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T1.3 Deliverable – SWOT analysis of LF characterisation methods

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WP T1 ENHANCED INVENTORY FRAMEWORK (EIF)

AT.1.3 Uliège deliverable- SWOT analysis of LF characterisation methods

The study of landfills is conventionally carried out using intrusive methods such as core drilling or trenching, combined with various laboratory analysis (e.g. composition, humidity, temperature, organic content, microbiology) (e.g. Reddy et al., 2011; Zornberg et al., 1999). This methodology is time-consuming and costly. It often provides sparse and local information which is difficult to extrapolate between boreholes located less than 30 m apart (Zornberg et al., 1999). Geophysical methods are generally more cost-effective than drillings and sampling when applied to large areas (Table 1). These techniques are also non-invasive when performed from the soil surface and can reduce health and safety issues compared to conventional drillings (Bouazza and Kavazanjian Jr., 2000; Meju, 2000a). In addition to odor problems and cuttings removing, the landfill gas emitted by the discharge is composed of methane – which is explosive beyond 5% and flammable beyond 15 % (e.g. Cheremisinoff, 2003) – as well as carbon dioxide which can cause asphyxiation. Geophysical imaging may provide insight of physical properties of the subsurface in two or three dimensions, making it possible to determine the geometry (size, shape and volume) of the deposit and the internal characteristics of the waste mass (composition, humidity, temperature, compaction, density). The geophysical signature of the waste material generally contrasts with the characteristics of the surrounding medium, so that the geophysical prospecting methods can be used to characterize the extension, the volume and filling of landfills. Most of the time, landfills are characterized by low densities and low seismic wave propagation velocities (related to the nature of the waste and their weak compaction compared to the host formation). Similarly, the electrical resistivity of landfills is generally low due to the high electrical conductivity of the leachate and the increase in temperature due to biodegradation of the waste.

<p style="text-align: center;">Strength</p> <ul style="list-style-type: none"> - Non invasive or less invasive - Cost effective - Spatial coverage - No need for long training for EM and MAG mapping methods 	<p style="text-align: center;">Opportunities</p> <ul style="list-style-type: none"> - Some methods can be used on covered landfill (at least as pre-investigation study) - Reduced risks (gas, drilling, trenching, etc.)
<p style="text-align: center;">Weakness</p> <ul style="list-style-type: none"> - Indirect measurement (to be interpreted, converted into the useful information) - Lower resolution of surface methods - Non-unique interpretation - Need for trained peoples 	<p style="text-align: center;">Threats</p> <ul style="list-style-type: none"> - Potentially misleading geological context - Non-uniqueness - Influence of technical infrastructures on the site, applicability in urban areas.

Table 1 : Strength, Weakness, Opportunities and Threats related to the use of geophysical methods for landfill investigation.

Waste deposits are characterized by various and heterogeneous geophysical signatures. We investigated the suitability of a large variety of geophysical methods (electric, electromagnetic, seismic, magnetometric and gravimetric) for the study of landfills. The geophysical characteristics (electrical resistivity, chargeability, magnetic susceptibility, density, seismic velocity) vary from site to site depending on the nature of the stored waste (organic, inert, and metal) and the waste deposit method (compaction or controlled infiltration). For the determination of the extension of a landfill (both horizontal and vertical); the geophysical characteristics of the host formation should also be considered in order to verify that strong contrasts of the geophysical parameter measured are expected. Relevant physical properties values for MSW deposit and typical host formation are summarized in Table 2, which presents the geophysical methods investigated during the literature review and their objectives. Some limiting or favoring factor such as site size, acquisition speed and cost are also indicated.

Papers cited in literature review from 2016 (Dumont, 2016)	Geophysical survey objectives				Choice parameters			
	Extension	Depth	Composition, structure Water content	Biodegradation activity (T°, redox)	Bulk(geop)physical property	Relevant information	Pros	Cons
ERT	50				Electrical resistivity	Water/Leachate content Pore fluid conductivity, temperature, porosity, lithology	Sensitive to many factors Relatively fast Good vertical and horizontal resolution Versatile Large covering Useful for monitoring	Minimally invasive in surface measurement mode (require planting electrodes) Require good electrical contact with soil Geomembrane in landfill impedes electrical current flow Depth of investigation varies with the resistivity of media
IP	17				Chargeability	Waste composition (metals, organics, wood, plastics), clay, lithology	Sensitive to many factors Relatively fast Good vertical and horizontal resolution Flexibility of use Large covering Useful for monitoring Allow to remove certain ambiguities related to ERT results.	Minimally invasive in surface measurement mode (require planting electrodes) Require good electrical contact with soil Geomembrane in landfill impedes electrical current flow Time consuming More difficult to interpret than ERT
EM	16				Electrical conductivity and magnetic susceptibility	Water/Leachate content Pore fluid conductivity, temperature, porosity, lithology, ferrous materials	Easy to deploy Sensitive to small variations of electrical conductivity Large extension Easy to interpret Low cost	Signal calibration/validation is non-trivial on a landfill Signal disturbed in the vicinity of metallic fences, buildings, pipes, etc. Sensitive to soil humidity and temperature variations
SP	9				Electrical charges and electrical conductivity	Organic material, waste maturation state, metallic objects, flow in porous media	Low cost large extension Relatively fast	Many sources of noise Requires non-polarizable electrodes Difficult to interpret
Magnetometry	12				Magnetic susceptibility	Magnetic materials (buried drums, pipes...)	Fast coverage Easy to deploy Low cost Large coverage	Signal disturbed in the vicinity of metallic fences, pipes, power lines, etc. Non-unique solution which makes the differentiation of objects difficult Sensitive to temporal variations of magnetic field
HVNSR	3				Seismic velocities (elastic moduli, density)	S-wave velocity, Deposit thickness	Low cost Easy to deploy	Sensitive to anthropogenic noise Only punctual information

Prior interest

Second interest	MASW	6	Yellow	Yellow	Green	Red	Seismic velocities (elastic moduli, density)	Compaction (S-wave velocity), density	Easy to deploy Relatively fast acquisition Easy to interpret Less sensitive to noise than other seismic methods (higher S/N)	Initial assumptions may not be valid in a landfill and can induce high uncertainties in the final model Difficult to detect small layers
	GPR	3	Yellow	Red	Yellow	Red	Dielectric constant and electrical conductivity	Buried, structures, water content, salinity, porosity, lithology	Method with the highest resolution Fast coverage Easy to deploy Large coverage	Low depth of investigation in conductive media Difficult to interpret when numerous reflectors
	Gravimetry	4	Yellow	Red	Yellow	Red	Density	Waste density, voids detection	Low cost	Time consuming Density hypothesis may lead to high uncertainty of thickness estimation Data processing
	Refraction Seismic	5	Yellow	Yellow	Yellow	Red	Seismic velocities (elastic moduli, density)	Compaction (P- or S-wave velocity), density, saturation	Seismic velocity has a direct connection to mechanical properties of the subsurface Fast acquisition Little processing	Scattering might hide refractions of interest Difficult to use in noisy environments (poor S/N) Sensitive to weather conditions (wind, rain) Seismic velocity must increase with depth Difficult to detect small layers Require large source-receiver offsets
	Reflection seismic	7	Yellow	Yellow	Yellow	Red	Seismic velocities (elastic moduli, density)	Compaction (P- or S-wave velocity), saturation, object with density contrast	Can image heterogeneities within the waste body	Scattering might hide reflections of interest. Data processing may be time consuming Expensive Difficult to interpret

Table 2 : Main geophysical methods for landfill investigation including main interest of the methods, sensitivity parameters and favouring/discouraging factors. In green: primary method, in yellow: may be used but not the best approach, in red: unsuitable .

