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TECHNICAL ARTICLE

Electrical Resistivity Imaging Applied to Tailings Ponds: An Overview

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Abstract

Geophysical methods based on electrical properties can be used to study tailings ponds studies because a site's spatial and temporal subsurface electrical resistivity values vary depending on its physical and chemical properties (texture, salinity, metals, water content, temperature, pH, etc.). This paper reviews published case studies in which electrical resistivity tomography (ERT) was successfully used to characterize and monitor tailings ponds.

Keywords Applied geophysics · ERT method · Internal structure · AMD · Dam instability · Physicochemical characterization · Monitoring

Introduction

Mining operations generate enormous quantities of waste rock and tailings, and their safe disposal poses great challenges for the mining industry. In general, tailings ponds consist of finely ground host rock from which valuable minerals have been extracted (Gupta and Yan 2006; Spitz and Trudinger 2008). These storage facilities are a potential source of adverse related-environmental and safety issues, such as dam failure, acid mine drainage, contaminant transport by wind erosion, run-off, seepage, and groundwater (Wills and Finch 2015). Permanent control and mitigation of these issues represent a high cost to mining companies. Also, closure of tailings ponds and follow-up reclamation and maintenance requires a long-term commitment of monetary resources to avoid future adverse impacts on the environment (Spitz and Trudinger 2008).

Historically, applied geophysics has been used to detect and characterize deep minerals and oil and gas deposits (Brant 1966). However, over the past 30 years, significant advances in computer technology, data processing, and digital transmission has allowed many researchers and practioners to take advantage of this technology's vast potential (Mita et al. 2018). Now, applied geophysics is routinely used to study many environmental (Aracil et al. 2003; Buselli and Lu 2001; Faz Cano et al. 2006; Martínez-Pagán et al. 2005, 2009a, b; Martínez-Segura et al. 2020; Sainato et al. 2010; Tinivella et al. 2013; Vásconez-Maza et al. 2019), hydrogeological (Chambers et al. 2012; Martínez et al. 2009; Nettles 2005; Nguyen et al. 2009; Ogilvy et al. 2009; Woodbury et al. 2015; Yuval and Oldenburg 1996), and other problems. Relevant to this paper, it has been used to non-invasively assess the inner structures of tailings ponds at high data density, and more importantly, at an affordable cost (Reynolds 2011).

Examples of geophysical surveys on tailings ponds include the use of: (1) magnetometry, as magnetic susceptibility changes are associated with progressive alteration of magnetite and pyrrhotite (Reynolds 2011; Styles 2012), which reveals information on the tailings' structure (Morris et al. 2002; Peña et al. 2013; Smith et al. 2004); (2) electromagnetics, as ground bulk electrical conductivity (EC) variations are associated with soil moisture and fluid EC (Chouteau 2005; Hammack et al. 2003; Kolaj and Smith 2013; Reynolds 2011; Smith et al. 2004), and the structural and hydrogeological setting of oil sands tailings dykes (Booterbaugh et al. 2015); (3) seismic, to record elastic refraction and reflection waves from pond boundaries due to changes in the mechanical properties of internal tailings

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layers (Haegeman and Van Impe 1999; Lghoul et al. 2012; Reynolds 2011) and; (4) direct-current geoelectrical imaging surveys, as electrical resistivity (ER) changes can be related to the spatial and temporal variability of many tailings properties (Loke et al. 2013; Samouëlian et al. 2005), including volume, depth, fractures, structure, texture, salinity, temperature, pH, water content, and fluid composition (Telford et al. 1990).

In this paper, we introduce and provide an overview on the application of electrical resistivity tomography (ERT) to tailings ponds, and examine some particular case studies. ERT is the primary geophysical technique used for tailing pond surveys (Martínez et al. 2014). In fact, among all the different geophysical techniques conducted on tailings ponds in the scientific literature, the use of ERT is remarkably dominant. This paper gives an updated overview on the use of ERT on tailings ponds, which might be useful to those who might be in charge of tailings ponds management (mining companies, local or/and regional governments, environmental advisors, etc.).

Electrical Resistivity Tomography (ERT)

Resistivity methods measure the apparent ER, which is a volumetric property that describes the resistance of electrical current flow within a medium and can be used, in a non-invasive way, to observe subsurface geochemical properties changes (Rucker et al. 2009). Direct electrical current is propagated in rocks and minerals by electrolytic and electronic conduction (Telford et al. 1990). Porous media favours the passing of electrical current through ions within the open structure of the saturated pore space by electrolytic conduction, which is favoured by the dissociation of ionic species (Rucker et al. 2009), and relies on the degree of mobility, concentration, and degree of dissociation. In contrast, electronic (ohmic) conduction is the normal type of current flow in materials containing free electrons, such as metal-based sulphide minerals (Telford et al. 1990).

ERT involves the injection of electric current into the ground through one pair of electrodes (the current dipole) and measuring the resultant electric field potential across another pair of electrodes (the potential dipole). The electric current is generated by equipment powered by batteries or an electric generator with the capacity of a few watts or a few tens of watts (Robinson and Coruh 1988). Field data are acquired using a multi-electrode array along linear transects (Fig. 1). A multi-electrode array enables rapid data acquisition over a large area with minimal reconfiguration of equipment. Common array configurations include Wenner, Schlumberger, and dipole–dipole arrays. The chosen array configuration influences the depth of investigation, vertical and horizontal resolution, and the signal-to-noise ratio (Sasaki 1992). Here, the Wenner–Schlumberger array has been successfully used in tailings ponds studies (Martín-Crespo et al. 2010). ERT requires increasing the separation between the current and potential dipoles, thus providing information from increasingly greater depths (Martín-Crespo et al. 2015).

Obtaining resistivity is not a simple and direct process (Rucker and Fink 2007). Ohm's law relates the applied current (I) [amperes, A], the measured voltage [volts, V], and the calculated resistance [ohm, Ω] (Everett 2013). ER (ρ) [ohm·m, Ω m] and resistance are related through a geometric factor (Fig. 2).

Field measurements comprise an indefinite volume of ground. Note that the quality of ERT data strongly depends on how well the electrodes are installed in the ground and the chosen electrode geometry. Thus, to guarantee the quality of the field measurements: (a) electrodes should be installed as tightly as possible into the ground with no gaps between the electrode and ground, (b) the contact resistance of the electrode against the ground should be less than 10 k Ω, (c) if the contact resistance is large, it should be reduced by adding electrodes or by pouring water or bentonite mud water around the electrode (Gakkai 2014).

