4TH INTERNATIONAL SYMPOSIUM ON ENHANCED LANDFILL MINING - MANAGING PAST LANDFILLS FOR FUTURE SITE DEVELOPMENT: A REVIEW OF THE CONTRIBUTION OF GEOPHYSICAL METHODS

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Introduction

For more than 100 years, Europe has been discarding its unwanted waste materials in landfill (LF) sites[1]. Estimates suggest that there are at least 500,000 of these sites – some closed, some still operational – in the EU-28. An additional factor that concerns many experts is that a lot of these LFs are located in semi-urban environments. Fortunately, as a result of the EU's Landfill and Waste Directives, most of the still-operational LFs are "sanitary" LFs that are equipped with state-of-the-art environmental protection and methane-collection systems. For these LFs, a leachate-recirculation system that allows biodegradation to take place more quickly, thereby increasing LF-gas production and shortening the exploitation time, can be installed. However, its success depends very much on the difficult-to-control water content, which affects both the completeness and the kinetics of biodegradation, and therefore the effectiveness and viability of subsequent LF-mining operations.

Although most of the currently operating LFs are sanitary, this still leaves a high proportion of Europe's LFs in a "non-sanitary" condition. These LFs, which generally predate the EU's Landfill Directive of 1999, have limited, poor or no protection technologies. As a result, such deposits could cause serious environmental problems, ranging from local pollution concerns (health, soil and water) and land-use restrictions to global impacts in terms of greenhouse-gas emissions. In order to avoid environmental and health problems, far-reaching remediation measures are needed in the short-to-medium term. Remediation, however, is a costly and environmentally impacting affair. In this context, the non-conventional Enhanced Landfill Mining (ELFM) concept offers a real way forward by transforming a large fraction of the excavated material into higher-added-value products in addition to recovering the land. In fact, the net economic balance of the combined remediation-ELFM activity can even be positive (especially for larger LFs) and generate revenues, which can then be used to cover the costs of remediating/mining the smaller, less-economic LFs. This means that for most of the EU's LFs, LF-mining operations will become an attractive solution. However, the primary obstacle to the development of ELFM initiatives in Europe is a lack of knowledge about resources – materials and energy – in terms of volume, content, extraction feasibility and environmental impact.

While the surface components of LFs are a very familiar part of our urban landscapes, the vast majority of the valuable resources reside and interact below surface, which is generally inaccessible to any direct form of observation. Any planning of LF mining requires us to have a good estimation of the extent, volume and nature of the buried waste, whereas accelerated LF biodegradation requires close control over the water content. Conventional approaches to exploration, characterisation and monitoring involve defining a drilling grid, which is often investigated blindly, without any prior knowledge of the spatial distribution of the resources. Furthermore, to assess the environmental impacts of LFs, we are forced to rely on sparse borehole observations to infer the presence and the extent of potential leaks, which is additionally problematic as the subsurface is highly heterogeneous in many aspects (e.g., concentrations and flow paths). As such, these conventional approaches usually lead to LF mining operations with very high risks, and frequently low returns, due the uncertainty about resources and incomplete LF biodegradation. The environmental impacts, on the other hand, are poorly quantified and this can lead to a dangerous underestimation of the environmental and health effects.

Advances in non-invasive, geophysical science and the technologies for exploration, characterisation and monitoring, allow us to reduce the costs and the environmental footprint of conventional surveys, to increase gas production, to accelerate mineralisation, to lower the environmental risks of sanitary LFs, and to better address the environmental effects associated with LFs. In the past decade, the number of reported geophysical studies in the literature has significantly increased (figure 1). In this contribution we review the most recent development and trends for geophysics applied to landfills in terms of survey objectives.