Value of individual geophysical methods:

- Electrical methods

Electrical methods are particularly well suited to delineate the lateral extent of a landfill given the strong resistivity contrasts that exist between the waste mass and the natural formation. The electrical resistivity of landfills is generally low due to the high electrical conductivity of the leachate and the increase in temperature due to biodegradation of the waste. In saturated media, many authors (e.g. Bernstone et al., 2000; Dumont et al., 2016; Grellier et al., 2007; Meju, 2000a; Naudet et al., 2012), have shown that the electrical resistivity of waste is generally between 0.5 and 30 Ωm . In unsaturated zone, the electrical resistivity is several dozen Ωm , or even less in the presence of metal objects, garden waste (with high water retention) or ashes (Bernstone et al., 2000). In terms of contrast between MSW and host formation, various authors (e.g. Bernstone et al., 2000; Chambers et al., 2006; Dahlin et al., 2010; Naudet et al., 2012) have shown that the natural environment resistivity is often one or two orders of magnitude higher than humid MSW resistivity, depending on the type of geology in place (soft or indurated soil, saturated or unsaturated). The most common natural sediment presenting a similar signature is clay. Doll et al. (2001) have also mentioned possible confusion with evaporite. The influence of the moisture content, pore fluid conductivity and waste temperature often dominate the other contributions for electrical properties, and therefore appears to control the distribution of the electrical resistivity of solid waste. An example of this phenomenon is shown by Chambers et al. (2006), whose electrical images show little variation in the saturated zone despite the buried waste have quite different electrical characteristics (matrix resistivity). In the same vein, Bernstone et al. (2000) did not identify possible correlations between waste composition and distribution of electrical resistivity on their experimental site. It is therefore advisable to use a complementary method to discriminate the influence of different waste compositions.

Electrical resistivity tomography (ERT)

The electrical resistivity is strongly influenced by the presence of leachate given the very high electrical conductivity of the latter, so that even for “low” water contents of 10-30%, the resistivity of the medium is very low (e.g. Bernstone et al., 2000; Dumont et al., 2016; Grellier et al., 2007; Imhoff et al., 2007; Shihada et al., 2013). The resistivity contrast between the saturated zone (or at least levels with free leachate) (0.5-20 Ωm) and unsaturated (tens of Ωm) is relatively large and often detected using electrical resistivity tomography (e.g. Bernstone et al., 2000; Chambers et al., 2006; Naudet et al., 2012; Soupios et al., 2007). In the context of bioreactor landfills, water content information derived from ERT investigation helps to focus waste humidification efforts on dry domestic waste. Time-lapse ERT can be used to monitor changes linked to water content variation during recirculation (Audebert et al., 2014b; Clément et al., 2011c, 2010a, Grellier et al., 2008, 2006a; Guérin et al., 2004; Morris et al., 2003).

The electrical resistivity tomography can detect the borders of a landfill. In the literature, the transition between the host formation and the waste deposit is clearly depicted (Bakker et al., 2008; Bergman et al., 2008; Frid et al., 2008; Gazoty et al., 2012; Naudet et al., 2012; Soupios et al., 2007). For instance, Chambers et al. (2006) showed that an electrical profile acquired through the presumed limit of the landfill (border of a former quarry) exhibits a strong change in electrical resistivity at that location (<10 Ωm in the landfill and > 100-200 Ωm out of the landfill). However, in the special case that electrical resistivity of underlying soil is similar to that of leachate, accurate observation of the boundary between waste disposal and soil presents a challenge (Frid et al., 2008). A field example of landfill installed in former clay and gravel quarry is given in Carlson and Scott (2004). The transition is sharp if no water escapes from the deposit site. When leachate can leave the deposit area (no synthetic liner), the resistivity change at the downstream border is gradual or conductive anomaly is detected well beyond the limit of the waste disposal site (e.g. Chambers et al., 2006). This observation would be a

sign of infiltration of leachate into the host formation. Sometimes, highly resistive anomalies suggest the occurrence of concrete or inert structural elements on the perimeter of the site (Bavusi et al., 2006).

The bottom geometry and sometimes the depth of some landfills has been successfully evaluated. For example, Bavusi, Rizzo, and Lapenna (2006) have shown a clear transition between the electrical resistivity of solid waste ($<100 \Omega.m$) and the underlying soil in place ($> 300 \Omega.m$) at a depth 6 meters, the known level of the bottom membrane HDPE. Other similar studies have shown a sharp transition between the solid waste and the soil in place (electrical contrasts were high) (Auken et al., 2011 (10m); Bergman et al., 2008 (25m); Dahlin et al., 2010 (25m); Naudet et al., 2012 (25-30m)). The difficulty in estimating the exact depth of the waste deposit with the ERT method is relayed by many authors (e.g. Bernstone et al., 2000; Chambers et al., 2006; Doll et al., 2001; Naudet et al., 2012). This could be related to the investigated site feature (no sharp contrast at the bottom of the landfill) or be intrinsic to the ERT method. Infiltration of conductive leachate in the soil results in a lower resistivity contrast between the waste and host formation (e.g. Bernstone et al. 2000). Moreover, even if a resistivity contrast exists and can be imaged, its exact depth is generally not guaranteed, as a consequence of the loss of resolution with depth and the equivalence phenomenon of the ERT method

Induced potential tomography (IP)

The simultaneous acquisition of chargeability data is sometimes implemented (e.g. Carlson, Mayerle, and Zonge 1999). The chargeability signature of municipal waste deposits is emphasized by many authors (Aristodemou and Thomas-Betts, 2000; Auken et al., 2011; Bavusi et al., 2006; Bergman et al., 2008; Carlson et al., 1999; Dahlin et al., 2010; Gazotti et al., 2012). Chargeability anomalies reach hundreds of mV and waste material contour is well depicted in both chargeability and normalized chargeability inverted section (e.g. Dahlin, Rosqvist, and Leroux 2010). The high values of chargeability are often attributed to the presence of metal scraps (Angoran et al., 1974; Aristodemou and Thomas-Betts, 2000; Bavusi et al., 2006) that results in the electrode polarization phenomenon. However, some authors also explain high chargeability in waste deposit by organic material¹ content (Aristodemou and Thomas-Betts, 2000; Leroux et al., 2010), wood content (Thierry et al., 2001) or the layering of plastic sheets that would act as electric capacitors (Carlson et al., 2001). Since the IP signal is not conditioned by the presence of large metal objects, the method is useful for the delimitation of non-metallic buried waste that cannot be detected by magnetometer (Carlson et al., 1999; Carlson and Scott, 2004).

A joint interpretation of electrical resistivity tomography and induced potential is particularly useful to differentiate waste of different nature (e.g. Household organic waste, industrial, clinker). Bavusi, Rizzo, and Lapenna (2006) interpreted zones of high chargeability ($> 50 \text{ mV/V}$) and low electrical resistivity ($<20 \Omega.m$) as being associated with the presence of metallic waste saturated with leachate. Leroux et al. (2010) showed that waste deposits and gypsum deposits have the same type of resistivity response, but gypsum has a much smaller IP response. Dahlin et al. (2012) have also shown the benefits of the combined use of resistivity and IP in the differentiation of industrial waste such as mixtures rich in non-ferrous metals, light fractions from the shredder (wood, plastics, rubber and textiles, but also metals in varying proportions; Gyllenhammar et al., 2011) relative to a reference natural ground. The waste composition differentiation is more difficult for waste deposits composed solely of MSW.