There are many electrode configuration arrays (Dahlin and Zhou 2004; Martorana et al. 2017; Zonge et al. 2005). The most widely used arrays are represented in Fig. 2. The choice of measurement array is crucial since it influences the depth of investigation, lateral and vertical resolution, and signal-to-noise ratio (Dahlin and Zhou 2004; Reynolds 2011; Zonge et al. 2005). Thus, the Wenner array has a high vertical resolution for horizontally-layered media an excellent signal-to-noise ratio, and the Schlumberger array has almost as high a vertical resolution as the Wenner array with a reasonable signal-to-noise ratio. However, the dipole–dipole array's signal contribution indicates poor vertical resolution and that the array is particularly sensitive to deep lateral resistivity variations, making it more suitable for detecting lateral inhomogeneities or resistivity profiling (Reynolds 2011); its signal-to-noise ratio is acceptable if the value of "n" is kept less than 8 (Telford et al. 1990).

Consequently, resistivity calculations are built on the proposed response for the given electrode geometry over a homogeneous, isotropic, half-space (Rucker et al. 2009). This result is what is termed "apparent" resistivity (ρ_a), which is calculated for a generalized electrode array configuration used in resistivity measurements (Kearey et al. 2013) as:

$$\rho_a = \frac{2\pi V}{I\left\{\left(\frac{1}{r_A} - \frac{1}{r_B}\right) - \left(\frac{1}{R_A} - \frac{1}{R_B}\right)\right\}} \tag{1}$$

Equation 1 is the basic equation for calculating the apparent resistivity for any electrode configuration. Apparent

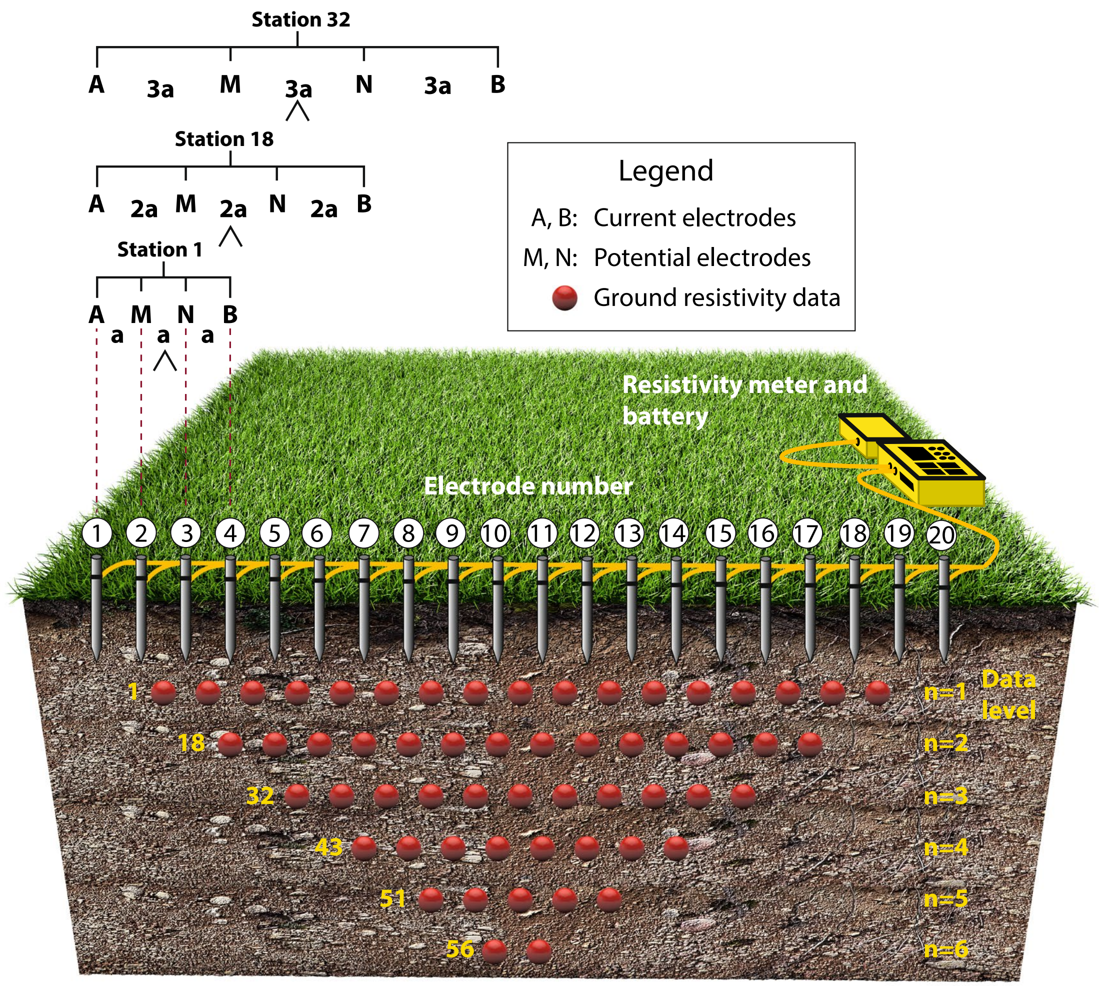

Fig. 1 Schematic diagram of a multi-electrode array to create a 2-D pseudo-section

