Characterization and Monitoring of Solid Waste Disposal Sites Using Geophysical Methods: Current Applications and Novel Trends

Pantelis Soupios and Dimitrios Ntarlagiannis

Abstract Landfilling remains the most attractive waste management method for solid waste. Although not the most efficient and environmental-friendly option, landfills offer a cost-efficient solution compared to other alternatives. For any landfill to be successful site selection, construction, operation, and post-closure monitoring is critical. Synergistic use of geophysical methods and traditional point sampling (e.g., borehole sampling) allows for high resolution characterization and monitoring of landfills during all stages of operation; from guided site selection, to construction integrity and waste characterization, to leachate recirculation and leak monitoring. Geophysical methods offer advantages, such as high temporal and spatial resolution, non (or minimally) invasive and cost-efficient operation, rendering them a very powerful tool for characterization, and long-term monitoring of waste disposal sites. Since geophysical methods involve the indirect imaging of the subsurface cautious implementation, including direct sampling, is needed for successful application. Multiple geophysical methods have been shown to be suitable for landfill characterization and monitoring. Electrical (resistivity, induced polarization, and self potential) and electromagnetic (transient electromagnetic methods, ground penetrating) are the common geophysical methods employed in waste management operations due to the increased conductivity of waste and leachate. Seismic methodologies can also be used to describe subsurface geology and possible waste horizons. In certain cases, magnetic measurements can also be used for the monitoring and characterization of landfills. Typically, geophysical methods are used to:

- spatially delineate landfills and define landfill geometry,
- monitor and characterize the spatial distribution of moisture, gas content, and leachate inside landfills,

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P. Soupios (✉)
Department of Environmental and Natural Resources Engineering, Technological Educational Institute of Crete, 3 Romanou, Chalepa, 73133 Chania, Crete, Greece
e-mail: soupios@staff.teicrete.gr

D. Ntarlagiannis
Department of Earth & Environmental Sciences, Rutgers University, 101 Warren Street, Newark, NJ 07102, USA

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- identify classes of buried waste based on material composition,
- monitor the integrity of the liner, and
- identify and monitor leachate leaks, and the associated contamination plumes.

With this chapter we aim to introduce common geophysical methods and provide examples for application in landfills. For the geophysical methods of interest the basics principles, along with up to date references are provided, and the advantages and limitations for waste management operations are discussed.

Introduction

Integrated waste management (IWM) can be defined as the selection and application of suitable techniques, technologies, and management programs to achieve specific waste management objectives and goals (Tchobanoglou and Kreith 2002). Although the specific objectives and approaches of IWM might differ, the primary target is to reduce the amount of solid waste end in landfills through waste reduction, reuse, recycling, and waste to energy programs. Solid waste management is a complicated process that starts with the proper site selection, and ends with post-closure monitoring that extents long after (decades) the closure of the landfill. Geophysical methods can be used in all stages of landfill operation to provide high resolution characterization and or monitoring. In most cases geophysical methods are used to provide information on the geometrical characteristics of the repository, and indirect information on the physiochemical properties of the infill (solid and leachate) (Tsourlos et al. 2014).

Site Selection and Landfill Construction

Geophysical surveys have been proven to be successful in the landfill site selection stage (Benson 1988). Geophysical characterization can identify areas that are not suitable for landfill construction due to geology (e.g., faults, fracture zones), former mining operations, karst, and high permeable formations. During site construction geophysical methods can be used to confirm the integrity of the containment basin and impermeable liners.

Leachate Monitoring

The most commonly used solid waste classification system separates the waste in three categories (Table 1) with the majority of the landfills designed for municipal solid waste (MSW). MSW is defined as the waste that comes from residential,

Table 1 Classification of landfills based on waste (from Tchobanoglou and Kreith 2002)

Class	Type of waste
I	Hazardous waste
II	Designated waste
III	Municipal solid waste (MSW)

commercial, institutional, and some industrial sources, but exclude hazardous materials. Although MSW appears to be free of dangerous materials, in reality very often contains toxic, and other unsafe, substances. In some instances, the discarded objects might be safe in the original form, but after the deposition in landfills they can become toxic, or release toxic byproducts, due to decomposition or degradation processes. The toxic chemicals can then be mixed with the available water and form the landfill leachate. Landfill leachate can pose a significant environmental and ecological risk, and in some cases even threaten human health. The most common leachate contamination incidents are the result of [a] poorly constructed and/or managed landfill, (Benson et al. 1988; Robinson and Gronow 1995; Hix 1998; Statom et al. 2004), [b] illegal landfills and dumping sites, [c] lack of regulation and enforcement policies (Piratoba Morales and Fenzi 2000; Ntarlagiannis et al. 2016).

To minimize the contamination risk in landfills the implementation of a comprehensive monitoring system is of paramount importance. A properly operated monitoring system can capture any leaks early in time, and prevent extensive damage. In older, typically unlined, landfills the use of a monitoring system is even more important. We should emphasize the landfill monitoring system should stay in place for decades after landfill closure, until the degradation and decomposition processes cease.

Landfill Dynamic Monitoring

During landfill operation geophysical methods offer the spatial and temporal resolution needed to provide information on the main elements of landfills. For example information on boundaries and nature of waste, the depth/thickness and dip of the layers of refuse and sealing materials, the integrity and shape of the capping zones or separating walls and basal floor slopes can be retrieved; furthermore continuous information on leachate, moisture and gas content can be collected, allowing the more efficient operation of bioreactor landfills (Carpenter et al. 1991; Aristodemou and Thomas-Betts 2000; Meju 2000a, b).

Illegal and Abandoned Landfills

Waste disposal sites, especially older ones, are not always properly constructed and monitored; in many cases there are illegal landfills in unknown locations and with unknown characteristics. Geophysical methods can be utilized in such cases to identify and characterize such waste disposal sites. In case of old, abandoned landfills historical information regarding the waste and construction might be missing; geophysical methods can be used to map the waste, and identify leachate pooling and leaks; in some cases, the waste class might be identified. In case of illegal landfills, geophysical methods can first identify the location, and then try to provide information on subsurface characteristics. We should always keep in mind that geophysical methods provide indirect information, so direct sampling could significantly enhance interpretation.

The complexity of the phenomena linked to waste disposal sites necessitates the synergistic use of a variety of characterization and monitoring methods, with geophysical tools playing an important role. Established direct sampling (e.g., borehole sampling) are required for providing detailed and accurate information on waste status and processes. Such information is typically sparse (in space and time); geophysical methods can be then utilized to provide a complete subsurface image of landfill status by constraining the spatially and temporally extensive—even continuous—geophysical data with the detailed direct sampling ones.