Generally, a sharp chargeability transition is observed between the solid waste and the natural soil (e.g. Carlson, Mayerle, and Zonge 1999; Dahlin, Rosqvist, and Leroux 2010). While the host formation is characterized by a very low chargeability (except for clays and mineralized rocks) and tabular or uniform resistivity, municipal waste landfills present chargeability anomalies up to 10-100 mV and irregular resistivity (Carlson et al., 1999).

¹ The possible effect of waste and leachate organic content on the chargeability signal is based on several studies on organic material – clay interaction (Olhoef, and King, 1991; Vanhala, 1997)

When it comes to landfill extension and depth assessment, the induced polarization method reduces the risk of misinterpretation (highlighted for the ERT method) related to leachate percolating into the host formation. The combined use of the electrical resistivity and the induced potential shows areas of high chargeability defining the extension of the discharge and low resistivity areas correlated to the leachate plume (e.g. Dahlin et al., 2010). However, some authors also suggest that leachate escaping in the host formation may have an IP signature, preventing the precise delimitation of the extension of the site. Indeed, Organic-clay interaction (Aristodemou and Thomas-Betts, 2000; Olhoeft, and King, 1991; Vanhala, 1997), the salinity-clay interactions (Ustra et al., 2011) and, the presence of heavy metals in suspension in the leachate (Abu-Zeid et al., 2004) may induce an IP signal.

The **spontaneous potential (SP)**

The **SP signal** measured over a contaminated site may be associated to different sources as the electrokinetic potential (low if the water movements are limited, but may be significant outside the landfill), electrodiffusion potential and the redox potential. Due to the low permeability of the landfill soil, it is likely that the electrical potential measured reflects almost exclusively the redox potential of the organic matter contained in the buried waste.

This contribution associated with redox phenomenon is not fully understood. Some authors (e.g. Nyquist and Corry 2002; Naudet et al. 2003; Bavusi, Rizzo, and Lapenna 2006) have shown negative abnormal SP signal at the waste dump location or in the reducing contaminant plume (the reference electrode is generally placed in non-polluted area, upstream of the site). Naudet et al. (2012) have shown that spontaneous potential anomalies are mainly controlled by the biodegradation of waste, with lower values at the more mature cells (-15 mV) and positive values in younger cells (5 mV). Some negative SP anomalies appear to be correlated with areas of low resistivity highlighted by the electrical resistivity of tomography and interpreted as leachate accumulation zones (Bavusi et al., 2006). Naudet et al. (2011) also mention that SP values could also result from cover layer thickness and clay content. If the results are promising in terms of site mapping, partial and inhomogeneous site coverage during the SP campaign in these studies did not allow the authors to map all the landfill boundaries. However, this method has been used for the study of leachate leaks in natural environments. The work of Naudet et al. (2003) et Linde and Revil (2010), for example, highlighted the opportunity to delimit the extension of a contamination plume (with a high organic content) in an aquifer.

- Electromagnetic methods

Electromagnetic surveys (EM)

The electromagnetic mapping method offers a fast and relatively cheap method to access the site electrical resistivity/conductivity, and is often used for preliminary investigation on large landfill. Soupios et al. (2007) used the **single frequency EM method** (EM31 GEONICS, 9.8 kHz) on a 12.5 ha-wide landfill on the island of Crete. The electrical conductivity of waste (120-200 mS/m) contrasts with the one of the host sediments (3-20 mS/m). Inside the waste deposit, higher electrical conductivity values are also correlated to a greater thickness of waste. EM methods (combined with radar and magnetometric methods) were also used by De Iaco et al. (2003) to locate the boundaries of a landfill. This work was then continued by a seismic reflection and refraction coverage of the site (De Iaco et al. 2003; see **section -**). The same approach was proposed by Lanz, Maurer, and Green (1998) prior to the characterization of a landfill by the seismic refraction.

In order to provide information at various depths, the distance between the transmitter and the receptor loops (and their orientation) is varied. Some devices also work with **multiple frequencies**, allowing 1D conductivity inversion (larger frequencies penetrating deeper into the ground). Bergman (Bergman, 2009; Bergman et al., 2008) used the geophex GEM2 (325 Hz - 20,025 Hz) to measure the

landfill electrical conductivity at various depth (up to 35 m), without reaching its bottom limit. Giang, Marquis, and Minh (2010) used the same device and imposed the electrical conductivity value below 6 m depth in order to increase the resolution in the upper part.

The ground penetrating radar method (GPR)

The radar method is also sensitive to the electrical conductivity changes of the subsurface. However, when the data is acquired in a highly conductive area, the signal is rapidly attenuated and the depth of investigation becomes very low. However, the depth at which the signal is attenuated can be interpreted in terms of electrical conductivity at shallow depth (1-2 m for 450 MHz antennas). Green, Lanz, and Maurer (1999) have revealed the correlation between the high attenuation of radar signals and electrical conductivity data acquired by the EM mapping. In the upper part, the radar signal is chaotic on the landfill and more homogeneous on the host formation. Splajt et al. (2003) identified the beginning of the saturated zone (at a 2 m depth) as the horizon where radar waves reflected and the signal quality substantially degraded.

- Seismic methods

The mechanical properties of landfills often offer relatively good contrast with those of natural soil, but generally lower contrast than for electrical properties. The use of seismic methods is favored when the host formation is made of highly competent rocks. The heterogeneous compaction of waste (resulting of the use of landfill compactors, and then its own weight) influences the seismic parameters: the higher the compaction rate, the higher the mechanical wave velocities. In saturated medium, water or leachate propagates the P-waves. The P-wave velocity in saturated waste is slightly larger or equal to the P-waves velocity in water (1450 m/s). Soupios et al. (2007) observed propagation speeds of P waves of about 1670 m/s in saturated solid waste while Meju (2000b) shows much lower values, between 180 and 700 m/s, for an unsaturated solid waste material. The saturation effect on the S-wave propagation velocity is limited because water and gas do not transmit shear forces. However, the saturation influences the Poisson's ratio.

Due to important scattering and inelastic attenuation, waste material deposits are generally poor transmitters of high-frequency components of seismic waves, which are important for high resolution seismic reflection studies (De Iaco et al., 2003). Cardarelli and Di Filippo (2004) showed that the frequency content of the signals measured at a geophone during a seismic refraction campaign is different inside and outside the landfill. These authors have shown that high frequencies are strongly attenuated and dispersed within the deposit. Indirectly, this observation helped to delineate the lateral extension of old landfills.

Seismic reflection

Few conclusive studies are available for seismic reflection on old landfills. The study by Pasasa, Wenzel, and Zhao (1998) allowed to locate a building buried under 15-25 m of waste and the base of the landfill, formed by a compact limestone plateau. De Iaco et al. (2003) identified several reasons that can cause the failure of the seismic reflection method in the investigation of landfills. (1) P-waves – especially at high frequencies – are highly attenuated because unconsolidated waste is a poor transmitter. (2) Refracted waves and surface waves mask reflections for shallower interfaces (Steeple and Miller, 1998). Finally, (3) strong lateral heterogeneity prevents the formation of a hyperbole that identifies the reflectors (De Iaco et al., 2003; Lanz et al., 1998). The determination of the depth of a seismic reflector also requires an estimate of the P-waves velocity. The Common-Mid-Point method (CMP) or by seismic refraction (often acquired at the same time) (e.g. De Iaco et al. 2003).

Konstantaki et al. (2015b) used S-wave reflection data and the CMP method to compute the S-wave distribution in the waste mass with a higher resolution than the MASW method (performed for comparison). Konstantaki et al. (2015, 2013) proposed to use seismic interferometry (SI) applied to S-wave reflection seismic to help improve the detection and localization of scatterers (as high-density contrast areas) in the waste mass. Finally, a relationship between the S-wave velocity and the waste density (proposed by Choudhury and Savoikar, 2009) has been used by (Konstantaki et al., 2015b) to estimate waste density from S-wave velocities. The P-wave/S-wave velocity ratio is interpreted in term of leachate bearing (high V_p/V_s) and gas bearing (low V_p/V_s) region (Konstantaki et al., 2016).