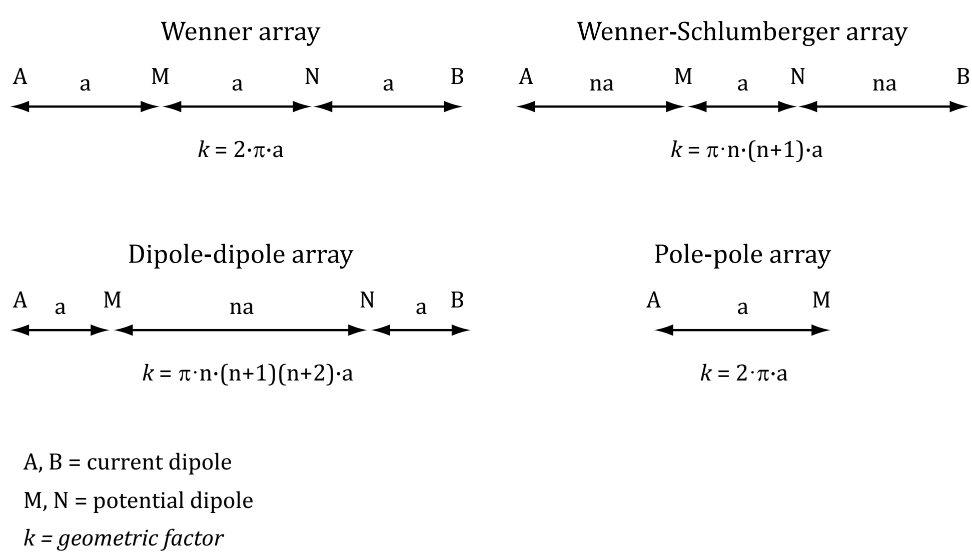

Fig. 2 Geometric factor for different array configurations (Telford et al. 1990)

resistivity values are plotted as a pseudo-section, where each electrode configuration yields a different pseudo-section, since a pseudo-section is not a true vertical cross section (Binley and Kemna 2005). Then, an estimate of the "true" resistivity is calculated through an inverse procedure (Loke et al. 2013; Rucker and Fink 2007) to facilitate interpretation, since the inverted resistivity distribution presents a more quantitative comparison to natural geologic features. The development of multi-electrode acquisition systems and 2-D and 3-D inversion procedures have made the advancement of resistivity imaging of complex subsurface structures possible (Everett 2013; Loke et al. 2013) (Fig. 3).

ERT imaging is performed by matching the measured apparent resistivity pseudo-section to a computed pseudo-section that is obtained by solving, for a given subsurface true resistivity model (Fig. 4). The model is then adjusted, and the apparent resistivity re-computed until it matches the measured apparent resistivity to within an acceptable tolerance or error (Everett 2013). This inversion procedure and the methods by which true resistivity is calculated can be found in several sources (Everett 2013; LaBrecque et al. 1996; Li and Oldenburg 2007; Loke and Barker 1996; Loke et al. 2013). In general, the method uses a finite element scheme to solve the 2-D forward problem and the blocky

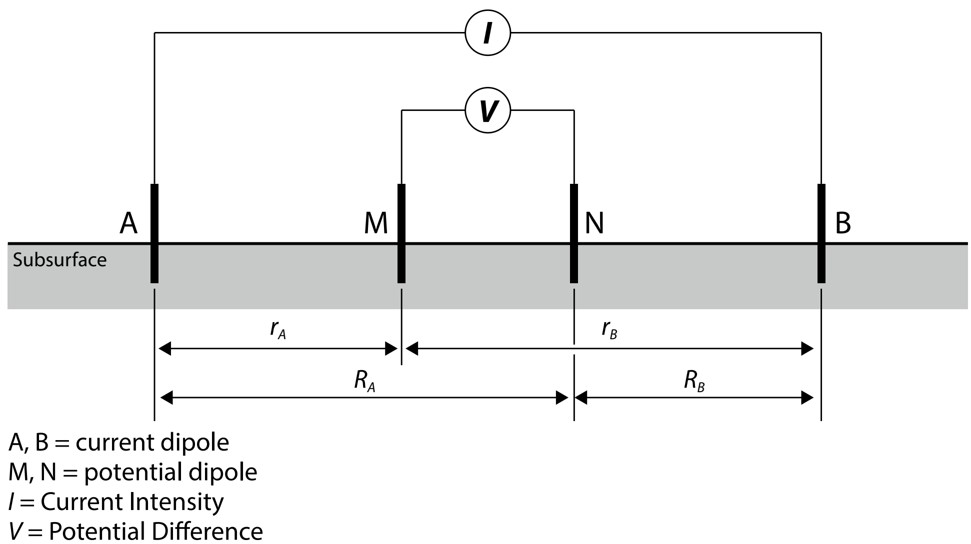

Fig. 3 The generalized form of the electrode configuration used in resistivity measurements (Kearey et al. 2013)

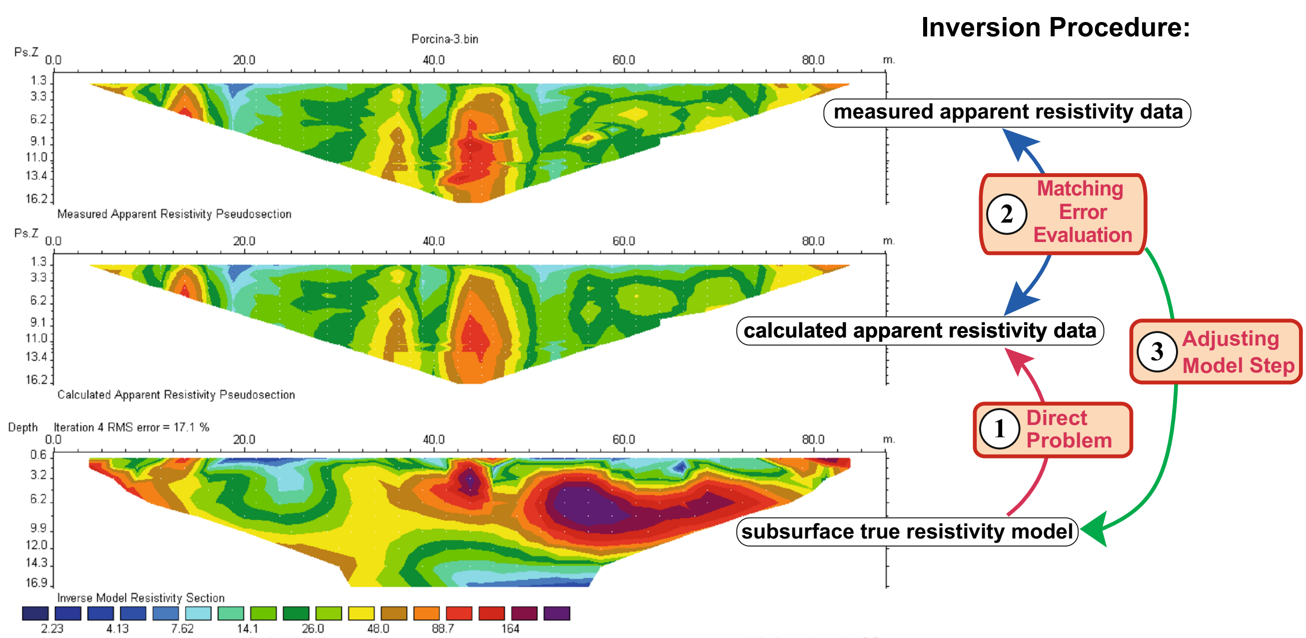

Fig. 4 Accepted resistivity model and its calculated apparent resistivity response through the inversion procedure