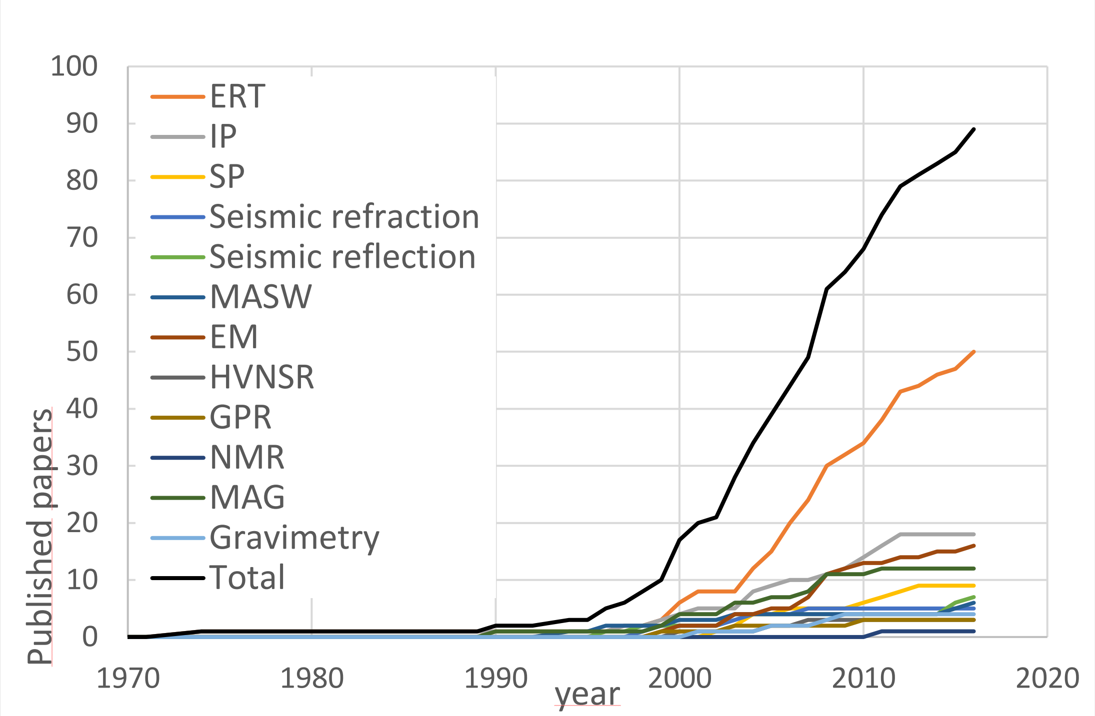

Figure 1: Published papers (source: Scopus) concerning landfills and geophysics.

Geophysical investigation of landfills

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)[2,3]. This methodology is time-consuming and costly and often provides sparse and local information[3]. Non-invasive geophysical methods could represent a pre-investigation strategy that would help designing the drilling grid and would provide indirect information on the waste material with a greater spatial coverage than boreholes. and can reduce health and safety issues compared to conventional drillings[4,5]. A multi-method approach reduce the non-uniqueness of the interpretation that may result from the analysis of a single physical parameter distribution. A multi scale non-invasive investigation is also generally more cost-effective than drillings and sampling when applied to large areas. A common approach is to provide a rapid acquisition method to locate the boundaries of the disposal site, followed by an estimation of the landfill depth and further characterization of the waste mass [6,7].

Parameters of interest for landfill mining operation

The **site extension and depth** determine the volume of waste buried in the pit and influences possible economy of scale. The **waste composition** (metallic content, organic content, and aggregates) are critical as these will determine the potential revenues associated with the operation. Different kinds of reusable materials can be recovered: Ferrous metals; Non-ferrous metals; Glass; Plastics; Combustible waste; Stones and construction waste; Waste of electrical and electronic equipment; Reclaimed soil used as landfill cover material. Waste from the mid 1960's to the mid 1990's is likely to yield the most valuable materials as this corresponds to a period of increased disposal of potential valuable materials and predates widespread recycling activities[8]. The occurrence of non-degraded organic waste might impede some valorization process. The **water content** of the material influences the profitability of landfill mining operations. Leachate arrival during trenching or digging would slow down the waste material extraction from the pit. The moisture content also affects the material separation efficiency[8] as any form of material or energy recovery requires mechanical treatment of the waste (such as shredding, trommel screen or metal extraction), which efficiency is limited by the water content (clogging, formation of sticky sludge), and may therefore also require an expensive drying process (e.g. Fisher, 2013). During energy valorization of waste through incineration process, the calorific value of humid waste is reduced, as a result of the energy needed to turn the waste humidity into water vapors [10].

Physical properties of waste

Waste deposits are characterized by various and heterogeneous (geo)physical signatures. In most cases, waste material is characterized by low densities and low seismic wave propagation velocities. Similarly, the electrical resistivity is generally low, due to the high electrical conductivity of the leachate and the increase in temperature resulting from waste biodegradation. These parameters generally contrast with the characteristics of the surrounding environment, so that geophysical prospecting methods can be used to characterize landfill geometry (size, shape and volume) and the internal characteristics of the waste mass (composition, humidity, temperature, compaction, density).

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 [5,11–14], 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 [11].

The electrical chargeability signature of municipal solid waste (MSW) deposits is emphasized by many authors [15–21]. Chargeability anomalies reach hundreds of mV and waste material contour is well depicted in both chargeability and normalized chargeability inverted section [20]. The high values of chargeability are often attributed to the presence of metal scraps [15,17,22] that results in the electrode polarization phenomenon. However, some authors also explain high chargeability in waste deposit by organic material content [15,23], wood content [24] or the layering of plastic sheets that would act as electric capacitors [25].

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 [26,27].
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 [28]). Kavazanjian [29] published a unit weight profile starting from 0.6 t/m³ at the surface to 1.3 t/m3 at 45 m and higher.