Seismic refraction

Although seismic refraction provides a smaller vertical resolution than seismic reflection, it is less affected by the dispersion and attenuation phenomena (Lanz et al., 1998). The refracted wave tomography allows to take into account the lateral variations and enables more accurate representation of the subsurface. For example, Lanz, Maurer, and Green (1998) used this approach successfully to determine the geometry of a 10 m thick landfill. A sudden velocity increase (from 1000 to 1500 m/s) highlighted the interface between the waste and the host formation. However, the detection of the landfill borders with the seismic refraction method appeared not trivial as they were not able to distinguish the discharge (implanted in a former gravel quarry) from gravel deposits in place (P-wave velocity <1000 m/s in both cases).

Since liquid can transmit compression waves, **seismic refraction** can detect the depth of the water level. Soupios et al. (2007) have shown a correlation between the resistivity drop and the increase in P-wave velocity along a same interface. Surficial sediments, dry, are characterized by a 340 m/s P-wave velocity and a 25-50 Ωm resistivity; saturated waste by 1670 m/s and 0.2-6 Ωm .

Surface wave velocity dispersion curve

The analysis of the dispersion of surface waves allows to characterize the evolution of the shear-wave velocity with depth. The work of Bouazza and Kavazanjian (2000) and Kavazanjian et al. (1994) have both shown an S-wave propagation speed of 80 m/s at the surface to 290-300 m/s at 30 m depth. The S-wave velocity increases with depth (+ 5-10 m/s per meter of depth). The same studies also showed an increase in the S-wave velocity with the age of the waste (e.g. 10 m deep and age <1 year: 120 m/s; 7-8 years, 150 m/s in Bouazza and Kavazanjian, 2000). Kavazanjian et al. (1996) presented several deeper S-wave vertical profiles and recommended a range of S-wave velocity values for Californian MSW landfill up to 60 m depth. Notably, S-wave velocity for other type of waste deposits may differ from these recommendations. Values up to 550 m/s at 30 m depth were recorded on a waste deposit who accepted inert deposit in the past (Kavazanjian et al., 1994).

Unlike seismic refraction, this method is effective even when the seismic velocity does not necessarily increase with depth. The analysis of surface waves is a method of choice for characterizing landfills which cover layers are often more compact than solid waste. The seismic velocity of the compacted top surface layer is sometimes higher than that of superficial waste (e.g. 170 m/s at 4 m depth, within the compacted layer, against 120 m/s at 6 m in Bouazza and Kavazanjian, 2000). Kavazanjian et al. (1994) describes similar results.

In the literature, the inversion of surface wave dispersion curves is commonly used to analyze the geometry of the bedrock (e.g. Carnevale et al., 2005; Casto et al., 2010; Miller et al., 1999). Although the method seems adapted to detect the transition between a compact host formation and waste material, few landfill studies offer a sufficient depth of investigation. A speed/wavelength curve slope change (the data are not inverted) was interpreted as the landfill bottom limit by Kavazanjian et al. (1994).

The Horizontal to Vertical Noise Spectral Ratio

The HVNSR method is sensitive to both the transmission properties of the S-waves and the thickness of the deposit, which effects are often impossible to discriminate with a single method. If the thickness of the deposits is known, the HVNSR method is used to estimate the average velocity of shear waves in the underlying waste mass. (Soupios et al., 2007, 2005) highlighted S-wave speeds of 90 m/s to 230 m/s. Peaks of secondary resonances at higher frequency indicate the presence of a very loose thin layer at the surface (Guéguen et al., 2000).

Landfills cannot always be approximated by a tabular medium (e.g. Guéguen et al. 2000). For a steep-side landfill, Guéguen et al. (2000) showed that the resonance frequency is constant and the amplitude is maximal at the middle of the site. Guéguen et al. (2000) also differentiated the landfill (7 Hz, related to the 2D / 3D resonance of the deposit) from the soil in place (1 Hz resonance peak).

- Potential methods

Magnetic method

Magnetometric methods are widely used to estimate the lateral extension of old landfills. Indeed, the latter regularly contain metallic elements or even massive foundry waste (e.g. Godio 2000) or clinker, the magnetic signatures of which strongly differs from most types of host formation. The magnetic susceptibility of solid waste is mainly related to the presence of ferromagnetic objects and is often 2-4 orders of magnitude above that of sedimentary rocks (Prezzi et al., 2005; Telford et al., 1990). While the magnetic susceptibility of the material is responsible for the Earth's magnetic field perturbation measured at the surface, it is generally not computed. Perturbations of the magnetic field are directly interpreted for site characterization. Furthermore, the method can help detecting large metallic object (drums, fridge, etc.) inside the waste mass. The shape of the magnetic field surface anomaly gives insight on the size and depth of the buried objects (e.g. Godio, 2000).

The gradiometry was used by De Iaco, Green, and Horstmeyer (2000) et Green, Lanz, and Maurer (1999) to delineate the lateral extent of waste deposits. The method was also tested successfully for the delimitation of Camp Roberts site in California (Doll et al., 2001), where a difference of 3 orders of magnitude was noticed between the magnetic gradient measured on MSW and the host formation. However, the exact delimitation of the lateral extension of a former landfill strongly depends on the content of the latter. So Carlson, Mayerle, and Zonge (1999) showed that the use of magnetometry on a site characterized by a low proportion of metallic elements was not indicated. In fact, these authors were only able to detect minor anomalies due to metal objects at the surface. MSW with low metal content may not be distinguished from host formation with a magnetic signature (e.g. Igneous and metamorphic rocks). Metallic infrastructure elements (e.g. degasification wells) would most likely also induce significant magnetic responses.

Gravimetric method

Municipal waste is characterized by relatively low densities that are intrinsic to their composition and their low compaction compared to the natural host rocks/sediments. Generally, the density varies from 1 to 2 t/m³ (e.g. 1.6 t/m³ in Roberts et al., 1990b). Kavazanjian et al. (1995) published a unit weight profile starting from 0.6 t/m³ at the surface to 1.3 t/m³ at 45 m and higher. Meju (2000b) mentions that other waste densities vary from 300 kg/m³ (e.g. for uncompacted dry waste) to 6.4 t/m³ (e.g. for waste containing many metallic objects). For comparison, a natural environment presents densities between 2 t/m³ for soft ground and 3 t/m³ for hard soils (e.g. Telford et al. 1990). Therefore,

a density contrast of 2-3 between MSW and the host formation is expected when the waste deposit lays over a dense indurated host formation.

Theoretically, this range of density contrast could be detected with the gravimetric method. However, the acquisition of numerous gravity data in order to map the landfill extension is a long and costly process. Roberts et al., (1990b) acquired 7 gravity profiles and interpolated them to produce a gravity anomaly map that fairly delimits the landfill borders.

Other applications of the gravimetry for landfill investigation found in the literature (e.g. Mantlík et al., 2009; Roberts et al., 1990b; Silva et al., 2008) focused on recalculating density values from bedrock geometry and vice versa. Thus, by means of gravity profiles acquired perpendicular to the axis of a former landfill, Roberts et al. (1990b) were able, with an estimate of the density contrast and the landfill maximum depth, to estimate the morphology of the landfill bottom. Silva et al. (2008) took up this study using a density/depth model for landfill as input information. When the bottom geometry of the landfill is known (from old topographical maps of the career or the valley, surveys, other geophysical methods), the gravity anomaly measured at the surface is used to estimate the waste mass density. Doing so, Roberts et al. (1990b) were able to show a density increase with the age of waste. In case waste of very high or very low density would be buried in a specific areas of the site, the gravity method could be used to identify different types of waste (Mantlík et al., 2009). However, the interpretation of the density in terms of composition is not straightforward as the degree of compaction – and indirectly age – also influences the density of the waste.