Geophysical Methods

Electrical and electromagnetic methods are the most popular geophysical methods used in waste management operations due to their sensitivity in conductivity contrasts; such contrasts are very common in waste deposition sites due to mixed waste, and leachate formation (Meju 2000b; Tsourlos et al. 2014). Common electrical methods (geoelectrical) employed in landfill studies are the direct current (DC) resistivity, induced polarization, (IP) and self potential (SP) (e.g., Naudet 2003a; Rubin and Hubbard 2005; Arora et al. 2007; Soupios et al. 2007a, b, 2008; Grellier et al. 2008; Reynolds 2011; Gazoty et al. 2012; Kemna et al. 2012; Revil et al. 2012b; Belghazal et al. 2013; Tsourlos et al. 2014; Genelle et al. 2014; Vargemezis et al. 2015; Wang et al. 2015; Çınar et al. 2016; Konstantaki 2016). Common EM methods include transient electromagnetic (TEM), radio- or audio-frequency magnetotelluric (RMT/AMT) (Mack and Maus 1986; Tezkan et al. 1996; Meju 2000b; Belghazal et al. 2013; Belmonte-jiménez et al. 2014). Furthermore ground penetrating radar (GPR) and seismic methods can be used to characterize subsurface boundaries and other structural features, including geological ones (Pellerin 2002; Porsani et al. 2004; Rubin and Hubbard 2005; Shemang et al. 2011; Wang et al. 2015). Finally, magnetic surveys can be utilized in cases where ferromagnetic objects are buried (e.g., drums) (Meju 2000b; Prezzi et al. 2005; Huliselan et al. 2010; Belghazal et al. 2013; Almadani et al. 2015) while gravimetric ones can be used when density contrasts are present (Whiteley and Jewell 1992).

In the next sections we will briefly describe the principles of common geophysical methods, provide references for in depth study, and discuss case studies of applications in environmental waste management.

Surface Applications

Electrical Resistivity Imaging (ERI)

Electrical resistivity imaging (ERI) aims at determining the spatial distribution of resistivity ρ in the subsurface, typically with the use of four electrode measurements (Rubin and Hubbard 2005). One pair of electrodes is used for current injection and a pair of electrodes is used to measure the potential difference (Reynolds 2011). Multichannel ERI systems allow for the simultaneous measurement of multiple pairs of potential electrodes; most modern instruments allow the automated acquisition of a sequence of measurements, permitting the creation of 2D, and even 3D, images of the subsurface apparent resistivity (Rubin and Hubbard 2005; Çınar et al. 2016; Konstantaki 2016; Ntarlagiannis et al. 2016). Inverse methods can be used to determine the true subsurface resistivity image (Rubin and Hubbard 2005).

A variety of standard electrode configurations have been developed over the years that offer different survey characteristics and can be suited for different applications; in addition, custom made sequences can be utilized that address the specific objectives of the project (Rubin and Hubbard 2005; Reynolds 2011; Tsourlos et al. 2014). ERI measurements are acquired at various electrode spacing and positions to provide information at various lateral and vertical locations of the study area. Typical applications of the ERI methods involve characterization and monitoring for saltwater and contaminant plumes (Mack and Maus 1986; Slater et al. 2000; Slater 2007; Heenan et al. 2015; Ntarlagiannis et al. 2016), mapping and characterization of buried waste, characterization of engineered structures (e.g., landfill boundaries) (Tsourlos et al. 2014), geological characterization (Robinson et al. 2015a, b), and leak detection and monitoring (Johnson and Wellman 2015).

Time Domain-Induced Polarization (IP)

The induced polarization (IP) method is a natural extension of the resistivity methods whereas not only the resistive, but also the capacitive properties of the earth are measured (Rubin and Hubbard 2005; Reynolds 2011). In certain cases, IP surveys offer additional information about the subsurface, while in general it is more time consuming than ERI; it should be highlighted that during IP surveys ERI data are inherently collected.

Field application of the IP method is similar to the ERI method, where four electrodes are used (two for current injection, and two for potential measurement); additional care should be taken to utilize electrode configurations that provide high S/N ratio, and maintain good contact with the ground (e.g., Mwakanyamale et al. 2012). In addition to the voltage difference measured during ERI surveys, in an IP survey the voltage decay with time, after current injection is stopped, is measured. The recorded gradual voltage decrease is a complex function of charge polarization at the interfaces (e.g., fluid-grain) and charge conduction within the fluid and along the grain (Rubin and Hubbard 2005). The IP method has its origins from ore prospecting, specifically for disseminated metallic minerals (Reynolds 2011; Kemna et al. 2012). Advances in instrumentation, along with better understanding of the underlying processes, led to the resurrection of the IP method in the past couple of decades; IP is now more routinely used in environmental, and other near surface geophysical applications, due to the unique sensitivity in interfacial processes (Rubin and Hubbard 2005; Kemna et al. 2012; Revil et al. 2012b; Abdulrahman et al. 2016; Günther and Martin 2016; Ntarlagiannis et al. 2016).

Self Potential (SP)

Self potential (SP), also known as spontaneous potential, is a passive geophysical method that measures naturally occurring electrical field in earth. SP involves only the use of two, or more, nonpolarizable electrodes (Petiau 2000; Linde et al. 2011); no active signal source is used, as implied by the term 'passive'. SP signals can be caused by multiple processes such as electrokinetic mechanisms (Revil et al. 2003, 2012b), temperature gradients (Reynolds 2011; Revil et al. 2012a), and electrochemical mechanisms (Naudet 2003a; Revil 2003; Reynolds 2011); there is still some uncertainty on the exact physical processes associated with SP signal generation (Reynolds 2011).

Common applications of the SP method involve groundwater movement monitoring, cave detection, sinkhole mapping, contaminant delineation, and leak/seepage detection (e.g., dams) (Rozycki et al. 2006; Suski et al. 2006; Arora et al. 2007). Recently the use of the SP method has been suggested for monitoring microbial processes in the subsurface (Naudet 2003a; Arora et al. 2007; Revil et al. 2010); the proposed model is analogous to the classic geobattery model (Sato and Mooney 1960), but the signal generating processes are biotically driven. Limitations of the SP method are sensitivity to cultural geophysical noise, multiple signal sources, use of specialized electrodes, and difficulties with data processing and interpretation (Reynolds 2011).

