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ORIGINAL ARTICLE

Application of integrated methods in mapping waste disposal areas

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Abstract An integrated suite of environmental methods was used to characterize the hydrogeological, geological and tectonic regime of the largest waste disposal landfill of Crete Island, the Fodele municipal solid waste site (MSW), to determine the geometry of the landfill (depth and spatial extent of electrically conductive anomalies), to define the anisotropy caused by bedrock fabric fractures and to locate potential zones of electrically conductive contamination. A combination of geophysical methods and chemical analysis was implemented for the characterization and management of the landfill. Five different types of geophysical surveys were performed: (1) 2D electrical resistance tomography (ERT), (2) electromagnetic measurements using very low frequencies (VLF), (3) electromagnetic conductivity (EM31), (4) seismic refraction measurements (SR), and (5) ambient noise measurements (HVSR). The above geophysical methods were used with the aim of studying the subsurface properties of the landfill and to define the exact geometrical characteristics of the site under investigation.

Keywords Crete Island · Landfill · Environmental geophysics

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Introduction

Environmental contamination is one of the main concerns of earth scientists and researchers worldwide. The accelerated pace of industrial development coupled with uncontrolled growth of the urban population has resulted in the increasing production of solid/liquid residues. Urban waste materials, mainly domestic garbage, are usually disposed without the appropriate measures imposing a high to the underground water resources. Ground-water pollution happens mostly due to percolation of pluvial water and the infiltration of contaminants through the soil. The contaminant fluid results from the decomposition of organic matter and is rich in dissolved salts, containing a substantial amount of polluting substances. When the contaminant liquid reaches the ground-water table, it affects the potability of underground water putting the local community under serious health risk.

One of the most frequent demands in metropolitan areas includes the detection of the location and extent of contamination patches in areas as small as landfill sites. In such a context, the integrated use of various geophysical methods provides an important tool for the evaluation and characterization of contaminants generated by urban residues (domestic and/or industrial). Among the available geophysical methods, electrical and electromagnetic methods have been found remarkably suitable for such environmental studies, due to the conductive nature of most contaminants (Ulrych et al. 1994; Lanz et al. 1994; Sauck 2000; Atekwana et al. 2000; Orlando and Marchesi 2001). Electromagnetic terrain conductivity surveys have been proved particularly useful as they can delineate waste, conductive fluids, and buried metals and provide a three-dimensional model of the buried waste. Degradation of organic material in field-saturated conditions produces a terrain conductance signature that is enhanced above background conditions. The elevated signature can be used to locate waste, delineate the waste boundaries and provide a rough estimate of depth of wastes. Furthermore, geophysical methods can be used to reveal the past history of a landfill as different types of landfills exhibit different properties.

In the current work, fifteen profiles were investigated across the area of the largest waste disposal site of Crete Island, the Fodele landfill, using ERT dipole–dipole techniques, VLF and electromagnetic techniques, seismic refraction and ambient noise measurements. Similar methods were applied in the past for landfill characterization and delineation (Stanton and Schrader 2001; Carpenter et al. 1991; Karlik and Kaya 2001; Powers et al. 1999; Porsani et al. 2004; Bernstone et al. 2000). Initially, the existing borders of the waste site were determined and mapped in detail using Differential Global Positioning System (DGPS) and Geographic Information System (GIS) methods. As a result, the measurement loci were located with the maximum possible accuracy. A detailed geophysical survey was conducted across the Fodele's landfill to define its geometric characteristics. The obtained images revealed the geometry of the less electrically resistive (more conductive) waste material sitting within a quarried-out structure of more electrically resistive (less conductive) bedrock material. Both electrical resistivity imaging and electromagnetic ground conductivity techniques were used to locate and monitor probable leachate plumes escaping from landfill sites. Since the electrical conductivity of landfill leachates is so much higher than that of the natural groundwater, plumes could also be detected. In this case, the known base of the landfill was outlined on the image and the less resistive leachate was seen extending beneath the base of the landfill into the surrounding ground. Verification of the above conclusions was further attempted through the use of seismic and VLF survey techniques.

The particular integrated approach contributed to the evaluation of the effectiveness of the suite of geophysical techniques used in determining the geophysical parameters of the urban landfill.

Geology of the study area

The largest waste disposal landfill of Crete Island, the landfill of Pera Galinous, 3 km west of Fodele village was selected as the application site (Fig. 1). It is situated at a latitude between 35º23′05″N and 35º23′29″N and a longitude between 24º55′18″E and 24º55′46″E, at a distance of approximately 25 km, west of Heraklion, the largest city of the island and about 1 km of the northern shore. The broader area is characterized by NW–SE basin topography while the so-called Fodele landfill, covers an area of 0.125 km^2 with its maximum axis oriented NW–SE as well.