Method applicability:

The geophysical signature of the waste material generally contrasts with the characteristics of the surrounding medium, so that the geophysical prospecting methods can be used to characterize the extension, the volume and filling of landfills. Most of the time, landfills are characterized by low densities and low seismic wave propagation velocities (related to the nature of the waste and their weak compaction compared to the host formation). Similarly, the electrical resistivity of landfills is generally low due to the high electrical conductivity of the leachate and the increase in temperature due to biodegradation of the waste. However, some specific natural formations may present similar physical properties the waste material.

Some natural sediments present a **similar electrical resistivity** than the waste material. The most common is clay, but Doll et al. (2001) have also mentioned possible confusion with evaporite. However, in the special case that electrical resistivity of underlying soil is similar to that of leachate, accurate observation of the boundary between waste disposal and soil presents a challenge (Frid et al., 2008). A field example of landfill installed in former clay and gravel quarry is given in Carlson and Scott (2004).

Clay formation are also characterized by a strong **chargeability** signature. Some authors also suggest that leachate escaping in the host formation may have an IP signature, preventing the precise delimitation of the extension of the site. Indeed, Organic-clay interaction (Aristodemou and Thomas-Betts, 2000; Olhoeft, and King, 1991; Vanhala, 1997), the salinity-clay interactions (Ustra et al., 2011) and, the presence of heavy metals in suspension in the leachate (Abu-Zeid et al., 2004) may induce an IP signal.

Igneous and metamorphic rocks are often characterized by relatively high **magnetic susceptibilities**. In this case, waste material with low metal content may not be distinguished from the host formation. The detection of the landfill borders with the **seismic refraction** method appeared not trivial when the landfill is installed over unconsolidated sediments. As an example, Lanz, Maurer, and Green (1998) were not able to distinguish the discharge (implanted in a former gravel quarry) from gravel deposits in place (P-wave velocity <1000 m/s in both cases).

- Influence of technical infrastructures:

All the technical infrastructure present around or on top of the site may favor or impede to use of a particular geophysical method.

A **HDPE bottom membrane** forms an electrical current barrier. The occurrence of the synthetic liner strongly influences the distribution (in the waste material) of current and potential lines during the electrical current injection. This may result in critical artifacts in inverted electrical resistivity tomography. Audebert et al. (2014a) have shown that a minimum distance (of $0.64 \cdot L$ from the landfill boundary and $0.58 \cdot L$ from the landfill bottom membrane; L is the ERT line total length) is necessary to neglect boundary effects. When ERT profiles (i.e. Dumont et al. 2016) are located too close to the landfill HDPE membrane, the bottom HDPE membrane morphology should be considered in the inversion grid (i.e. with homogeneous Neumann conditions, resulting in no current flow in normal direction).

The occurrence, or the absence of a synthetic liner also influences the potential leachate leakage from the waste material towards the natural soil. Once contaminated with electrically conductive leachate, the host formation presents a higher electrical conductivity (and potentially a higher chargeability). Thus, this contamination reduces electrical properties contrast between the waste material and the host formation and complicates the detection of the landfill lateral and vertical limits.

Covering layers also influences the choice of the geophysical methods. While a covering HDPE membrane is invisible for EM techniques, it hampers the use of the ERT method. In order to inject electrical current in the waste material (and measure the resulting potential), it is necessary to puncture the covering membrane. This operation is not detrimental if LFM operations starts soon after. In case LFM operation are not considered any further, the membrane patching induces additional costs. Nevertheless, the use of non-intrusive (less-intrusive) investigation methods is favored compared the conventional investigation techniques such as drilling or trenching. **Asphalt or concrete** (i.e. car park areas) layers induce similar issues. **Highly compacted layers (clinker or sandy cover layers)** are characterized by higher seismic velocities the underlying waste material. The specific seismic velocity vertical profile limits the applicability of seismic geophysical methods. With the seismic refraction method, soft sediment underlying a compacted layer (such as a capping layer of a landfill) remains invisible (Pelton, 2005; Telford et al., 1990), as seismic wave preferentially propagates through the cover layer. Unlike seismic refraction, the MASW method is effective even when the seismic velocity does not necessarily increase with depth. The analysis of surface waves is a method of choice for characterizing landfills which cover layers are often more compact than the underlying waste. A **clinker covering layer** also induces a strong magnetic response. The lateral extension mapped with a magnetometer likely correspond to the extension of the cover layer, and not the waste material, whose extension might be identical or different. **A too thick inert cover layer** limits the use of geophysical methods that are solely sensitive to superficial layers, namely the EM mapping (with a short transmitter-receiver distance) and the gradiometry.

Metallic infrastructure elements (e.g. degasification wells, cables) would most likely induce significant magnetic responses.

Estimated prices

We provide in Table 3 a cost estimation of most appropriate geophysical methods for landfill characterization based on our own experience as it is difficult to find such information in the literature. Therefore, the proposed values are only indicative. They may vary from country to country, from site

to site and may also depend on the particular configuration. Note that the proposed costs include reporting.

Table 3: estimated cost of most appropriate geophysical methods for landfill investigations

Methods	Cost in € (excl. taxes)	Units
ERT	1650 -2100	1 profile with 64 electrodes
ERT + IP	1900 - 2500	1 profile with 64 electrodes
HVNSR	20 - 40	1 measurement point
MASW	1200 - 2000	1 profile with 24 geophones
EM	0.013 -0.1	m ²
Magnetometry	0.07 - 0.17	m ²
SP	400 - 830	1 profile with 64 measurement points

Cost benefit analysis

One of the main advantages of geophysical methods is that they allow to investigate quickly large areas at relatively low cost. They can help providing information to locate boreholes and trial pits by targeting anomalous areas. As stressed by Reynolds (2011), instead of being seen as a survey cost, geophysics should be seen as an added value by making the whole site investigation more cost-effective. In order to illustrate the cost-benefit of using geophysics in landfills, we consider the case of the Onoz site investigated in the scope of the RAWFILL project. The site has a total area of 12 000 m² and can be divided in two zones of respectively 8 000 m² and 4 000 m². In the first zone, the thickness of waste is around 20 m whereas in the second one, it is approximately 6 m. A traditional “drilling-sampling-analysis” approach for characterizing such area would have implied conducting a 20 m long borehole every 500 m² in the first zone, and a borehole of 6 m long and a trial pit every 500 m² in the second zone. Assuming a cost of 100 € per meter of drilling (including sampling and analysis), 2 days of trenching (at 800 € a day) and a transport cost of the drilling machines estimated at 1000 euros, we would have ended up with a total characterization cost of 39 400 euros. The approach promoted in RAWFILL using a combination of different geophysical methods (here ERT, IP, magnetometry and EM) allowed to drastically reduce the number of boreholes and trial pits required to investigate the site. Indeed, we first used magnetometry and EM to delineate the landfill and identify anomalous zones. The cost of EM mapping was estimated at 1 200 euros and the cost of magnetometric mapping was estimated at 2 000 euros. Based on the mapping results, we used imaging methods (ERT and IP) to study more in details anomalous zones. 3 profiles of 64 electrodes each were realized yielding a cost of 7 500 euros. Combining the information provided by selected geophysical methods, a sampling plan was proposed which consisted in 5 boreholes (2 in the first zone and 3 in the second zone) which finally yields a total length of drilling of 65 m (a little more than expected) for a total cost of 6 500 euros and 10 trenches (2 days of field work at 800 € each). Taking into account the transport cost of the drilling machines (1000 euros), the total cost of the RAWFILL approach for characterizing the site was 19800 €, i.e. almost 50 % less than the traditional approach.