Refraction Seismic (RrS)

Seismic refraction is a geophysical method that allows subsurface reconstruction based on the travel properties of P- or S-waves (ASTM 2006; Reynolds 2011). Seismic P- and S-waves generated typically on the surface, then propagate through the soil and rock; a seismograph then is used, along with specific sensors (termed geophones) at known distances from the source, to record the P and S waves. Depths to different layers, and P and S velocities can then be calculated based on recorded arrival times. In general, the refraction method assumes that velocity of the layers increases with depth, thickness of the layers is adequate (depends on survey parameters), and the velocity contrast between layers is sufficient. Common applications of the method include depth to bedrock, geological strata thickness, and subsurface structure characterization. Additionally, several geotechnical parameters and in situ elastic moduli (i.e., bulk and shear modulus, poisson ratio, etc.) can be estimated from RrS (Doll et al. 1996; Soupios et al. 2007a; Almadani et al. 2015; Wijesekara et al. 2015; Benson and Yuhr 2016; Valois et al. 2016).

RrS measurements are sensitive to acoustic noise and vibrations. In cases of low velocity layers which violate the basic assumption of conventional refraction seismic, the refraction tomography method should be applied. For higher resolution, the seismic reflection method can be applied. The primary application of seismic reflection method is the accurate determination of depth and thickness of geologic strata in complex structural environment.

Multichannel Analysis of Surface Waves (MASW) and Spectral Analysis of Surface Waves (SASW)

The MASW and SASW are relatively new in situ seismic methods for determining shear wave velocity profiles. The basis of the methods are the dispersive characteristic of Rayleigh waves when traveling through a layered medium. The Rayleigh wave velocity is determined by the material properties (primarily shear wave velocity, but also compression wave velocity and material density) of the subsurface to a depth of approximately 1–2 wavelengths. Longer wavelengths penetrate deeper and their velocity is affected by the material properties at greater depth. The MASW/SASW methods have significant advantages. The near surface (top 10 m) resolution is typically greater than with other methods. Testing is performed at the ground surface, allowing for a less costly measurement than those carried out with the conventional seismic methods (refraction and reflection). The MASW/SASW testing can be used to obtain Vs profiles for earthquake site response of waste disposal sites and determine soil and rock elastic properties (Greenwood et al. 2015; Yin et al. 2015; Anbazhagan et al. 2016; Gouveia et al. 2016; Ramaiah et al. 2016).

Horizontal to Vertical Spectral Ratio (HVSR)

The usefulness of microtremor (HVSR) measurements as a geophysical tool has been presented by Delgado (Delgado et al. 2000b). The method relies on the relationship between [a] the main resonance frequency (f) of a given soil as obtained from the HVSR of microtremors, [b] its thickness (z) as estimated from other geophysical methods (e.g., ERI, RrS) and [c] the average shear velocity (Vs) according to the following equation:

$$f = Vs/4z \tag{1}$$

HSVR is primarily used for seismic hazard mitigation through seismic response analysis of the waste deposition site that could allow prediction of seismic displacements of cover sliding (Zekkos 2005). Applications of the HSVR method, including studies for waste management sites, have been implemented by multiple scientists (Malte Ibs-von and Wohlenberg 1999; Delgado et al. 2000a, b; Parolai et al. 2001; Parolai 2002; Soupios et al. 2007a; Karagoz et al. 2015).

Time Domain (TEM or TDEM) and Frequency Domain (FDEM) Electromagnetic Method

The TDEM method measures the electrical conductivity of soils and rocks by inducing pulsating currents in the ground with a transmitter coil and monitoring the decay of the induced current over time with a separate receiver coil (ASTM 2001); in the frequency domain variant (FDEM) the magnitude and phase of an induced electromagnetic current is measured (ASTM 2001; Reynolds 2011). TDEM and FDEM measurements are ideal to map lateral changes in subsurface conductivity, determine depth and thickness of natural geologic and hydrologic layers, detect and map landfill leachate plumes, monitor seepage from brine pits and saltwater intrusion and determine fracture orientation (Chongo et al. 2015; Soupios et al. 2015; Kourgialas et al. 2016). The advantages of TDEM and FDEM methods are the good lateral and vertical resolution and the extended depth range (from a few meters to 1 km). FDEM methods can provide more accurate subsurface conductivity images when constrained by ERI surveys (Minsley et al. 2012; Briggs et al. 2016). Both methods though have the following limitations, (a) deep measurements require a large transmitter coil for which space may not be readily available, (b) susceptibility to interference from nearby metal pipes, cables, fences, vehicles, and induced noise from power lines, and (c) the effectiveness of electromagnetic measurements decreases at very low conductivities.

Ground Penetration Radar (GPR)

Ground penetrating radar (GPR) uses high-frequency electromagnetic waves to acquire subsurface information (ASTM 2005). Energy is radiated downward into the ground from a transmitter and the reflected/refracted energy is sensed by a receiving antenna. The reflected signals can produce continuous cross-sectional profiles of the shallow subsurface. Reflections of the radar wave occur where there is a change in the dielectric constant or electrical conductivity between two materials. Changes in conductivity and in dielectric properties can be the result of changes in hydrogeology, geology, moisture content, and presence of void spaces; large changes in dielectric properties often exist between geologic materials and man-made structures such as buried utilities or underground tanks. As a result, GPR can be used to provide detailed images of subsurface structures, to map buried waste, and contaminant or saline plumes (Chira Oliva et al. 2015; Iwalewa and Makkawi 2015; Wang et al. 2015; Wijewardana et al. 2015). Measurements are relatively easy to make, allowing for fast spatial coverage, and provide relatively high resolution (depending on the antennae used and ground properties). One important limitation of the method is that the penetration depth in conductive materials (>20 mS/m) such as silts and clays is very limited.

Radio/Audio-Magnetotelluric Methods (RMT/AMT)

The RMT method is an extension of the well-known very-low frequency (VLF) technique to higher frequencies (Reynolds 2011). RMT uses radio transmitters in the frequency range between 10 and 300 kHz, sometimes extended to 1 MHz. The RMT method has been used for waste disposal site characterization (Tezkan et al. 1996, 2000; Zacher et al. 1996; Newman et al. 2003). RMT surveys have been successfully used for waste site characterization, e.g., (Tezkan 1999; Tezkan et al. 2000; Newman et al. 2003). RMT data can be inverted to provide 2D and 3D subsurface reconstruction, with variety of approaches (e.g., the L2 and Laplacian norm of model parameters); generally, a priory information used during the inversion process can help produce more accurate results, especially with depth (Newman et al. 2003).