inversion method for inverting the ERT data (Loke et al. 2013; Oldenburg and Li 2005). The 2D electrical section finally obtained is constituted by selected, spatially distributed ER data, which are related to variations in the tailing ponds' physicochemical properties. Then, the true resistivity model is used to infer the subsurface lithological structure at the interpretation stage, where complementary information from borehole samples or geological studies can be used to help validate it.

Practical Applications and Discussion

Acid Mine Drainage

Abandoned tailings ponds containing metallic sulphides are a favourable environment for the generation of acid mine drainage (AMD), which is one of the most significant issues facing the mining industry (Chouteau 2005; Cidu et al. 2011; Dold 2014; Hudson-Edwards and Dold 2015; Spitz and Trudinger 2008). Thus, electrical resistivity imaging (ERI) or ERT has been used to identify the internal pathways that control water and oxygen fluxes responsible for the oxidation of sulphidic minerals and possible generation of AMD (Buselli and Lu 2001; Chouteau 2005; Gómez-Ortiz et al. 2010; Martín-Crespo et al. 2010, 2019; Yuval and Oldenburg 1996), since the AMD is considerably more electrically conductive than the host material through which it flows (Glaser et al. 2009; Grissemann et al. 2007). Thus, ERT is an excellent tool to learn about internal structures and AMD preferential pathways (Banerjee et al. 2011; Lghoul et al. 2012). In fact, according to Campbell and Fitterman (2000), most tailings are electrically conductive relative to natural soils or bedrock forming tailings storage layout, edges and bottoms, and most ground containing AMD plumes is more electrically conductive than ground containing uncontaminated groundwater. An example of ERT applied to tailings ponds is depicted in Fig. 5, where ER values less than 2 Ω m corresponds to AMD preferential pathways (Gómez-Ortiz et al. 2010).

These low resistivity values were affected by the presence of water-saturated silt and clay materials with an abundance of sulphides, mainly pyrite (Gómez-Ortiz et al. 2010). This illustrates the importance of controlling water run-off as the ERT results showed how water surface inflow into the pond promoted the generation of undesirable AMD (Martín-Crespo et al. 2019).

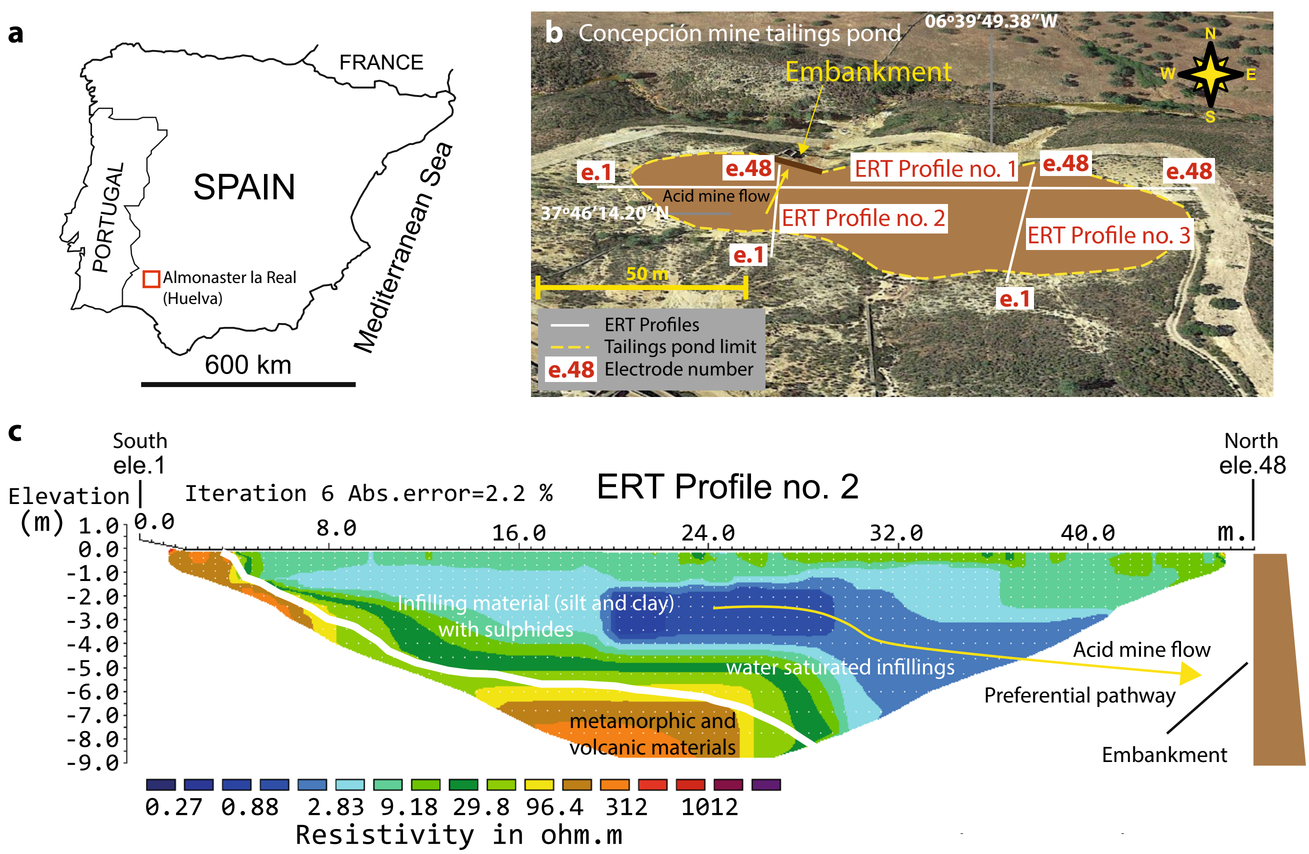

Fig. 5 Application of ERT to acid water drainage assessment at Mina Concepcion (Huelva, Spain) (Gómez-Ortiz et al. 2010)