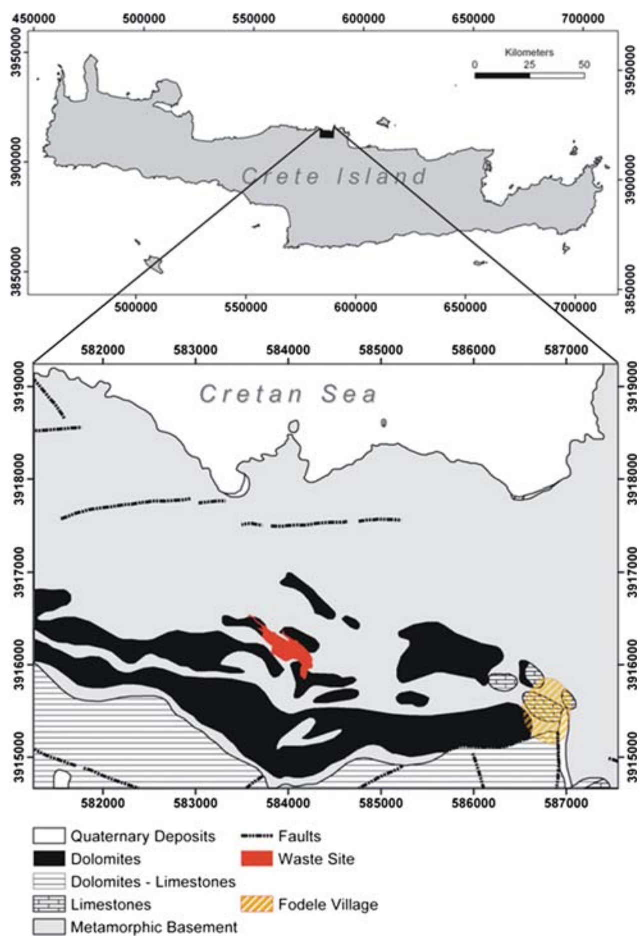

Fig. 1 Location map of the Fodele waste site as well as the geological map of the broader landfill area. The waste site is indicated with *black color*

In a daily base, the Fodele landfill receives wastes from seven municipalities including the local municipality of Gazi as well as the Heraklion municipality. This results in a daily waste deposition equivalent of 200,000 and up to 350,000 people during the winter and the summer period, respectively. The landfill is operational since 1995 and even though it is licensed to receive these vast amounts of wastes, it is not a sanitary landfill, creating a large number of environmental and health/safety problems.

The surficial geology of the study area comprises metamorphic rocks which consist mainly of stratified and trenched carbonates, phyllites, schists and quartzites of the Phyllite–Quartzite formation, that spans in age from Late Carboniferous to Oligocene (Fig. 1). The basin basement exposes the Fodele and Sisses formations which both are composed of Triassic limestones, dolomites, marbles, quartizes, phyllites and conglomerates and are only croped out in the borders of the basin. The local tectonic regime is characterized by discontinuities or fractures of WNW–ESE, W–E and NE–SW directions. The major discontinuity feature, which is responsible for a possible contamination of the subsurface (soil and water), is the WNW–ESE oriented tectonic structure (Fig. 1).

Moreover, the Fodele landfill lies to the east of the stream Flega watershed which covers an area of 7.25 km^2. Ten irrigative boreholes and four springs are registered in the vicinity of the study area and the nearest borehole is almost 500 m east of the landfill. Based on the measurements of the water level in the above-mentioned boreholes, the aquifer is estimated to reach a depth of about 70–80 m below the ground surface.

Surface-geophysical methods and data collection

Geophysical methods provide an efficient tool for characterizing subsurface geology and hydrology. The methods used in this study measure the electrical, electromagnetic and acoustic properties of the subsurface. Iterative and integrated data collection and interpretation using multiple geophysical methods provides a more synergistic interpretation of data that often results in a more accurate model of the complex structures and processes of the subsurface.

Geophysical surveys were conducted along fifteen profiles (Table 1) across the area depicted in Fig. 2. Fifteen ERTs were obtained using a 5 m electrode spacing with dipole–dipole array. Ten very low frequency (VLF) and shallow electromagnetic (EM31) profiles were measured using a 5 m station interval. Two seismic refraction (SR) and twenty ambient noise (HVSR) measurements along three profiles were also carried out. The measurement lines were common for all methods, and they were in an almost NE–SW and NW–SE orientations having variable lengths.

The above-mentioned methodologies (ERT, VLF, EM31 and SR) were selected because according to the literature (Stanton and Schrader 2001; Karlik and Kaya 2001; Porsani et al. 2004; Bernstone et al. 2000), are the best choices for detailed geophysical characterization of waste disposal areas. Specifically, electromagnetic terrain conductivity profiling and electrical resistivity measurements were used to delineate landfill boundaries, trace leachate migration and provide a three-dimensional overview of the buried wastes. Seismic refraction, using time–distance modeling method, was used to determine bedrock topography at/and near the boundaries of the landfill and the wastes thickness. VLF measurements were carried out in an experimental way to track dissolved phase plumes associated with other conductive materials (e.g., a landfill leachate plume). More commonly, VLF is used to help locate fracture zones containing water that may also act preferentially as pathways for the leachate flow. Detection depth for all methodologies depends largely upon overall ground conductivity and velocity with a minimum of approximately 30 m.