Conclusions

To summarize, landfill investigation necessitates the quantification of the waste deposit volume (extension and depth) and the characterization of the waste material in terms of composition, mineralization state and water content. Generally, a multi-scale geophysical investigation is essential

to provide an attractive and cost-effective alternative/complementary solution to the traditional “drilling-sampling-analysis” characterization methodology. In this deliverable, the role of each individual method has been presented, in order to select the optimal combination of geophysical methods. Quick and cost-effective methods, such as magnetometry or electromagnetic mapping, are needed for the detection of the horizontal borders. Then, the landfill depth is determined at some location with ERT / IP tomography or seismic methods. The deeper the waste deposit, the more difficult the estimation of the bottom limit location. In order to estimate the potential benefit of a landfill mining operation, the characterization of the waste material humidity is of uttermost importance. For that purpose, the electrical resistivity appears as the most suited method. The waste composition appeared difficult to estimate in MSW landfills but could be an interesting target in mixed (industrial and MSW) landfills where larger waste physical property contrast exists.

References

- Abu-Zeid, N., Bianchini, G., Santarato, G., Vaccaro, C., 2004. Geochemical characterisation and geophysical mapping of Landfill leachates: the Marozzo canal case study (NE Italy). *Environ. Geol.* 45, 439–447. <https://doi.org/10.1007/s00254-003-0895-x>
- Angoran, Y.E., Fitterman, D.V., Marshall, D.J., 1974. Induced polarization: a geophysical method for locating cultural metallic refuse. *Science* 184, 1287–1288. <https://doi.org/10.1126/science.184.4143.1287>
- Aristodemou, E., Thomas-Betts, A., 2000. DC resistivity and induced polarisation investigations at a waste disposal site and its environments. *J. Appl. Geophys.* 44, 275–302.
- Audebert, M., Clément, R., Grossin-Debattista, J., Günther, T., Touze-Foltz, N., Moreau, S., 2014a. Influence of the geomembrane on time-lapse ERT measurements for leachate injection monitoring. *Waste Manag.* 34, 780–790. <https://doi.org/10.1016/j.wasman.2014.01.011>
- Audebert, M., Clément, R., Touze-Foltz, N., Günther, T., Moreau, S., Duquennoi, C., 2014b. Time-lapse ERT interpretation methodology for leachate injection monitoring based on multiple inversions and a clustering strategy (MICS). *J. Appl. Geophys.* 111, 320–333. <https://doi.org/10.1016/j.jappgeo.2014.09.024>
- Auken, E., Gazoty, A., Fiandaca, G., Pedersen, J., Christiansen, A., 2011. Mapping of Landfills using Time-domain Spectral Induced Polarization Data - The Eskelund Case Study, in: *Near Surface 2011 – 17th European Meeting of Environmental and Engineering Geophysics*. Presented at the Near Surface 2011 – 17th European Meeting of Environmental and Engineering Geophysics, Leicester (United kingdom), pp. 12–14.
- Bakker, M., Hoekstra, N., Onk, J., 2008. Characterisation of landfills in the Netherlands using a multidisciplinary approach, in: *The First Workshop on Geophysical Measurements at Landfills*. Presented at the The first Workshop on geophysical measurements at landfills, Malmö (Sweden), p. 2p.
- Bavusi, M., Rizzo, E., Lapenna, V., 2006. Electromagnetic methods to characterize the Savoia di Lucania waste dump (Southern Italy). *Environ. Geol.* 51, 301–308. <https://doi.org/10.1007/s00254-006-0327-9>
- Bergman, B., 2009. Geofysiska analyser (stängslingram, CVES och IP) av lagerföljd och lakvattenrörelser vid Albäcksdeponin, Trelleborg. Geologiska inst., Lunds Univ.
- Bergman, B., Jeppsson, H., Håkansson, B., Persson, K., 2008. A geophysical investigation of the landfill Albäck, Trelleborg, South Sweden with the use of GEM2 (stängslingram), in: *The First Workshop on Geophysical Measurements at Landfills*. Presented at the The first Workshop on geophysical measurements at landfills, Malmö (Sweden).
- Bernstone, C., Dahlin, T., Ohlsson, T., Hogland, H., 2000. DC-resistivity mapping of internal landfill structures: two pre-excavation surveys. *Environ. Geol.* 39, 360–371. <https://doi.org/10.1007/s002540050015>
- Bouazza, A., Kavazanjian, E., 2000. Characterization of municipal solid waste sites using the continuous surface wave method, in: *Proceedings International Conference on Geotechnical and Geological Engineering, GeoEng. Melbourne (Australia)*, p. 6p.
- Cardarelli, E., Di Filippo, G., 2004. Integrated geophysical surveys on waste dumps: evaluation of physical parameters to characterize an urban waste dump (four case studies in Italy). *Waste Manag. Res.* 22, 390–402. <https://doi.org/10.1177/0734242X04046042>

- Carlson, N., Mayerle, C., Zonge, K., 1999. Extremely fast IP used to delineate buried landfills, in: Proceedings of the 5 Th Meeting of the Environmental and Engineering Geophysical Society European Section. Budapest (Hungary).
- Carlson, N., Scott, A., 2004. Comparisons of IP and resistivity data at several old, buried landfills, in: 17th EEGS Symposium on the Application of Geophysics to Engineering and Environmental Problems. Presented at the 17th EEGS Symposium on the Application of Geophysics to Engineering and Environmental Problems, Colorado Springs (USA), pp. 744–752.
- Carlson, N.R., Hare, J.L., Zonge, K.L., 2001. Buried landfill delineation with induced polarization: Progress and problems, in: Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP).
- Carnevale, M., Hager, J., Brinkmann, J.W., Jones, B.R., 2005. Masw and GPR Survey To Delineate Depth-Tobedrock and Crystal Cavities for Mineral Exploration, Hiddenite, North Carolina, in: 18th EEGS Symposium on the Application of Geophysics to Engineering and Environmental Problems.
- Casto, D.W., Calderón-Macías, C., Luke, B., Kaufmann, R., 2010. Improving MASW Results for a Site with Shallow Bedrock through the Use of Higher-Mode Data, in: GeoFlorida 2010. American Society of Civil Engineers, pp. 1360–1368.
- Chambers, J., Kuras, O., Meldrum, P., Ogilvy, R., Hollands, J., 2006. Electrical resistivity tomography applied to geologic, hydrogeologic, and engineering investigations at a former waste-disposal site. *Geophysics* 71, 231–239. <https://doi.org/10.1190/1.2360184>
- Cheremisinoff, N.P., 2003. Handbook of Solid Waste Management and Waste Minimization Technologies. Butterworth-Heinemann.
- Choudhury, D., Savoikar, P., 2009. Simplified method to characterize municipal solid waste properties under seismic conditions. *Waste Manag.* 29, 924–933. <https://doi.org/10.1016/j.wasman.2008.05.008>
- Clément, R., Descloitres, M., Günther, T., Oxarango, L., Morra, C., Laurent, J.-P., Gourc, J.-P., 2010. Improvement of electrical resistivity tomography for leachate injection monitoring. *Waste Manag.* 30, 452–464. <https://doi.org/10.1016/j.wasman.2009.10.002>
- Clément, R., Oxarango, L., Descloitres, M., 2011. Contribution of 3-D time-lapse ERT to the study of leachate recirculation in a landfill. *Waste Manag.* 31, 457–467. <https://doi.org/10.1016/j.wasman.2010.09.005>
- Dahlin, T., Hellman, K., Johansson, S., Mansson, C.-H., Svensson, M., Rosqvist, H., 2012. Pilot Study of Using Magnetics, EM & Resistivity-IP for Separation of Industrial Waste, in: Second Workshop on Geophysical Measurements in Waste Management. Presented at the Second workshop on geophysical measurements in waste management, Malmö (Sweden).
- Dahlin, T., Rosqvist, H., Leroux, V., 2010. Resistivity-IP mapping for landfill applications With case studies from South Africa and Sweden. *First Break* 28, 101.
- De Iaco, R., Green, A., Horstmeyer, H., 2000. An integrated geophysical study of a landfill and its host sediment. *Eur. J. Environ. Eng. Geophys.* 4, 223–263.