Dam Instability

Another serious concern is about dam instability due to faults or water pathways in the embankment structure that severely compromise the safety of the tailings pond (Kossoff et al. 2014; Spitz and Trudinger 2008). Dam failures can flood river systems with vast amounts of tailings and invariably affect water and sediment quality, and aquatic and human life (Ji et al. 2013; Kossoff et al. 2014; Martín-Crespo et al. 2012). ERT has been successfully used to detect those faults as seepage sources in embankments, supporting restoration (Cortada et al. 2017; Martín-Crespo et al. 2018; Sjödahl et al. 2009, 2005) and maintenance work (Bolèkve et al. 2009), since moist areas in the embankment are electrically conductive relative to mine or rock waste used in the dams (Spitz and Trudinger 2008). Here, ERT plays an essential role, highlighting the seepage pathway(s) and monitoring changes in seepage velocity over time, thus enabling remedial measures in the early development phase of these serious problems (Bolèkve et al. 2009; Hübner et al. 2015; Karimi Nasab et al. 2011; Martínez et al. 2012, 2014; Mita et al. 2018).

Internal Structure

Frequently, tailing pond managers or local governments in charge of their placement need to know the precise internal structure of mine wastes, either to evaluate the cost of a pond relocation where tailings are dangerously close to towns or properly undertake reclamation work to reduce environmental damage (Acosta et al. 2014; Conesa et al. 2008; Peña et al. 2013; Ramalho et al. 2009). However, this sort of information, such as tailings volume, bedrock-tailings boundary, internal moisture regions, particle size distribution, and faults occurrence, is not always available (Spitz and Trudinger 2008). ERT method has played a remarkable role in shedding some light on those issues (Acosta et al. 2014; Loke et al. 2013). Similarly, some ERT studies conducted at sites where there were plans to construct tailings ponds have pinpointed the occurrence of previously unknown faults or weak subsurface materials, thus enabling the correct decision about site suitability (Zarroca et al. 2015).

A number of studies describe the use of ER imaging for providing the internal geometry of tailings dams and assessing their potential environmental risks (Chouteau 2005; Grissemann et al. 2007; Lghoul et al. 2012; Martín-Crespo et al. 2015; Martínez et al. 2012, 2014; Rey et al. 2013). Pronay et al. (2015) and Camarero et al. (2019) carried out ERT geoelectric tests to map contaminated water flow to tailings embankments and to support the geotechnical stability characterization of the dam. Similarly, ERT was employed by Mita et al. (2018) to monitor the displacement of unstable slopes to prevent landslide occurrences. So, using geoelectrical methods to understand the geotechnical properties of embankment materials is crucial to avoiding future failures, as reported elsewhere (Banerjee et al. 2011; Bery 2016; Campbell and Fitterman 2000; Hatta and Osman 2015; Hudson et al. 2018; Loke et al. 2013).

Next, is an example of electrical imaging application on an abandoned tailings pond, where ER values helped to characterize the particle size distribution of different surficial regions, since particle size distribution is closely related to EC in soils (Samouëlian et al. 2005). This near-surface particle size distribution was essential to a European remediation project creating a spontaneous and permanent vegetation cover (Acosta et al. 2018). The slurry discharge system, discharging the slurry by gravity from wooden sluices, was located on the dam (Fig. 6). This influenced the way that particles settled on the impoundment since coarse sizes were deposited near the embankment and finer particles further from the discharge points. Consequently, the very near-surface tailings (from 0 to ≈ 2 m depth) can be classified according to their particle size, which in turn influences the permeability, pH, moisture content, etc., characteristics that are needed in phytoremediation actions (Acosta et al. 2018).

Figure 7c depicts an electrical section obtained on the Gorguel tailings pond from ERT profile no. 1 (Fig. 7b). ERT profile no. 1 was conducted with a Wenner-Schlumberger measurement array and its electrical section was achieved with an absolute error of ≈ 10% after five iterations. In Fig. 7c, surficial ER values above 8 Ω•m correspond to a region near the embankment mainly composed of coarse particles (50–2000 µm; (Gabarrón et al. 2020). Following the latter region, comes the fines (0.02–50 µm), characterized by lower ER values below 8 Ω•m. It is important to highlight that the area constituted of fines particles had lower pH values, and the highest salinity, inorganic carbon, and concentrations of bioavailable Cu, Cd, Pb, Ni, Cr, and As. Hence the ERT method was able to identify coarse and fine particle regions, which was important in defining the suitable amount of soil amendments (marble waste and pig slurry) to be added during the phytoremediation of this tailings pond (Acosta et al. 2018). These ER results were confirmed by physico-chemical analysis obtained from subsurface samples.

Another practical application of ERT on tailings ponds has been the study of bedrock-tailings interface (Zornoza et al. 2017), specifically in abandoned tailings ponds, to detect faults from which AMD could affect aquifers and evaluate the tailings storage (Martínez et al. 2014; Rey et al. 2013). Figure 8 depicts a practical example where different ERT profiles were carried out on a tailings pond, named "Santa Antonieta" (Murcia, SE Spain), to determine the volume of tailings (Fig. 8a). These ERT profiles were carried out with a Wenner-Schlumberger measurement array and the absolute error to which the electrical sections were obtained was about