Knowing the depth to bedrock (using the ERT results), the material (wastes, cover layer, etc.) properties

Table 1 Implementation of the geophysical methods in Fodele landfill

Applied geophysical methods	Transects															
	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	LB1	LB2	LB3	LB4	LB5
SR					√	√										
EM	√	√	√	√	√	√	√	√	√	√						
VLF	√	√	√	√	√	√	√	√		√	√					
ERT	√	√	√	√	√	√	√	√	√	√		√	√	√	√	√
H/V	√				√	√										

SR seismic refraction method, *EM* electromagnetic terrain conductivity method, *VLF* very low frequency method, *ERT* electrical resistivity tomography method, *H/V* horizontal to vertical spectral ratio method

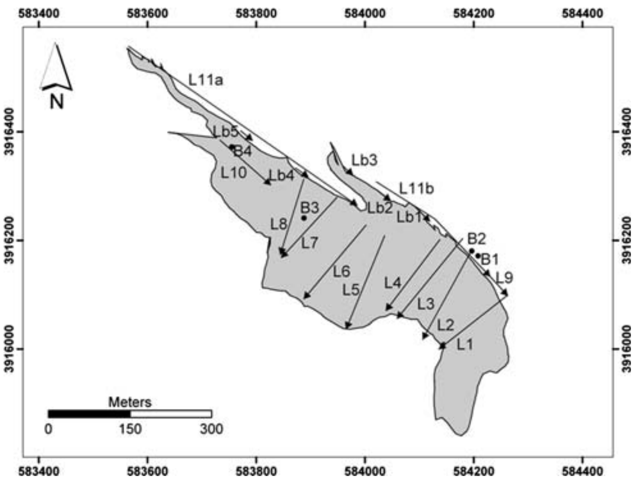

Fig. 2 Location map of the profiles (*L*) along which ERT, EM31, VLF and SR measurements were conducted. The borehole locations were indicated with the *black dots* labelled as *B1–B4*

as extracted from refraction study and the geotechnical study of the area under investigation, it can be possible to make quantitative estimates of ground shaking amplification resonances in the deep soil and landfill area by measuring microtremors at a number of sites in the landfill. Spectral ratios of the signals recorded at the soil and bedrock sites as well as of the horizontal and vertical components at the soil sites are being used to estimate the amount of ground shaking amplification expected on the soil sites as well as the frequencies at which strong resonances are observed. These spectral ratios are useful information to structural engineers and sanitary landfill designers in their efforts to construct earthquake-resistant constructions.

Electrical resistivity survey: ERT

In many cases, the ground cannot sensibly be resolved into plane homogeneous layers, as required for a VES (Vertical Electrical Sounding) study, or into simple zones of lateral conductivity variation as required for profile interpretation. A combination of the two techniques is applied. Electrical resistivity imaging (Griffiths and Barker 1993; Loke 1999; Acworth 1999; Tsourlos 1995) is one approach to this problem. Electrical images can be measured either in two-dimensions, with the assumption that little variation exists in bulk material values in the third (normally the -y-) dimension, or in three-dimensions. Two-dimensional application is routine and the field and interpretation procedures have been developed to the extent that the process is now almost as rapid as for one-dimensional sounding investigation.

For imaging depths of about 30 m, it is more convenient to use an electrode spacing of 5–10 m, depending on the subsurface resistivity. Each electrode (all the combinations of C1-P1-P2-C2) are connected to a take out on the multicore cable which is connected to a manually controlled switching box or to a switching module which is computer-controlled.

Electrical resistivity surveys were planned to determine the lateral extent and thickness of the landfill and to help locate any contamination plume. The geoelectrical data were collected using an IRIS-Syscal Jr. Switch 48 instrument. The system features forty-eight electrodes, enabling fully automated measurements of the shallow subsurface apparent resistivity using the dipole–dipole configuration. This technique has the advantage of a very good horizontal resolution while its main disadvantage is the relatively low signal strength. Fifteen geoelectrical profiles were measured using dipole–dipole configuration (Table 1, Fig. 2). The logs from four geotechnical boreholes were also used for the finer interpretation of the results of ERTs. The dipole–dipole spacing "a" was set equal to 2–5 m enabling the detection of bodies and/or structures up to a 40 m depth, which could be considered satisfactory for exploring near-surface environmental problems due to probable leakages in the study area.

The collected geoelectrical data were processed by means of the RES2DINV (Loke 1997) modelling software in order to perform 2D geoelectrical data inversion. The inversion routines are based on the smoothness-constrained least squares method (Sasaki 1989, 1992; Loke and Barker 1995, 1996a, b) and the forward resistivity calculations were executed by applying an iterative algorithm based on a Finite Element Method (FEM). The inversion program attempts to determine the resistivity values of the model prisms directing towards minimizing the difference between the calculated and the observed apparent resistivity values. The goodness of fit is expressed in term of the RMS error.

Shallow electromagnetic measurements: EM

Electromagnetic terrain conductivity (EM) surveys have been employed for landfill investigations for over 20 years (McNeill 1980). Advantages of electromagnetic terrain conductivity survey mapping over other geophysical methods include: excellent resolution in conductivity; no current injection problems; simple multi-layered earth calculations; and easy, rapid measurements. Disadvantages of EM for exploratory investigations are few but include: limited dynamic range; setting and maintaining the instrument zero; and limited vertical sounding capability. The later has been recently approached through the development of multi-frequency EM instruments.

EM surveys are principally used for landfill boundary detection (Mack and Maus 1986; McQuown et al. 1991; Rumbaugh et al. 1987; Scaife 1990; Stenson 1988) and detection of leachate contaminant plumes (Hall and Pasicznyk 1987; Mack and Maus 1986; Russell 1990; Walther et al. 1986). Several researchers strongly recommend EM surveys for the identification of volatile organic plumes such as gasoline (Fawcett 1989; Olhoeft 1986; Olhoeft and King 1991; Saunders and Cox 1987).