Magnetic Susceptibility (MS)

Magnetic susceptibility (MS) describes the magnetization of materials under an externally applied field, per unit of the applied field (Huliselan et al. 2010; Bijaksana et al. 2013; Kim et al. 2015). Strictly speaking, MS is the ratio of the material magnetization to the strength of the applied magnetic field; MS typically refers to the volume affected by the external field, and it depends on the magnetic properties of the components. Based on their MS properties materials can be categorized in paramagnetic, ferromagnetic, or diamagnetic. In most sediments elevated magnetic susceptibility values indicate the presence of iron-rich materials. The use of both total magnetic field and magnetic susceptibility measurements allow the detection of ferromagnetic minerals such as pyrite (FeS_2). The measurement of the three orthogonal magnetic field components (magnetic zones), represent the local value of the normal ambient field of the Earth as modified by the remnant magnetization of adjacent sediments (Prezzi et al. 2005; Almadani et al. 2015). The identification of such magnetic zones indicates layers that may have higher permeability and therefore may be potential flow paths for groundwater. Recently MS has been suggested as a proxy for characterizing and monitoring hydrocarbon degradation processes (Atekwana et al. 2014; Jobin et al. 2016).

Borehole Applications

Geophysical methods can be applied on the surface, but also in boreholes (Rubin and Hubbard 2005; Reynolds 2011). Borehole geophysical methods provide continuous profiles, point measurements at discrete depths in a borehole, and cross-borehole tomographic images. Borehole methods provide detailed information with depth without resolution loss as with surface application. Borehole geophysical methods can be performed in single boreholes, in cross hole, and even in multi-borehole configuration.

Crosshole/Downhole Seismic (CS/DS)

For successful remediation of contaminated site an accurate characterization of subsurface geology is required. Currently, the established method for acquiring such information is well log data. Well logs provide very accurate and detailed information on a site's subsurface but are spatially limited, and highly invasive (in contaminated sites well pose the risk of extending contamination problems). Cross hole seismic imaging provides a means to extend geological characterization beyond the borehole, typically in the plane(s) between boreholes (Binley et al. 2002b; Delgado et al. 2002; Rubin and Hubbard 2005; Baker et al. 2015; Sahadewa et al. 2015; Anbazhagan et al. 2016; Dantas and Medeiros 2016). Crosshole and downhole seismic imaging involves the deployment of seismic source and receivers in two—or more—boreholes and/or on the surface, surrounding the area to be imaged. Commonly the seismic wave travel times are measured and then are processed (inverted) using tomographic approaches. Borehole seismic method can be used for characterization, or in time lapse mode for monitoring the progress of remediation projects.

Electrical Resistivity Tomography (ERT)

Surface electrical surveys can be extended by placing electrodes in a single, or multiple, boreholes (Rubin and Hubbard 2005). The electrodes can either be placed permanently, or downloaded for each use, provided the borehole is uncased or PVC lined with sufficient slotted/open intervals. When two or more boreholes are used the suggested term is electrical resistivity tomography (ERT).

ERT offers certain advantages over ERI such as high resolution with depth, and not requirement for surface access (e.g., below buildings). The disadvantages are that boreholes are required, survey area is constrained by the boreholes, and data acquisition and processing might be more complicated and challenging. Very often surface electrodes are combined with borehole electrodes to provide more accurate image of the subsurface.

Cross-borehole ERT has been successfully used for a wide array of applications in different environments. One of the earliest examples of hydrological applications of ERT is Daily et al. (1992) in a study of vadose zone moisture migration due to application of a tracer. Other examples of unsaturated zone studies using ERT demonstrated how three- and two-dimensional ERT can be used successfully to monitor changes in moisture content in unsaturated sandstone (Kemna et al. 2000, 2004; Binley et al. 2002a; French et al. 2002).

Borehole Electromagnetic (BEM)

The electrical properties of the subsurface can also be investigated through EM induction in borehole configurations (BEM). As with ERT applications, BEM can be applied to single borehole configuration as well as in tomographic mode between two and more boreholes. Single borehole logging, the most common approach, can provide information on the vertical distribution of conductivity with high resolution (Williams et al. 1993).

Typical application of BEM include detection of [a] screened intervals in groundwater monitoring wells, [b] conductivity changes outside of cased wells, and [c] plume monitoring in the vadose zone (Dawson 2002). Although the BEM method does not offer the resolution of ERI/ERT, it does not rely on direct contact with the formation, is not limited to fluid filled boreholes and can provide rapid results.

Application in Landfills

Electrical Methods

Geoelectrical imaging techniques can be utilized for a variety of characterization and monitoring purposes in landfills and waste management processes (Klefstad et al. 1977; Aristodemou and Thomas-Betts 2000; Cassiani et al. 2006; Chambers et al. 2006; Grellier et al. 2008; Carlo et al. 2013; Vargemezis et al. 2015; Yin et al. 2015; Abdulrahman et al. 2016; Ntarlagiannis et al. 2016). Regulated waste management, and unregulated waste dumping, will result in significant changes to subsurface electrical properties that can be measured with geoelectrical techniques.

As it pertains to landfills, geoelectrical methods can provide subsurface images of conductivity distribution that can be linked (interpreted) to parameters of interest such as contaminant concentration gradients (e.g., leaks), structural integrity (e.g., fractures, clay caps), geological description of the surrounding area (e.g., faults, lithology), and extent of buried waste (Dawson 2002; Soupios et al. 2007a; Kemna et al. 2012; Revil et al. 2012b; Genelle et al. 2014; Tsourlos et al. 2014; Vargemezis et al. 2015). Furthermore, geoelectrical methods can be used as a cost-efficient method for long-term monitoring (Heenan et al. 2015), either for leachate leaks or for biogas production (Soupios et al. 2007a).

Leachate Monitoring

Geoelectrical methods have been routinely used to monitor for leachate leaks in landfills. Leachate monitoring involves [a] liner leak detection, and [b] contaminant plume monitoring methods. Liquid waste in landfills is generally associated with high ion concentrations, resulting in high conductivities. The conductive leachate can then be used to identify holes in the bottom liners and any movement of the plume past the landfill boundaries (Slater et al. 1997; Cassiani et al. 2006; Clément et al. 2010; Tsourlos et al. 2014).