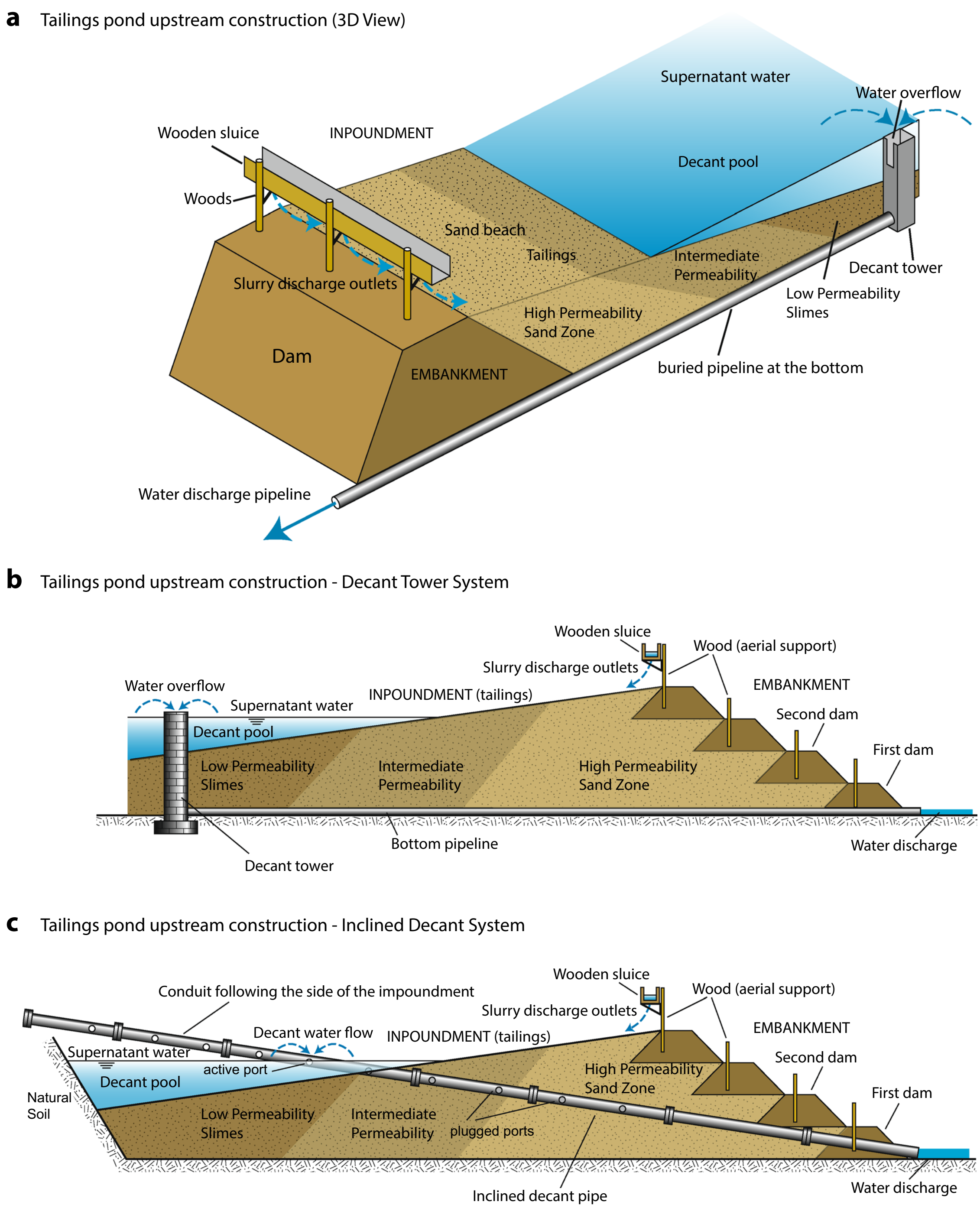

Fig. 6 Influence of the slurry discharge position on the type of impoundment particle settling

10% after 2–4 iterations. This electrical information was used as part of a more general framework of phytostabilization actions (Zornoza et al. 2017). Figure 8b shows the depth to the bedrock obtained via ERT, based on the revealed tailings-bedrock contact, since the tailings had electrical values < 8 Ω•m and the bedrock was characterized by electrical values ranging from 8 Ω m to > 150 Ωm. This enabled them to draw the bedrock basement (Fig. 8c) and calculate the tailings volume (140,000 m^3). The tailings thickness obtained through ERT method was confirmed with boreholes (Fig. 8c).