While groundwater monitoring wells are aerially limited and somewhat an expensive sentinel strategy, EM surveys are inexpensive and effective for establishing compliance (McNeill 1990; Rumbaugh et al. 1987). EM surveys can also be used to monitor the efficacy of a treatment system (Medlin and Knuth 1986). The electrical conductivity of soil is a function of the porosity, permeability, and fluids in the pore spaces (McNeill 1980). Degradation of solid waste generates conductive leachate that fills pore spaces and can be easily imaged with a frequency-domain terrain conductivity meter (Hutchinson 1995). The absolute values of conductivity obtained in a survey are not necessarily diagnostic but the variations in conductivity can be used to identify anomalies (Benson et al. 1988).

The field-collected electromagnetic terrain conductivity measurements can be modified through a simple algorithm based upon native soil conductivity to produce plan maps showing waste boundaries. Further, case studies of regional landfills confirm a linear relationship between measured waste (terrain) conductivity and thickness of waste (Hutchinson and Barta 2000). This relationship can be used to estimate waste volume without the need of seismic or resistivity surveys (the most effective geophysical tool for measuring depth of waste) or intrusive methods (i.e., borings).

A Geonics EM31-MK2 instrument was used for the EM-survey which induces currents to the ground by emitting a 9.8 kHz electromagnetic field. The prospecting mode had been set to carry out measurements in almost parallel profiles covering all the landfill area. Readings were taken stepwise at 5 m steps along the parallel profiles in order to achieve high-resolution mapping. The measurement layout is depicted in Fig. 2.

Due to the existence of metals at the investigated area, de-spiking algorithms were applied to filter out extreme values that aggravated the identification of interesting anomalies. Application of filtering was crucial in cases where data suffered instrumental and/or geological noise.

VLF measurements

VLF surveying is an effective method for detecting long, straight, electrically charged conductors, and it has been used to locate fractures, image subsurface voids, map landfill margins, and to delineate buried conductive utilities. High-powered military transmitters operating in the 15–30 kHz range propagate far-field planar electromagnetic waves that can induce secondary eddy currents in electrically conductive linear and planar targets. VLF meters record responses to the induced current and, through filtering, can accurately locate linear and steeply dipping planar subsurface anomalies.

VLF surveying is easy to use, deploy, and process and more important, is inexpensive. Despite this, geophysicists have been reticent to employ it because of the lack of source control (i.e., transmitter is operated by the military and it may be turned off during data collection) and limited knowledge of the tool's capabilities and limitations. Although, dependence on a military transmitter can be obviated by the use of a commercial transmitter, this decreases the rapid deployment of the tool.

Other limitations of VLF surveying are sensitivity to ferrous and nonferrous cultural noise, single-point data collection, and relatively shallow depth of investigation (probably no more than 75 m, but still within the depth window of environmental investigations). Nevertheless, the tool can provide an inexpensive alternative to drilling or other intrusive investigations.

In order to detect possible WNW–ESE fracture zones or contaminated plumes in the same direction, the stations of 20.7 kHz (UFT in France) and 17.1 kHz (UMS in Russia) were selected as the most suitable transmitters in the study area to acquire the L1-8 and L10 VLF profiles. The selection of the transmitters was based on their proper operation and orientation and the quality level of the transmitted signal (which depends on the propagation conditions and distance between the transmitting antenna and the prospection area). Afterwards, to detect any tectonic feature in the ENE–WSW direction, the stations of 21.41 kHz (NSS) and 24.0 kHz (NAA) both situated in USA were selected (Lines 11a and 11b).

We should mention that in this work the application of VLF method suffers from the following drawbacks: (a) the area under investigation is a narrow and deep elongated valley which means that it was quite difficult to have good quality of the electromagnetic signal, and (b) the noise was very high due to the interference from the nearby metallic materials such as, metal pipes, cables, fences, abandoned cars, etc.

Ambient noise measurements: microtremors

The usefulness of microtremors as a geophysical exploration tool has been analyzed. This application is possible due to the relationship between the main resonance frequency of a given soil, obtained from the H/V spectral ratios of microtremors, its thickness and average shear velocity. We first measured the ambient noise at twenty sites and determined their main resonance frequency. Geophysical information (geoelectrical tomographies and shallow electromagnetic surveys) was available for ten profiles perpendicular to the main strike of the landfill, thereby allowing us to have an accurate estimation of the thickness of the wastes. This knowledge could permit us to estimate the relationship between the resonance frequency and the thickness of the wastes and indirectly between either of them and the shear velocity of the top strata (wastes and soil). The calculated shear velocity could be easily confirmed using geotechnical parameters such as SPTs as acquired during the geotechnical study of the landfill. The practical application of this relationship has revealed its usefulness in determining the subsurface structure of a landfill with excellent accuracy, with an error of almost 10% in the shear velocity determination. These errors are derived from the complex structure of the study area. Specifically, the method assumes that the shear velocity varies constantly with depth throughout the study area, which is not always so evident, and that the input data and especially the microtremor measurements themselves intrinsically have a high degree of uncertainty. This method is therefore not valid when there is no mechanical contrast between the study area and the underlying stratum or when the shear velocity varies irregularly with depth and when the structure of the area investigated is fully three-dimensional. Detailed studies of the above-mentioned problems have been implemented by Delgado et al. (2000a, b); Seht Malte Ibs-von and Wohlenberg (1999); Parolai et al. (2001), (2002) and Delgado et al. (2002). Actual measurements of dynamic material properties for landfills are limited and have been estimated by others from empirical strong motion and field data collected from several landfills (Augello et al. 1998; Kavazanjian and Matasovic 1995; Kavazanjian et al. 1995; Matasovic and Kavazanjian 1998).

