the alteration are clearly indicated.

However, for very conductive layers a «family» inversion technique can be adopted: the interpretation of every sounding can be obtained using as a starting model the results of the inter-

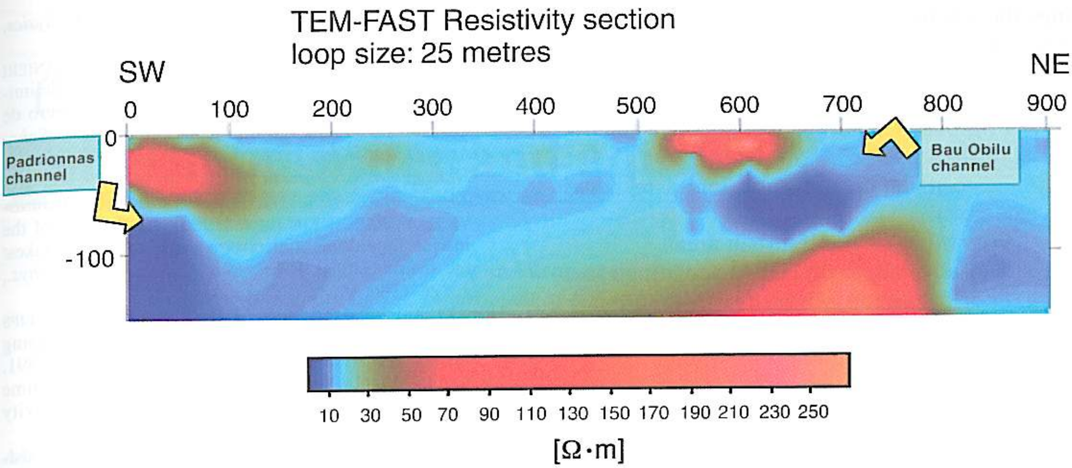

Fig. 15. Resistivity section showing salt water intrusion in channels opened for fish breeding (after Deidda *et al.*, 2000).

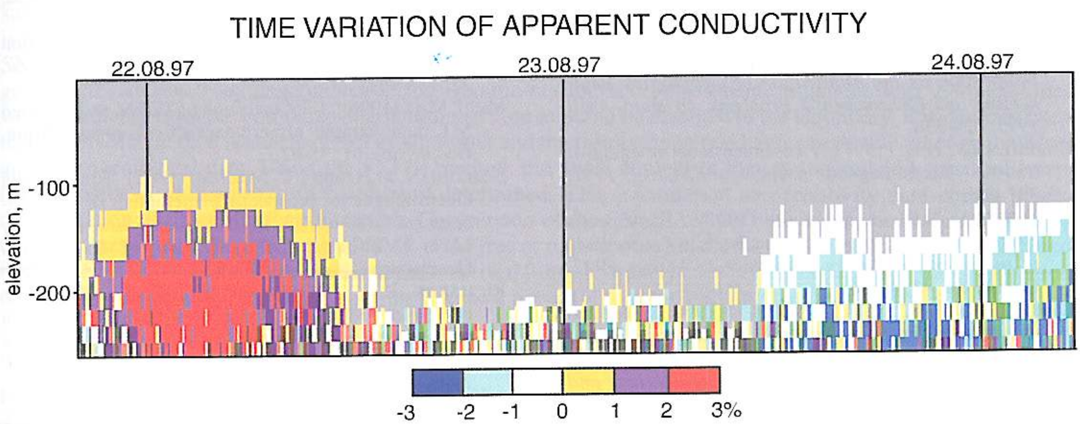

Fig. 16. Time variation of the apparent resistivity measured in water pumping. The dates are normalized to the initial apparent resistivity (by courtesy of AEMR - The Netherland).

pretation of the previous sounding and so on. Figure 15 shows a section of true resistivities obtained in salt water loss from fishing breeding in a very complex aquifer.

Another useful application of TDEM-FAST is the monitoring of resistivity variations in time. Figure 16 shows the time variation of the apparent resistivity during a water pumping operation.

9. Advantages of TDEM

The advantages of TDEM geoelectric sounding over conventional DC resistivity sounding are significant. They can be summarise as follows (Fainberg, 1999):

– Improved speed of operation (we can perform about 30 soundings per day, in a very small space, while in conventional DC soundings the AB line could be more than 2 km long when the surface layers are very conductive – for sounding to 100 m).

– Improved lateral resolution.

– Improved resolution of conductive electrical equivalence.

– Easy injection of current into a resistive surface layer.

– Possibility of use in urban areas.

The disadvantages of TDEM soundings are:

– Poor resolution in very resistive soils.

– The interpretation programs are only limited to 1D or 2D structures.

– The cost of equipment tends to be great.

In conclusion, the TEM FAST soundings represent a very usuful tool, complementary to conventional DC, to reveal the hydrogeological features of the subsoil.

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