Bottom liners in landfills are used to keep the waste from interacting with the surrounding environment, effectively electrically isolating the landfill. The basic principle of leak detection in landfills relies on this property: electrical isolation of the landfill as long as there are no holes in the liner. The integrity of the liner can be simply investigated by testing if current can move past the liner (Binley et al. 1997; Carlo et al. 2013; Tsourlos et al. 2014). There are two common methods used to test for leaks in landfills: [a] the roving (moving) electrode method (Fig. 1), and [b] permanent monitoring installation (Reynolds 2011). In the former case a pair of electrodes is used to inject current placed outside the liner, and a pair is used to detect any signal generated inside the landfill (Tsourlos et al. 2014) (Fig. 1). Response is expected only if there is a hole in the liner, allowing the current to penetrate; by moving the measuring pair of electrodes the location of the hole can be located (Fig. 1). Variations of the method include the use of one roving measurement electrode, with the second being placed outside the landfill (Reynolds 2011). In many newer landfills a monitoring network is established by permanently installing electrodes below the bottom liner; in this case the potential is being measured between different electrodes (no need for roving electrodes) and the monitoring can be continuous, and is usually automated (Reynolds 2011). ERI leak monitoring is not only limited to bottom liners, but can be successfully used to map landfill caps, and identify any damage (Genelle et al. 2014).

Landfill leachate (municipal, and mine waste piles) is generally very conductive due to elevated total dissolved solids (TDS) and high ion concentration. As a result, leachate plumes are prime targets for geoelectrical methods. Indeed, ERI has been routinely used for monitoring of leaks in active, closed, and abandoned landfills

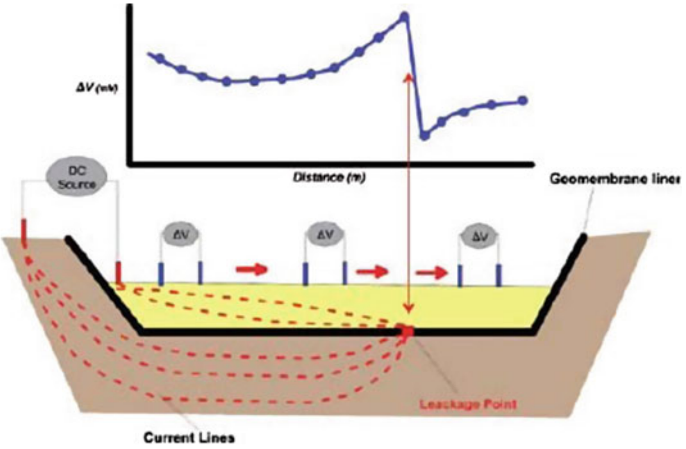

Fig. 1 Schematic showing the basic principle for liner hole detection in landfills (from Tsourlos et al. 2014)

(Greenhouse and Harris 1983; Greenhouse and Monier-Williams 1985; Bevc and Morrison 1991; Blum 1998; Chambers et al. 2006; Soupios et al. 2007a, b; Tsourlos et al. 2014; Ntarlagiannis et al. 2016). Tsourlos et al. (2014) used ERI over a closed landfill and was able to identify leaks through fractured rock; they were successful in reconstructing the leaking fracture zones based on intensive ERI characterization (Fig. 2). Ntarlagiannis et al. (2016) recently showed that ERI and IP can be successfully utilized for temporal leachate monitoring; they monitored an olive oil mill waste deposition pit for 15 months showing that conductive leachate is leaking from the pit at times of high waste load. Furthermore, ERI can be used to monitor water fluxes in landfills including leachate recirculation in bioreactor landfills (Guérin et al. 2004; Grellier et al. 2008); in the latter case ERI appears to be a very valuable tool for optimizing leachate recirculation, hence improving bioreactor landfill performance (Rosqvist and Destouni 2000; Barlaz and Reinhart 2004; Guérin et al. 2004; Rosqvist et al. 2005; Grellier et al. 2008; Valois et al. 2016).

ERI and IP are also used to reconstruct the subsurface structure of landfills. ERI has been successfully used to map the spatial distribution of parameters of interest, such as TDS and chloride content (Meju 2000b; Gazoty et al. 2012). Furthermore, the inner structure of the landfill waste can be described with electrical methods (Soupios et al. 2007a, b; Tsourlos et al. 2014; Çınar et al. 2016) (Fig. 3). Additionally, information on the structural integrity and the surrounding geology can be acquired. Such information can be used during the landfill design, and construction, but also for monitoring purposes during operation and post closure (Gazoty et al. 2012). It should be noted that although commonly only the ERI method is used since it is easier to apply (Ntarlagiannis et al. 2016), IP can provide a wealth of additional information, sometimes critical (Weller et al. 2000; Placencia-Gómez et al. 2010, 2014; Villain et al. 2011; Gazoty et al. 2012; Günther and Martin 2016; Ntarlagiannis et al. 2016).