For the determination of the resonance frequency in the landfill, three traverse lines were conducted, and a total of twenty HVSR measurements were taken. Two acquisition systems were employed, City Shark logger with Lennartz 3D-5 s and Reftek 130A logger with Guralp CMG-40T 1 Hz. Lennartz 3D-5 s seismometer has the same response in the frequency range 0.2–20 Hz, therefore the spectral ratios were calculated without instrument correction in that range of frequencies. For the Guralp CMG-40T 1 Hz seismometer, the flat response range is 1–20 Hz. Measurements were taken for 20 min, and the HVSR was calculated using automated window selection of 20 s. Fourier spectrum was calculated for each window, applying a Hanning window and a taper of 5%. The resulting spectra were smoothed according to Konno and Omachi (1998). The average spectral ratio of the horizontal-to-vertical ratio was calculated with quadratic average.

Seismic refraction measurements: SR

Published seismic refraction investigations are common in engineering seismology and engineering geophysics (Bhowmick et al. 1996). The objective of this part of experiments was to examine whether simple seismic refraction techniques could be used to determine soil thickness and identify differences in the acoustical properties of fractured and unfractured rock.

Seismic refraction data were acquired along two profile lines (lines 5 and 6) as is shown in Fig. 2. The data were acquired with a Geometrics R-24 Strataview digital seismograph and the signals were recorded by twenty-four 12-Hz OYO-Products geophones deployed at 10 m and occasionally at 7 m intervals along the refraction lines. A 7 kg sledgehammer striking a metal plate was used as the seismic source. Geophones were almost buried beneath the surface to reduce interference from the ground-coupled sound wave. Data were then downloaded to a microcomputer for processing and interpretation.

Selected shots were used to build velocity profiles for each line using the SIP family of routines (Rimrock Geophysics 1995). The SIPT-2 code allows co-processing of up to seven shots for each geophone spread. First arrivals were picked using the SIPIK code. Picking was quite difficult since the first arrivals have VLF content, and thus are ‘‘emergent’’ (the amplitude builds slowly, rather than abruptly). These attributes of the first breaks result in a higher likelihood of having a few milliseconds of error in the selected arrival times, and can result in a final model that is less precise. Once first breaks were selected, they were incorporated into a data file for each profile line, using the SIPIN and SIPEDT codes.

The data file includes precise positions for each geophone and shot point, and all of the first arrival picks. Each pick was assigned to a specific subsurface layer in the data file. In our data sets, this was more

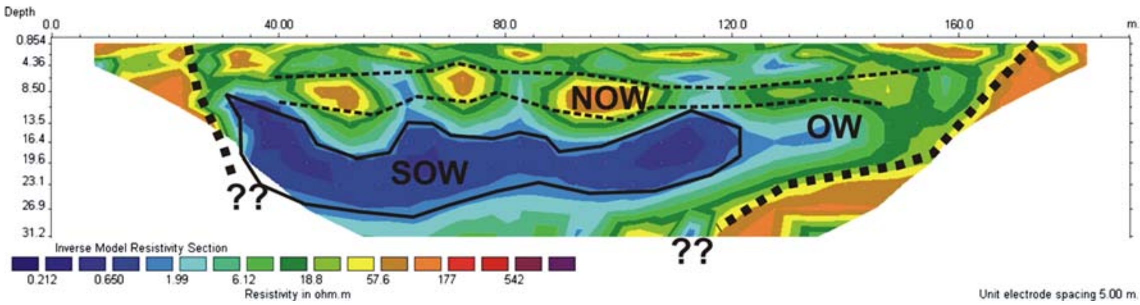

Fig. 3 The 2D inverse model resistivity section of *line 2*. The *thick dark dotted line* shows the boundaries between the bedrock and the waste. The inner structure of the landfill is also given as described below. *SOW* organic waste saturated in leachates, *OW* the area filled with organic waste, *NOW* completely inorganic materials ranging from metallic wastes, debris made of concrete to weathered rocky materials and bedrock formation

difficult than for other sites because the high complexity of the subsurface. SIPT-2 processing assumes the existence of discrete layers that are laterally continuous and have constant velocity. The layers which were selected at the course of processing were based on the assumption of constant velocity strata.

Results of geophysical investigations

ERT interpetation

The results of two of the fifteen ERT profiles are displayed as cross sections of the "true" resistivity distribution of the earth (Fig. 3, 4). Concerning Fig. 3, a shallow conductive zone was detected from about 25 to 100 m along the survey line. This zone is interpreted to be either a plume of conductive leachate in the unconsolidated material, an area of different sediment type, or more saturated sediment.

The bedrock under the landfill appears to be more conductive than the bedrock to the side of the landfill; however, modeling indicates that the decreased resistivity may be an artifact generated during the inversion process by the conductive landfill contents. Bedrock in both Figs. 3 and 4 is suggested at depths of 30–35 m.