- De Iaco, R., Green, A., Maurer, H.-R., Horstmeyer, H., 2003. A combined seismic reflection and refraction study of a landfill and its host sediments. *J. Appl. Geophys.* 52, 139–156.
- Doll, W.E., Gamey, T.J., Nyquist, J.E., Mandell, W., Groom, D., Rohdewald, S., 2001. Evaluation of new geophysical tools for investigation of a landfill, Camp Roberts, California, in: 14th EEGS Symposium on the Application of Geophysics to Engineering and Environmental Problems. Denver (Colorado, USA).
- Dumont, G., 2016. Geophysical characterization and monitoring of a municipal solid waste landfill. University of Liege.
- Dumont, G., Pilawski, T., Dzaomuh-Lenieregue, P., Hilgsmann, S., Delvigne, F., Thonart, P., Robert, T., Nguyen, F., Hermans, T., 2016. Gravimetric water distribution assessment from geoelectrical methods (ERT and EMI) in municipal solid waste landfill. *Waste Manag.* <https://doi.org/10.1016/j.wasman.2016.02.013>
- Frid, V., Liskevich, G., Doudkinski, D., Korostishevsky, N., 2008. Evaluation of landfill disposal boundary by means of electrical resistivity imaging. *Environ. Geol.* 53, 1503–1508. <https://doi.org/10.1007/s00254-007-0761-3>
- Gazotti, A., Fiandaca, G., Pedersen, J., Auken, E., Christiansen, A.V., 2012. Mapping landfills with Time Domain IP: The Eskelund case study., in: 14th EEGS Symposium on the Application of Geophysics to Engineering and Environmental Problems. Presented at the Second workshop on geophysical measurements in waste management, Malmö (Sweden).
- Giang, N., Marquis, G., Minh, L.H., 2010. EM and GPR investigations of contaminant spread around the Hoc Mon waste site, Vietnam. *Acta Geophys.* 58, 1040–1055. <https://doi.org/10.2478/s11600-010-0023-8>
- Godio, A., 2000. Magnetic data interpretation in an industrial waste landfill. *Ann. Geofis.* 43, 297–307.
- Green, A., Lanz, E., Maurer, H., 1999. A template for geophysical investigations of small landfills. *Lead. Edge* 18, 248–254.
- Grellier, S., Guérin, R., Robain, H., Bobachev, A., Vermeersch, F., Tabbagh, A., 2008. Monitoring of leachate recirculation in a bioreactor landfill by 2-D electrical resistivity imaging. *J. Environ. Eng. Geophys.* 13, 351–359.
- Grellier, S., Reddy, K., Gangathulasi, J., Adib, R., Peters, A., 2006. Electrical Resistivity Tomography Imaging of Leachate Recirculation in Orchard Hills Landfill, in: *Proceedings of the SWANA Conference*. Charlotte.
- Grellier, S., Reddy, K., Gangathulasi, J., Adib, R., Peters, C., 2007. Correlation between Electrical Resistivity and Moisture Content of Municipal Solid Waste in Bioreactor Landfill. *Geotech. Spec. Publ.* 1–14.
- Guéguen, P., Chatelain, J.L., Guillier, B., Yepes, H., 2000. An indication of the soil topmost layer response in Quito (Ecuador) using noise H/V spectral ratio. *Soil Dyn. Earthq. Eng.* 19, 127–133.
- Guérin, R., Munoz, M.L., Aran, C., Laperrelle, C., Hidra, M., Drouart, E., Grellier, S., 2004. Leachate recirculation: moisture content assessment by means of a geophysical technique. *Waste Manag.* 24, 785–794. <https://doi.org/10.1016/j.wasman.2004.03.010>

- Gyllenhammar, M., Davidsson, K., Jonsson, T., AB, S.M., 2011. Co-firing of shredder light fraction with waste and sewage sludge., in: Swedish-Finnish Flame Days 2011.
- Imhoff, P., Reinhart, D., Englund, M., Guérin, R., Gawande, N., Han, B., Jonnalagadda, S., Townsend, T., Yazdani, R., 2007. Review of state of the art methods for measuring water in landfills. *Waste Manag.* 27, 729–745. <https://doi.org/10.1016/j.wasman.2006.03.024>
- Kavazanjian, E., Matasovic, N., Bonaparte, R., Schmertmann, G.R., 1995. Evaluation of MSW properties for seismic analysis. Presented at the Proceedings of the Specialty Conference on Geotechnical Practice in Waste Disposal. Part 1 (of 2).
- Kavazanjian, E., Snow, M.S., Matasovic, N., Poran, C., Satoh, T., 1994. Non-intrusive Rayleigh Wave Investigation at Solid Waste Landfills, in: 1st International Congress in Environmental Geotechnics. Presented at the 1st international congress in Environmental Geotechnics, Edmonton (Canada).
- Kavazanjian, E., Stokoe, K.H., II, Bray, J.D., 1996. In Situ Shear Wave Velocity of Solid Waste Material From Surface Wave Measurements, in: Proceedings, Second International Congress on Environmental Geotechnics. Presented at the Proceedings, Second International Congress on Environmental Geotechnics, Osaka (Japan).
- Konstantaki, L.A., Draganov, D., Ghose, R., Heimovaara, T., 2015a. Seismic interferometry as a tool for improved imaging of the heterogeneities in the body of a landfill. *J. Appl. Geophys.* 122, 28–39. <https://doi.org/10.1016/j.jappgeo.2015.08.008>
- Konstantaki, L.A., Draganov, D., Heimovaara, T., Ghose, R., 2013. Imaging scatterers in landfills using seismic interferometry. *Geophysics* 78, EN107–EN116. <https://doi.org/10.1190/geo2013-0099.1>
- Konstantaki, L.A., Ghose, R., Draganov, D., Diaferia, G., Heimovaara, T., 2015b. Characterization of a heterogeneous landfill using seismic and electrical resistivity data. *Geophysics* 80, EN13–EN25. <https://doi.org/10.1190/geo2014-0263.1>
- Konstantaki, L.A., Ghose, R., Draganov, D., Heimovaara, T., 2016. Wet and gassy zones in a municipal landfill from P- and S-wave velocity fields. *GEOPHYSICS* EN75–EN86. <https://doi.org/10.1190/geo2015-0581.1>
- Lanz, E., Maurer, H., Green, A., 1998. Refraction tomography over a buried waste disposal site. *Geophysics* 63, 1414–1433. <https://doi.org/10.1190/1.1444443>
- Leroux, V., Dahlin, T., Rosqvist, H., 2010. Time-domain IP and Resistivity Sections Measured at Four Landfills with Different Contents, in: Near Surface 2010 – 16th European Meeting of Environmental and Engineering Geophysics. Presented at the Near Surface 2010 – 16th European Meeting of Environmental and Engineering Geophysics, Zurich (Switzerland), p. 5.
- Linde, N., Revil, A., 2010. Inverting self-potential data for redox potentials of contaminant plumes. *Geophys. Res. Lett.* 34, 5.
- Mantlík, F., Matias, M., Lourenço, J., Grangeia, C., Tareco, H., 2009. The use of gravity methods in the internal characterization of landfills—a case study. *J. Geophys. Eng.* 6, 357–364. <https://doi.org/10.1088/1742-2132/6/4/003>
- Meju, M., 2000a. Environmental geophysics: the tasks ahead. *J. Appl. Geophys.* 44, 63–65. [https://doi.org/10.1016/S0926-9851\(00\)00006-9](https://doi.org/10.1016/S0926-9851(00)00006-9)