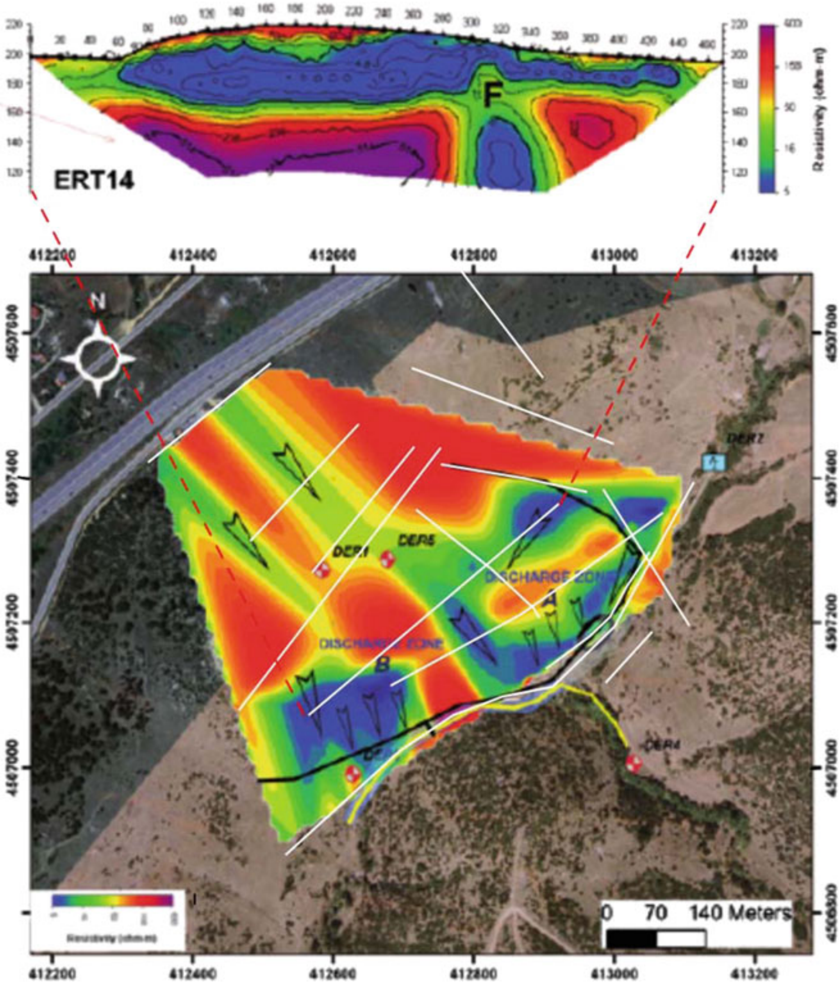

Fig. 2 2D and 3D resistivity images from and ERI survey over a landfill. ERI was successful to identify fractures (*black arrows*) that allow the landfill leachate to pollute nearby streams. *White lines* show the location of the ERI surface survey (*red dotted lines* show the location of the 2D *panel*). Modified from Tsourlos et al. 2014

The SP method's sensitivity to groundwater movement—including contaminant plumes, direct link to redox gradients typically found at plume boundaries, and easy and cost-efficient application make it an attractive option for landfill monitoring and characterization (Fig. 4). Many researchers identified SP as a potential contaminant plume monitoring tool (Weigel 1989; Hämmann et al. 1997; Buselli and Lu 2001; Nimmer 2002; Nyquist and Corry 2002; Naudet 2003a; Revil et al. 2003; Maineult et al. 2006; Arora et al. 2007). If properly applied SP data can provide information on groundwater movement, identifying the flow direction of possible contaminant

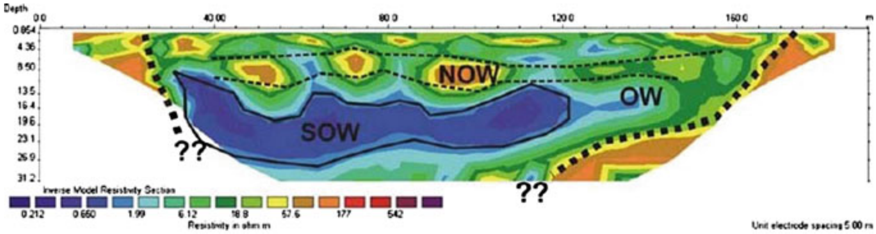

Fig. 3 Inverted ERI image showing resistivity changes that allow subsurface waste characterization. SOW (saturated organic waste), OW (organic waste), and NOW (non-organic waste) highlight areas interpreted to have saturated organic, unsaturated organic, and inorganic waste respectively. From Soupios et al. (2007a)

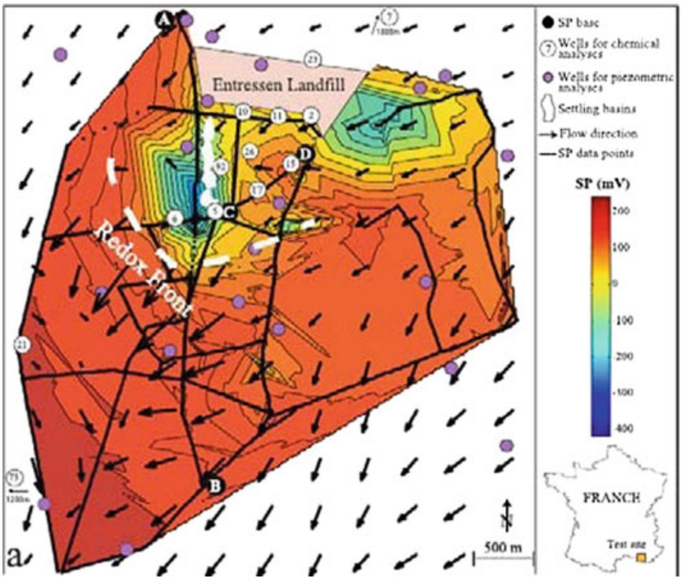

Fig. 4 SP map around the Entressen landfill; SP represents residual values after the electrokinetic contribution has been removed. SP, in agreement with redox measurements, shows a sharp anomaly at the contaminated plume front (from Naudet 2003a)

plumes. Moreover, residual SP signals have been linked to redox processes in contaminated areas, including landfills (Nyquist and Corry 2002; Naudet 2003a); this observed link is an area of active research where quantitative interpretation is the objective. One very promising model is the biogeobattery model, introduced over a decade ago that provides a direct link between microbial degradation processes, and observed SP signals (Naudet 2003a; Arora et al. 2007; Revil et al. 2010).

Summarizing, geoelectrical methods can be used to convincingly demonstrate how a proposed landfill will be sited, designed, constructed, operated, closed, and post-closure cared in order to protect the groundwater resources, public health, and the environment (Soupios et al. 2007a, b).

Electromagnetic (EM) Methods

As discussed earlier degradation of domestic putrescible solid waste, and the accumulation of liquid wastes into landfills can generate conductive leachate that fills the pore spaces; this conductive leachate can be imaged with EM methods such as FDEM and TDEM (Hutchinson 1995). In general, EM surveys are used for the rapid characterization of landfill's boundaries (Hutchinson and Barta 2000; Pellerin 2002; Monteiro Santos et al. 2006; Belmonte-jiménez et al. 2014; Wang et al. 2015; Ammar and Kruse 2016; Jodeiri Shokri et al. 2016), mapping different waste (organic, inorganic, etc.) (Mack and Maus 1986; Stenson 1988; McQuown et al. 1991; Bisdorf and Lucius 1999; Stanton and Schrader 2001; Soupios et al. 2005, 2007a, b) and detection of leachate contaminant plumes (Mack and Maus 1986; Walther et al. 1986; Hall and Pasicznyk 1987; Fawcett 1989; Russell 1990; Olhoeft and King 1991). Joint processing of geophysical data can lead to improved subsurface characterization; recently it was shown that subsurface reconstruction from FDEM can be enhanced when constrained by ERI data collected in a very small part of the surveyed area (Minsley et al. 2012; Briggs et al. 2016). Based on Hutchinson and Barta (2000), there is a linear relationship between measured terrain conductivity and waste thickness; this relationship can be used to estimate the bulk waste volume in a landfill.