Similar results were obtained from the profile 6, where a conductive zone (noticed as liquid phase in Fig. 4) was detected from about 35 to 90 m along the survey line and from the depth of 14 m till the depth of 27 m. This zone is interpreted to be a plume of conductive leachate in the unconsolidated material. As mentioned above, the bedrock under the landfill appears to be more conductive than the bedrock to the side of the landfill, and is interpreted at a depth of 20–31 meters (black dotted thick line in Fig. 4).

The mean values of RMS errors for all the conducted geoelectrical profiles ranged from 10 to 55%. High RMS errors (greater than 20%) could be reasonably explained by the highly inhomogeneity of the area under investigation (high resistivity contrast between the deposits of wastes and the bedrock). These terminally resistivity values (0.05–540 Ohm.m) cause several computational problems during the inversion process since it is difficult to find a unique mathematical model which could reconstruct quite well this complex environment. Moreover, bad contact between the electrodes and the ground (wastes) could be responsible for higher noise levels that could further affect the inversion process.

Digitizing the interface between the deposited wastes and the bedrock in the study area as estimated by applying the 2D ERT survey, could provide an estimate of the depth to the bedrock (thickness of the waste). The calculated depths were interpolated with geostatistical and deterministic techniques. We used the inverse distance–weighted (IDW) deterministic interpolation method to create the waste thickness map as is shown in Fig. 5. Maximum waste thickness is suggested for the central area of each profile following the basin orientation (black dashed line in Fig. 5). This information can be used in the decision making process for the appropriate remediation method depending on the characteristics (thickness, type of wastes, etc.) of the landfill.

Moreover, the determination, classification and the spatial distribution of the different strata (SOW, OW and NOW) were extracted from the successive application of the geoelectrical tomography (Table 2).

EM interpretation

De-spiking filters based on the mean value and the standard deviations of the measured values were applied on the EM measurements in order to remove the extreme conductivity values from the data set.

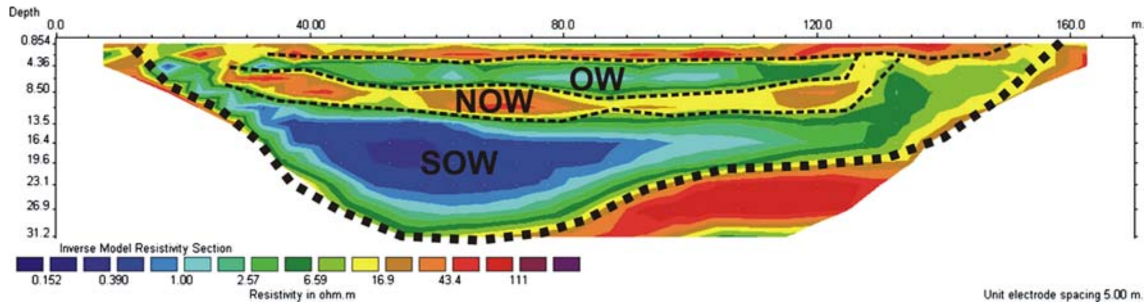

Fig. 4 The 2D inverse model resistivity section of line 6. The *thick dark dotted line* shows the boundaries between the bedrock and the waste and the inner structure of the landfill is also given by *dashed lines*. *SOW NOW* and *OW* are the same as in Fig. 3

Application of filtering was crucial in cases where data suffered from instrumental and/or geological noise.

The collected EM measurements exhibit the variation of conductivity (mS/m) or resistivity (Ohm) along the profiles. The electrical conductivity (EC) ranges from 45 mS/m to about 170 mS/m (Fig. 6). The EC pattern clearly demonstrates areas of high and low conductivity. The lowest EC values are found at the boundaries of our model defining directly the lateral boundary between the bedrock and the deposited wastes. The high EC values between 40 and 150 m could be easily correlated with the presence of leachate and deposited wastes in this area which contains the highest salt concentration.

The results of shallow electromagnetic measurements are in good agreement with the geoelectrical tomography in terms of either the absolute values of conductivity/resistivity or the identification of the spatial extend of the landfill. As an example, the comparison between the resulted shallow electromagnetic image of line 3 and the 2D resistivity image for the same location is given in Fig. 6. The variation of the measured conductivity along the profile as is shown in the aforementioned figure (upper scheme) appears to have similar "shape" as is shown in the lower part of the Fig. 6 by the thick dashed black line. The only discrepancy reported at 105 m along the profile, where the EM measurements indicate a high conductivity area while the ERT profile shows a shoaling of the high