- Meju, M., 2000b. Geoelectrical investigation of old/abandoned, covered landfill sites in urban areas: model development with a genetic diagnosis approach. *J. Appl. Geophys.* 44, 115–150.
- Miller, R.D., Xia, J., Park, C.B., Ivanov, J.M., 1999. Multichannel analysis of surface waves to map bedrock. *Lead. Edge* December 1999, 1392–1396.
- Morris, J.W.F., Vasuki, N.C., Baker, J.A., Pendleton, C.H., 2003. Findings from long-term monitoring studies at MSW landfill facilities with leachate recirculation. *Waste Manag.* 23, 653–666. [https://doi.org/10.1016/S0956-053X\(03\)00098-9](https://doi.org/10.1016/S0956-053X(03)00098-9)
- Naudet, V., Genelle, F., Dabas, M., Sirieix, C., Riss, J., Rénié, S., Dubéarnes, B., Bégassat, P., 2011. On the geoelectrical characterization of an old landfill cover. Presented at the EAGE Near Surface 2011, the 17th European Meeting of Environmental and Engineering Geophysics of the Near Surface Geoscience Division of EAGE.
- Naudet, V., Gourry, J.C., Girard, J.F., Deparis, J., 2012. Geoelectrical characterization of the internal structure and biodegradation of an old Municipal Solid Waste, in: Second Workshop on Geophysical Measurements in Waste Management. Presented at the Second workshop on geophysical measurements in waste management, Malmö (Sweden).
- Naudet, V., Revil, A., Bottero, J.-Y., Bégassat, P., 2003. Relationship between self-potential (SP) signals and redox conditions in contaminated groundwater. *Geophys Res Lett* 30, 4.
- Nyquist, J.E., Corry, C.E., 2002. Self-potential: The ugly duckling of environmental geophysics. *Lead. Edge* 21, 446–451.
- Olhoeft, G., King, T., 1991. Mapping subsurface organic compounds noninvasively by their reactions with clays, in: Proc. 4th Toxic Substances Technical Meeting. Monterey (California, USA), pp. 1–18.
- Pasasa, L., Wenzel, F., Zhao, P., 1998. Prestack Kirchhoff depth migration of shallow seismic data : Shallow seismic reflection papers. *Geophysics* 63, 1241–1247.
- Pelton, J.R., 2005. Chapter 8, Near-Surface Seismology: Surface-Based Methods, in: Near-Surface Geophysics. Society of Exploration Geophysicists, Tulsa (Oklahoma USA), p. 46.
- Prezzi, C., Orgeira, M.J., Osters, H., Vásquez, C.A., 2005. Ground magnetic survey of a municipal solid waste landfill: pilot study in Argentina. *Environ. Geol.* 47, 889–897. <https://doi.org/10.1007/s00254-004-1198-6>
- Reddy, K.R., Hettiarachchi, H., Gangathulasi, J., Bogner, J.E., 2011. Geotechnical properties of municipal solid waste at different phases of biodegradation. *Waste Manag.* 31, 2275–2286.
- Reynolds, J. M. (2011). *An introduction to applied and environmental geophysics*: John Wiley & Sons.
- Roberts, R.L., Hinze, W.J., Leap, D.I., 1990. Application of the Gravity Method to Investigation of a Landfill in the Glaciated Midcontinent, U.S.A., in: Stanley H. Ward (Ed.), *Geotechnical and Environmental Geophysics*. Society of Exploration Geophysicists, pp. 261–266.
- Shihada, H., Hossain, M.S., Kemler, V., Dugger, D., 2013. Estimating Moisture Content of Landfilled Municipal Solid Waste without Drilling: Innovative Approach. *J. Hazard. Toxic Radioact. Waste* 17, 317–330. [https://doi.org/10.1061/\(ASCE\)HZ.2153-5515.0000155](https://doi.org/10.1061/(ASCE)HZ.2153-5515.0000155)
- Silva, J., Teixeira, W., Barbosa, V., 2008. Gravity data as a tool for landfill study. *Environ. Geol.* 57, 749–757. <https://doi.org/10.1007/s00254-008-1353-6>

- Soupios, P., Papadopoulos, N., Papadopoulos, I., Kouli, M., Vallianatos, F., Sarris, A., Manios, T., 2007. Application of integrated methods in mapping waste disposal areas. *Environ. Geol.* 53, 661–675. <https://doi.org/10.1007/s00254-007-0681-2>
- Soupios, P., Vallianatos, F., Papadopoulos, I., JP Makris, 2005. Determination of a landfill structure using HVSR, SPT's & geoelectrical tomographies, in: *Proceedings of the International Workshop in Geoenvironment and Geotechnics. Milos (Greece)*, p. 83.
- Splajt, T., Ferrier, G., Frostick, L.E., 2003. Application of ground penetrating radar in mapping and monitoring landfill sites. *Environ. Geol.* 44, 963–967. <https://doi.org/10.1007/s00254-003-0839-5>
- Steeple, D., Miller, R., 1998. Avoiding pitfalls in shallow seismic reflection surveys. *Geophysics* 63, 1213. <https://doi.org/10.1190/1.1444422>
- Telford, William Murray, Telford, W. M., Geldart, L.P., Sheriff, Robert E., Sheriff, R. E., 1990. *Applied Geophysics*. Cambridge University Press, United Kingdom.
- Thierry, B., Weller, A., Schleifer, N., Westphal, T., 2001. Polarisation effects of wood. Presented at the Proceedings of 7th Meeting of EEGS-ES, Birmingham.
- Ustra, A.T., Elis, V.R., Mondelli, G., Zuquette, L.V., Giacheti, H.L., 2011. Case study: a 3D resistivity and induced polarization imaging from downstream a waste disposal site in Brazil. *Environ. Earth Sci.* 66, 763–772. <https://doi.org/10.1007/s12665-011-1284-5>
- Vanhala, H., 1997. MAPPING OIL-CONTAMINATED SAND AND TILL WITH THE SPECTRAL INDUCED POLARIZATION (SIP) METHOD. *Geophys. Prospect.* 45, 303–326. <https://doi.org/10.1046/j.1365-2478.1997.00338.x>
- Zornberg, J.G., Jernigan, B.L., Sanglerat, T.R., Cooley, B.H., 1999. Retention of free liquids in landfills undergoing vertical expansion. *J. Geotech. Geoenvironmental Eng.* 125, 583–594.

Contact

Feel free to contact us.

Local contact details:

BELGIUM	ATRASOL Cleantech Flanders / VITO OVAM SPAQuE Université de Liège	renaud.derijdt@atrasol.eu annick.vastiau@cleantechflanders.com ewille@ovam.be c.neculau@spaqua.be f.nguyen@ulg.ac.be
FRANCE	SAS Les Champs Jouault	champsjouault@gmail.com
GERMANY	BAV	wolf@bavmail.de
THE UK	NERC	jecha@bgs.ac.uk

Coordination office:

BELGIUM	SPAQuE Boulevard d'Avroy 38 4000 Liège	c.neculau@spaqua.be
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