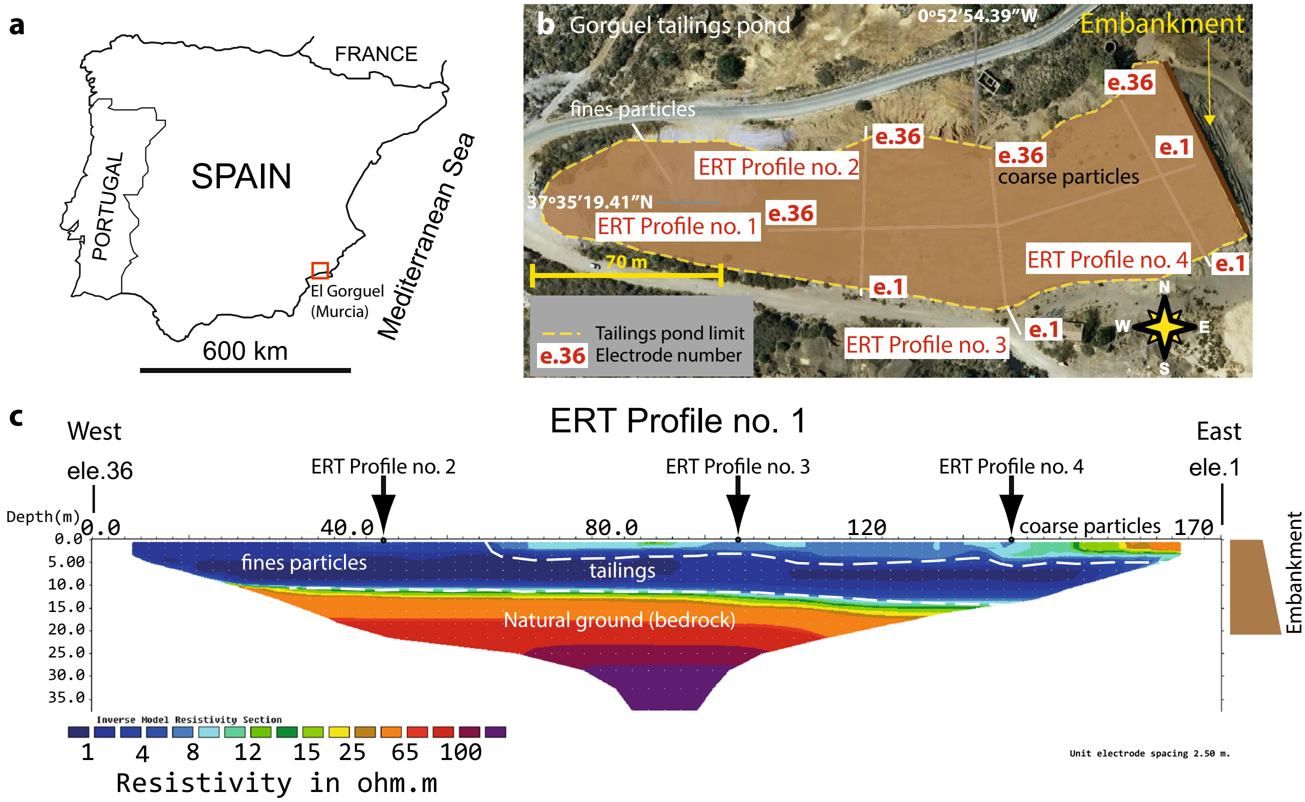

Fig. 7 Application of ERT to the characterization of particle size distribution on Gorguel tailings pond (Murcia, Spain)

Physico-chemical Characterization

ERT is being broadly applied to collect physicochemical information for site remediation (Acosta et al. 2014; Martínez-Pagán et al. 2009a, 2011; Martínez et al. 2016, 2012). Martínez-Pagan et al. (2009a) demonstrated the usefulness of combining ERT and soil chemical analysis to classify materials into three categories according to their ER values; tailings with low ER (< 8 Ωm) fell into the category of fine particles with elevated levels of Cd, Cu, Pb, and Zn. Hatta and Osman (2015) established relationships between moisture content and the ER values of different sandy soil samples, while Hübner et al. (2015) evaluated volumetric groundwater content based on ER values, both of which are relevant to the water content of tailings. Recently, Gabarrón et al. (2020) correlated ER values with some of the most important tailings parameters (metal (Cu, Cd, Ni, Zn, and Fe) content, moisture, salinity, etc.) as depicted in Fig. 9; the chosen measurement array was dipole–dipole, which enabled them to obtain electrical sections with an absolute error value of < 10%. Similarly, Vásconez-Maza et al. (2019) also predicted the spatial concentration of contaminants (Cd, As, Cr, Cu, Ni, Pb, and Zn) in an abandoned phosphogypsum pond using ERT along with chemical analysis.

Recent Trends

Of all the recent ERT research, including ERT cross-hole, mobile systems, capacitive resistivity imaging, and unconventional electrodes use, automatic ERT monitoring systems might provide the most useful information at tailings facilities. The implementation of recent algorithms for 4D tomographic inversion and the development of ER survey instrumentation for monitoring systems makes them a serious option for permanent assessment of sensitive infrastructures such as tailings ponds (Takakura et al. 2013). Loke et al. (2013) describes in detail some case studies of tailings dams where permanent electrode arrays are remotely controlled by a microprocessor or PC, which periodically measures ER, enabling continuous monitoring of parameters such as temperature, moisture content, internal physicochemical reactions, potential AMD occurrence, and dam stability (Versteeg and Johnson 2008) and their temporal evolution (Dimech et al. 2018; Jirku et al. 2014; Ogilvy et al. 2009; Uhlemann et al. 2015). Moreover, the automation of data acquisition and the management of large volumes of recorded data have enabled the wide use these systems (Amabile et al. 2017; Loke et al. 2013; Ogilvy et al. 2009).

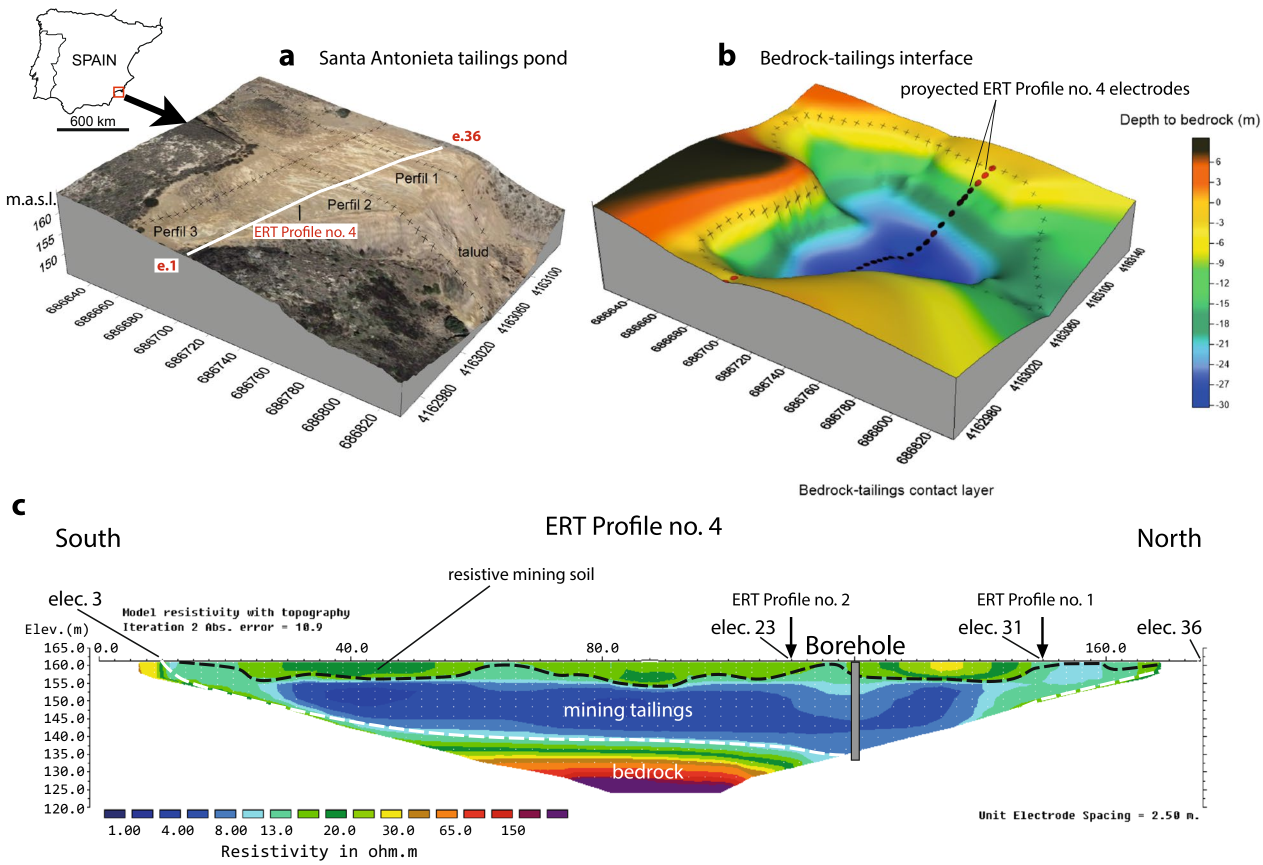

Fig. 8 Application of ERT to volume valuation on Santa Antonieta tailings pond (Murcia, Spain)