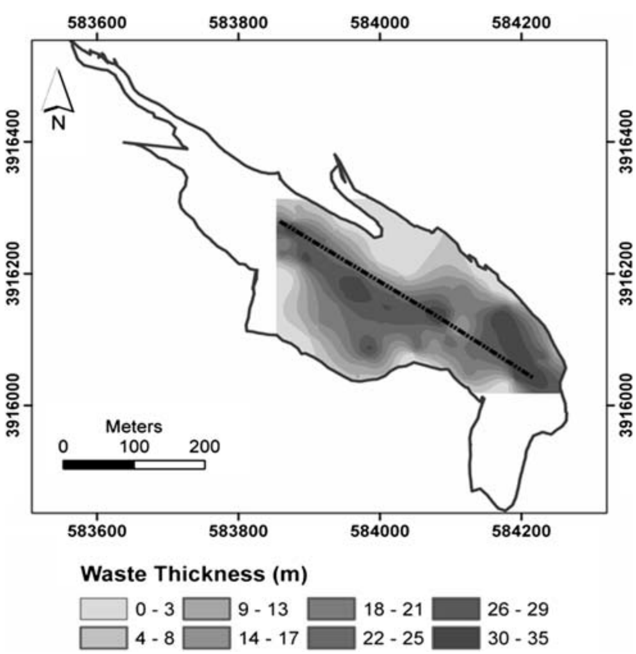

Fig. 5 The waste thickness map for the central part of the under investigation waste site of Fodele. The NW–SE trending distribution of the waste is shown using the *black dashed line*. The maximum thickness values coincides with the basin orientation (NW–SE)

Table 2 Classification of the wastes in four categories

Line	X-location (m)	Thickness (m)
NOW (50.00–540.00 Ohm.m)		
1	60–80	17
3	0–30	20
8	20–30	15
LOW (20.00–50.00 Ohm.m)		
4	40–60	19
5	110–120	15
6	130–140	16
OW (4.00–20.00 Ohm.m)		
8	40–55	> 20
1	80–90	> 20
7	80–90	> 15
SOW (0.00–4.00 Ohm.m)		
5	40–50	20
6	45–50	7
3	65–75	8

The thickness in meters for each category in several places in the landfill is also given

SOW organic waste saturated in leachates, *OW* organic wastes, *LOW* low organic wastes and *NOW* completely inorganic materials ranging from metallic wastes, debris made of concrete to weathered rocky materials and bedrock formation based on the resistivity range

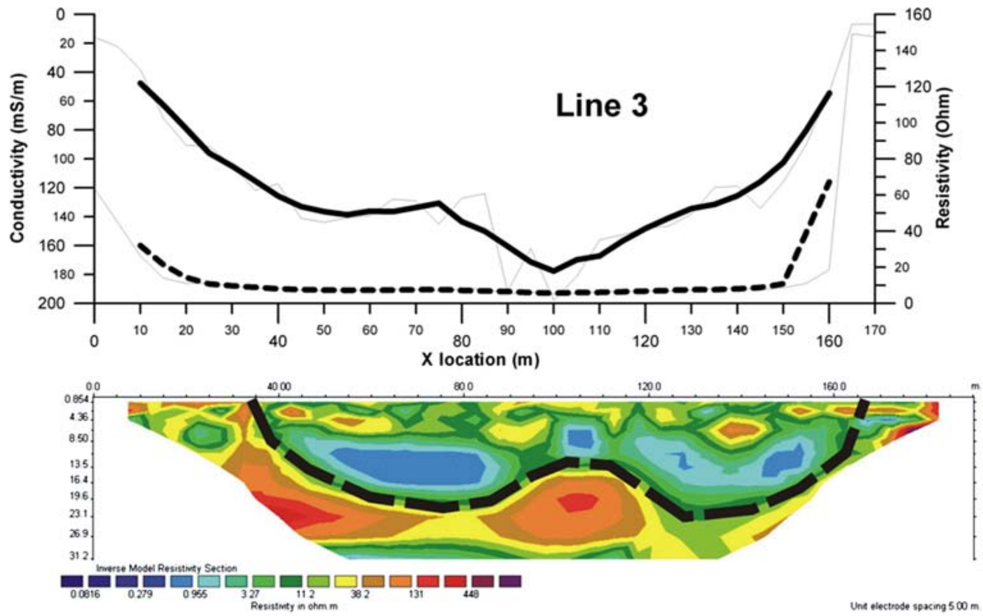

Fig. 6 Surface geophysical data for EM-3 (*upper figure*) and ERT-3 (*down figure*) profiles in Fodele landfill. *Black solid line* and *dashed line* represent the variation of inductive terrain conductivity and resistivity, respectively, along the profile and the *dashed thick black line* shows the boundary between the deposited wastes in the landfill and the bedrock. *Thin line* indicates the raw measured data and the *thick solid line* shows the filtered/ smoothed model

resistive bedrock. The divergence could be caused by the existence of surficial metal deposition (reinforcement concrete, home appliances, etc.) in the specific area, which causes noise to the sensitive EM measurements.

Conductivity measurements were conducted along nine selected profiles (P1-P9) with a measurement step of 5 m. In this way, a total of 284 regularly distributed points of known conductivity values were obtained. The above-mentioned measurements were imported as point data into a GIS environment and were contoured using interpolation functions. The conductivity map that was finally produced covers the main part of the study waste site (Fig. 7) and reveals a NW–SE oriented distribution of the maximum conductivity values which is spatially correlated (almost coincides) with the NW–SE orientation of the existed basin structure as well as with the waste thickness (Fig. 5). The high conductivity areas (more than 100 mS/m) could be directly correlated with the highest waste thickness and the areas where the leachates were accumulated due to the bedrock relief as are shown in Figs. 3, 4, 6, 9 and 10.