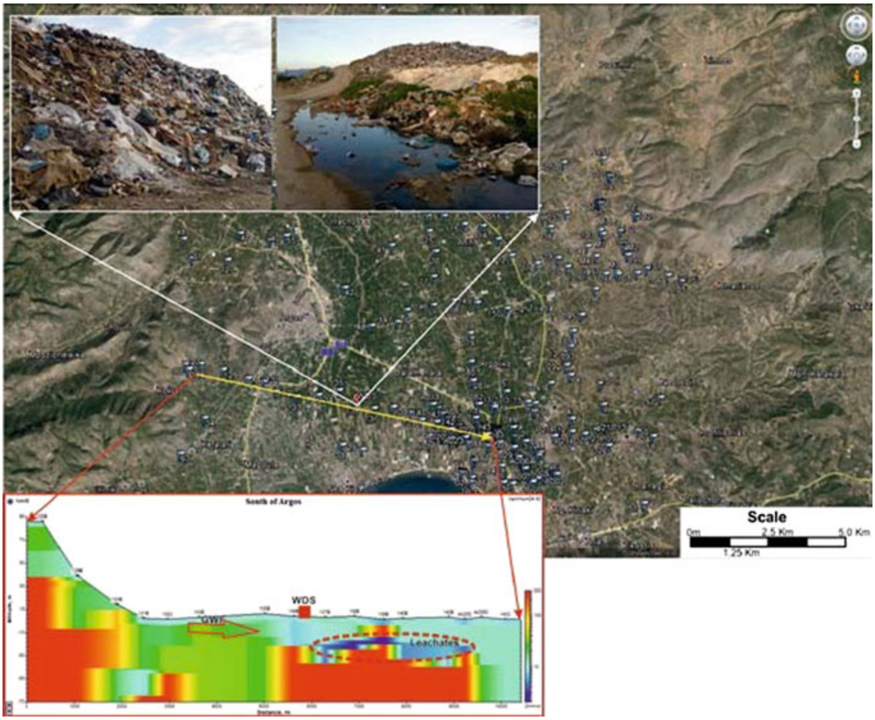

Fig. 5 The conductive anomaly (leachate) below the Argos landfill as identified by TEM survey

The depth of buried waste tends to increase with landfill operation. This process leads to increasing compaction of buried waste, which in turn changes the subsurface characteristics of the landfill (e.g. pore space and saturation). GPR is sensitive to such changes, and consequently can be used for waste age classification (Splajt et al. 2003). As other EM methods, GPR can be used for contaminant plume identification and monitoring (Davis and Annan 1989; Scaife and Annan 1991; Annan 1992; Nobes 1996; Sauck et al. 1998; Green et al. 1999; Atekwana et al. 2000; Sauck 2000; Orlando and Marchesi 2001; Porsani et al. 2004). Pujari et al. (2007) jointly used EM and GPR to map the subsurface of a landfill; they were successful in mapping clay depressions, and conductive pathways in the underlying limestone.

The TEM method has been used in environmental and hydrogeologic studies over the last couple of decades. In 2013, the TEM method was used to study the hydrogeological properties of the Argolis basin in Peloponnesus (Greece). One TEM profile was performed over the main waste disposal site of the city of Argos; this profile revealed a subsurface conductive feature at 25 m depth, extending over 3 km (Fig. 5). This conductive anomaly was interpreted as contaminated leachate, that was later confirmed by direct sampling and geochemical analysis.

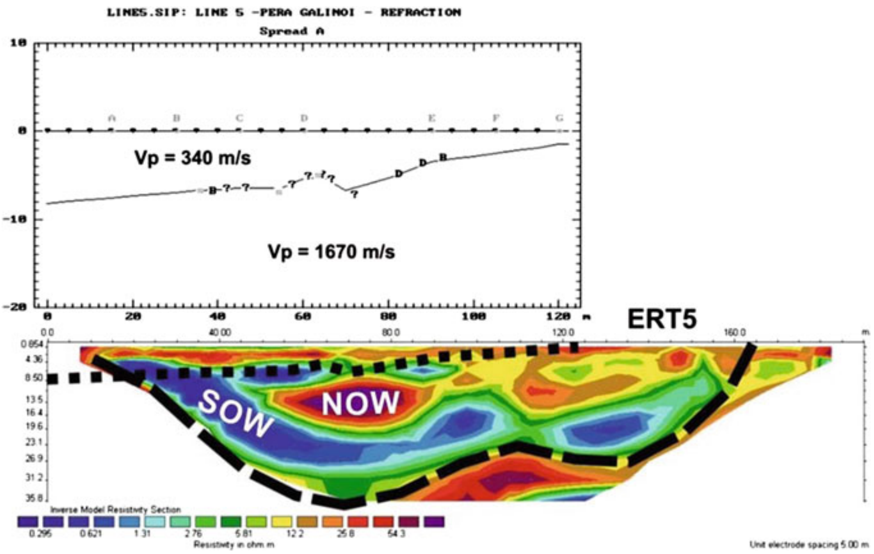

Fig. 6 Comparison of the refraction seismic (*upper*) with the ERI image (*lower*). The results are in good agreement (Soupios et al. 2007a)

Seismic Methods

The application of seismic methods can provide valuable information for the subsurface structure of a landfill. Seismic data interpretation should be performed with extra caution due to the heterogeneity that usually characterizes landfills. Common applications include characterization of the structural integrity and local geology, and mapping of the lateral continuity of buried waste (Rodriguez 1987; Slaine et al. 1990; Boyce et al. 1995; Doll et al. 1996; Cardarelli and Bernabini 1997; Doll 1998; Granda and Cambero 1998; Lanz et al. 1998; Green et al. 1999; Murray et al. 1999; De Iaco et al. 2003; Soupios et al. 2007a, b). Soupios et al. (2007a, b) applied an integrated suite of geophysical methods to characterize a landfill. The collected seismic and electrical data are in very good agreement as evidence in Fig. 6. The subsurface structure is characterized by an upper layer