Conclusions

This overview has emphasized the use of applied geophysics techniques, and ERT in particular, for gathering vital information to detect, monitor, and resolve different problems and issues at tailings storage facilities. This compilation of case studies from the literature has illustrated how ERT can be successfully used to address specific tailings pond problems such as: (1) acid mine drainage and dam instability; (2) internal structure; and (3) physico-chemical characterization. These studies have proven the value of ERT in obtaining essential data to characterize tailings ponds efficiently and affordably, providing managers with a tested tool to support them in reducing the risk of failure or adverse environmental effects.

So, ERT is a very attractive method for tailings pond characterization as the measured subsurface ER values are very sensitive to changes in moisture, temperature, salinity, contaminant concentrations, or the occurrence of AMD preferential pathways or faults. In this way, these variables can be monitored and quantified. Moreover, ERT is a non-invasive technique and can provide continuous measurements without altering the internal structure over a broad range of scales, reducing the needs for drilling and sampling.

A limitation of ERT is the quick reduction of resolution with distance from the electrodes, but that limitation can be mitigated by using subsurface electrodes placed near the area of interest or supplemented by surface-to-hole or cross-hole measurements. Also, if available, it is recommendable to contrast ERT data with other geophysical, physicochemical, hydrogeological, or geotechnical data, depending on the study objectives.

Automatic monitoring systems are powerful systems to continuously measure variations in both space and time

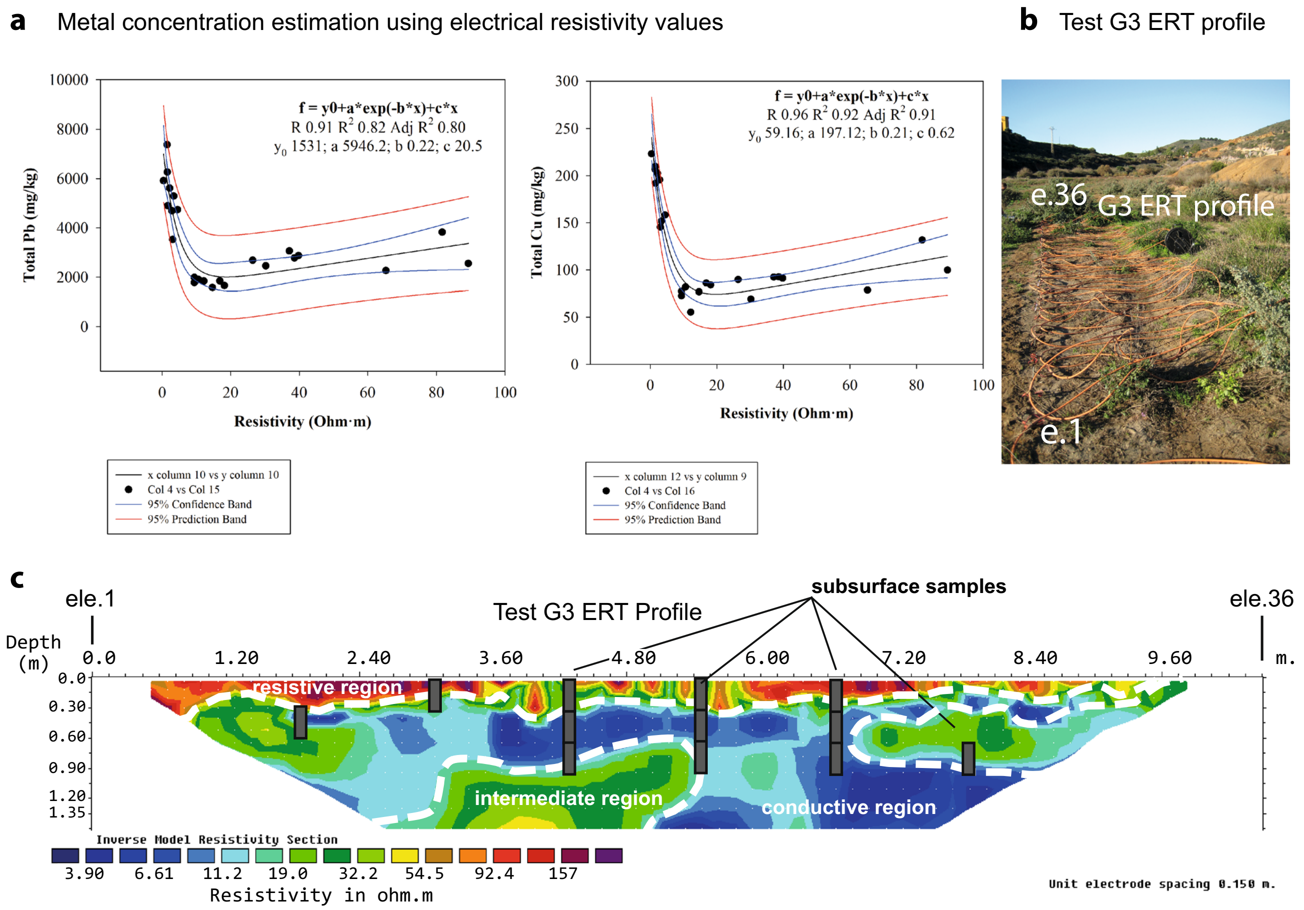

Fig. 9 Contaminant concentration estimation using ERT method in combination with chemical analysis (Gabarrón et al. 2020)

of ER values, thus giving dam managers early-warning responses of seepage, landslides, AMD occurrences, etc.

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