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 from the use of landfill compactors, and then from its own weight) influences the seismic parameters: the higher the compaction rate, the higher the mechanical wave velocities. In saturated medium, water or leachate affects the P-wave propagation. The P-wave velocity in saturated waste is slightly larger or equal to the P-waves velocity in water (1450 m/s). Soupios [30] observed propagation speed of P waves of about 1670 m/s in saturated solid waste, while Meju [5], Abbas [39] and Konstantaki et al. [34] find 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.

Geophysical methods as landfill investigation tools

multi-method geophysical survey can be used for the detection, the delimitation and the characterization of former landfill sites. The combined use of magnetometric, electromagnetic, gravimetric, seismic and electrical methods allows the estimation of the site extent and depth, and gives some insight on the waste material composition. Geophysical methods (i.e. magnetic and electromagnetic methods) might be used to identify a valuable fraction in the waste composition, such as metal. Then, geoelectrical methods are used to estimate the waste water content, which strongly affects the profitability of landfill mining operations. A prior knowledge of the site to be studied, even partial, represents an undeniable advantage for the design of the geophysical survey and for geophysical data interpretation.

Extension

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. In terms of contrast between MSW and host formation, various authors [11,14,20,31] have shown that the natural environment resistivity is often one or two orders of magnitude higher than humid MSW resistivity. The **electrical resistivity tomography (ERT)** can detect the borders of a landfill. The simultaneous acquisition of chargeability data is sometimes implemented. 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 distribution [19]. The electromagnetic mapping method offers a fast and relatively cheap method to access the electrical resistivity/conductivity of the site, and is often used for preliminary investigation on large landfills (e.g. Soupios et al., 2007). Electromagnetic methods are advantageously combined with **magnetometric methods** [6].

Depth / thickness

The bottom geometry and sometimes the depth of some landfills has been successfully evaluated with **ERT** [14,16,18,20]. However, difficulties in estimating the exact depth of the waste deposit could result from the site feature (e.g. no sharp contrast at the bottom of the landfill), or be intrinsic to the ERT method (loss of resolution with depth and the equivalence phenomenon of the ERT method). Few conclusive studies are available for **seismic reflection** or **seismic refraction** on old landfills. The **analysis of the dispersion of surface waves** (MASW) takes advantage of the propagation properties of surface waves that contains a large part of the recorded seismic wavefield and energy. . The method allows to characterize the evolution of the shear-wave velocity with depth[4,32]. 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[32]. The **HVNSR method**, which utilizes the horizontal-to-vertical spectral ratio of ambient vibrations, is sensitive to both the transmission properties of the S-waves and the thickness of the deposit; these two ffects are often impossible to discriminate with a single method.

Composition

The influence of the moisture content, pore fluid conductivity and waste temperature often dominates 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 [31], whose electrical images show little variation in the saturated zone although the buried wastes have quite different electrical characteristics (matrix resistivity). 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) [17, 23, 33]. The waste composition differentiation is more difficult for waste deposits composed solely of MSW. The **magnetic method** can help detecting large metallic object (drums, fridge, etc.) inside the waste mass. S-wave velocity (obtained with the MASW method) may differ with type of waste deposits, primarily distinguished by their densities [36]. Higher values are recorded in waste deposit sites that accepted inert deposits in the past [32].

Water content

The resistivity contrast between the saturated zone or at least the levels of free leachate (0.5-20 Ω.m) and the unsaturated zone (tens of Ω.m) is relatively large and often detected using ERT [11,14,30,31]. Dumont [12] have established that geoelectrical methods (ERT and borehole EM) can be used to estimate the moisture content over large areas, provided that environmental parameters (temperature and leachate electrical conductivity) can be measured at several locations. Since a liquid can transmit compressional waves, **seismic refraction** usnign P wave can also detect the depth of the water level [30]. The P-wave/S-wave velocity ratio distribution is interpreted in term of leachate bearing (high Vp/Vs) and gas bearing (low Vp/Vs) zones [34].

Geophysical methods applicability

Some natural sediments present a similar electrical resistivity than the waste material. The most common is clay, but Doll [35] have also mentioned possible confusion with evaporite. Clay formation are also characterized by a strong chargeability signature. 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 [7]. An adaptation of the **seismic interferometry** method seems to improve the delineation fo heterogeneities in waste in a MSW landfill [37, 38].

All the technical infrastructure present around or on top a LF site may favor or impede the use of a particular geophysical method. The bottom sealing system and the covering layers also influence 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.

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 (e.g. car park areas) layers induce similar issues. A clinker covering layer, or metallic infrastructure elements (e.g. degasification wells, cables) would most likely induce a strong magnetic response.

Conclusions

We report here a significant increase of geophysical studies applied to landfills. The target of the surveys may range from mapping landfills boundaries to advanced hydrodynamics characterization. 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 or compaction 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 paper, the role of each individual method has been presented and case studies reviewed, in order to select the optimal combination of geophysical methods given the landfill survey objectives.

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