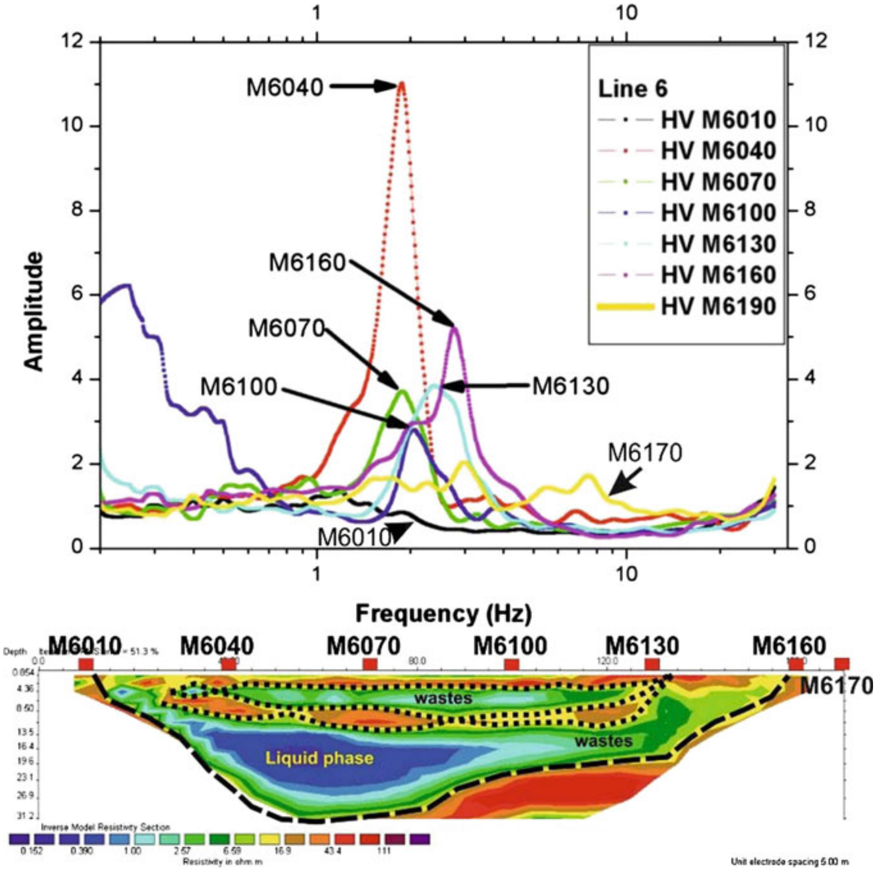

Fig. 7 HVSR measurements show a characteristic frequency peak clearly associated with waste thickness. From Soupios et al. (2007a)

($\sim$5 m thickness) with high resistivity/low velocity characteristics; below the top layer, and up to 20 m depth, we can observe a low resistivity/high velocity layer consistent with saturated conductive waste.

Possible faults and fracture zones may act as pathways for groundwater and contaminant transport to deeper horizons and the aquifer. In most cases landfills are characterized by much lower velocities (P wave velocity may range from 180 to over 700 m/s) than the surrounding sediments (Knight et al. 1978; Calkin 1989; Sharma et al. 1990), thus the seismic contrast is high and seismic refraction methods are a good choice for outlining their borders. There are only few successful applications of seismic reflection surveys across landfills (Pasasa et al. 1998). The main reasons that seismic reflection techniques may fail to be applied in landfill characterization are: (a) high levels of scattering and anelastic attenuation cause unconsolidated wastes to be generally poor transmitters of seismic waves, (b) source-generated noise (i.e., direct, refracted, guided, and surface waves) may mask shallow reflections (Robertsson et al. 1996; Roth et al. 1998), and (c) strong lateral velocity variations (inhomogeneous environment) may inhibit the recording of hyperbolic-shaped events, making identification of reflections difficult. Recently, Konstantaki et al. (2015), Konstantaki (2016) managed to apply successfully S-wave reflection seismic to map in high-resolution heterogeneities in a landfill and to estimate the density changes from S-wave velocity analysis using specific acquisition parameters and special processing steps during the velocity analysis (Konstantaki 2016).

Joint acquisition of multiple geophysical data, along with direct sampling and geotechnical data can enhance landfill characterization. Soupios et al. (2005, 2007a, 2008) highlights the synergistic use of multiple geophysical methods by interpreting shear velocity data, using Eq. 1, estimating the needed parameters with ERI (basement depth (z)) and HSVR (main resonance frequency). Shear velocities when then used to develop the stiffness model of the landfill, needed for calculating the response of the landfill in earthquakes. Figure 7 clearly shows that the estimated amplitude is proportional to the waste composition and thickness. The first (M6010) and the last (M6170) measurements have almost flat response (located at the outcrop of the bedrock), while all the other measurements (M6040-M6160) have resonance frequency that appears as a single pick in the spectrum. The amplitude (amplification) of M6040-M6160 sites depends on the thickness and composition of the underlying waste.

Information such as Vs model and/or amplification of a site can be safely used by the engineers for a detailed estimation of seismic site response analysis and the prediction and protection of seismic displacements of a landfill (Kavazanjian and Matasovic 1995; Kavazanjian et al. 1996; Augello et al. 1998; Matasovic and Kavazanjian 1998; Zekkos 2005) or other correlated environmental problems (landfill failure and uncontrolled release of the contaminants). A successful example is described in Soupios et al. (2007b) where the synergistic use of ERI and HVSR identified a subsurface karstic void in a location where the leachate collecting tanks (large static load) where to be placed; the engineers updated the landfill geotechnical design based on the geophysical information. The application of ambient noise (HVSR) measurements in similar cases is very promising since this method is cost-effective, nondestructive, and easy to apply (Soupios et al. 2007a, b).

Concluding Statement

Currently used methods for landfill characterization and monitoring typically rely on a network of geotechnical and/or monitoring wells; this approach is expensive, invasive, and spatially and temporally limited. The complementary use of noninvasive geophysical methods offers unique advantages that could significantly improve waste management practices. We should highlight that geophysical methods are not intended to replace well monitoring/characterization, but to enhance and optimize existing protocols (including cost reduction).

All geophysical methods discussed can be used during the design, construction, operation, and post-closure monitoring of a landfill site. Synergistic use of the methods can provide information on almost every aspect of a waste management site, from the geological setting and the structural integrity, to leachate monitoring and recirculation, to leak detection, and liner and cap integrity monitoring. Care should be taken on geophysical data interpretation, and joint processing of geotechnical, geochemical, and geophysical is recommended.

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