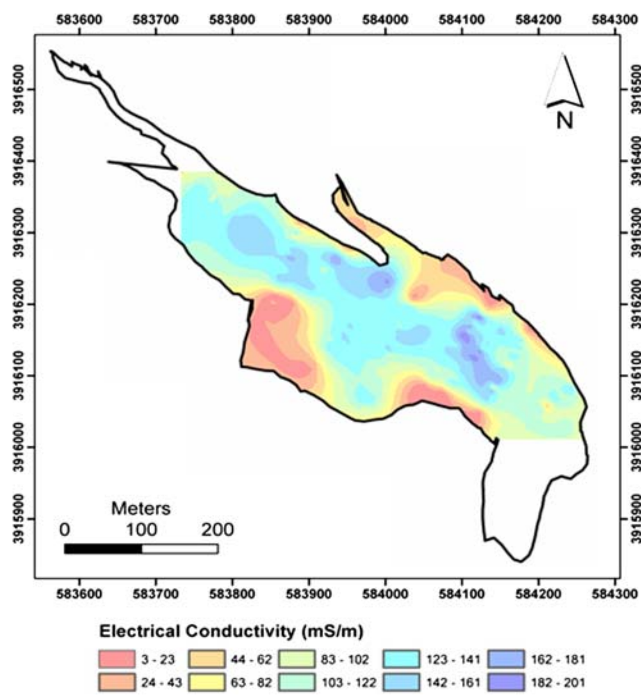

Fig. 7 Electrical conductivity map for the central part of the under investigation waste site of Fodele. The spatial distribution of the conductivity values shows a NW–SE trend, parallel to the basin orientation

VLF interpretation

The IRIS T-VLF system was also employed in this survey. Ten VLF profiles were carried out along selected profiles of the electrical tomography and EM31 survey.

The Karous-Hjelt and the Fraser filters were applied (Karous and Hjelt 1983; Fraser 1969) to give an easier correlation between the anomaly and the structure. The Fraser filtered data of profile 6 are given in Fig. 8. The Fraser filter is designed for the noise suppression of the data. Specifically, the modified 5-point Fraser filter was used to plot the output of the filter at the same locations as the tilt angle measurements. After

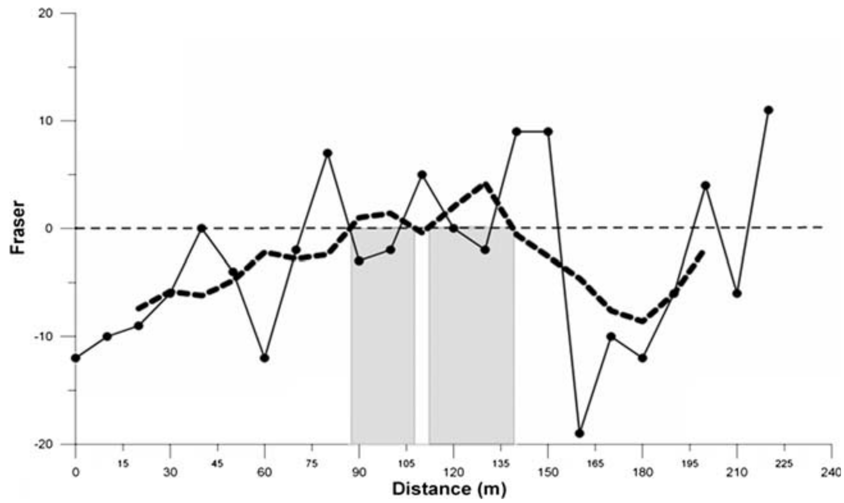

Fig. 8 VLF profile 6. In the *x*-coordinate, the distance from the beginning of the profile is given. In the *y*-coordinate, the filtered data with Fraser filter are given. The *solid line* indicates the observed VLF data. *Thick dashed line* is the 5-point filtered/smoothed line of the raw data

application of the Fraser derivative, the maximum of the Fraser curve is located just above the position of the anomaly. Based on that, two conductive zones (possibly leachate plumes) are located between 87 and 110 m and between 115 and 140 m.

Unfortunatelly, the results from VLF survey are not very precise when compared with the tomographic images resulted from ERT survey (see Fig. 4, SOW area) for the majority of the profiles. Singularities of the study area such as: (a) the morphological characteristics (deep-V shape and narrow gorge) of the valley where the landfill is situated, (b) the functional inability of the method in horizontal layers of soil and rock when soil is electrically conductive (this is our case), (c) the difficulty to find the appropriate VLF transmitter oriented approximately towards the fracture axis and (d) the high interference from nearby metals such as pipes, cables, fences, vehicles, etc., could have caused the unclarity and the unreliability of the VLF measurements in this complex area.

Microtremors interpretation

In most of the microtremor measurements a single peak is observed, while in some sites two peaks appear. An anomalous result appears at site L5060 (Line5 at 60 m), where frequency appears flat while ERT shows that waste deposits extent to a depth of more than 35 m. It is probable that the noise measurement coincided with strong gust of wind; the amplitudes in the low frequencies range were high and masked the peaks of the spectrum.

Based on the relationship, $f = V_s/4z$, and having an estimate of the basement depth from the resulted ERT images, we were able to derive a shear velocity model for the waste deposits. On the other hand, it was difficult to derive an analytical relationship between resonance frequency and depth, since the landfill exhibits extreme lateral variations due to the nature of waste deposits.

Across Line 6 (Fig. 9), seven measurements were taken with Lennartz Le 3D-5 s. Sites M6010 (solid yellow line) and M6170 (solid black line) have almost

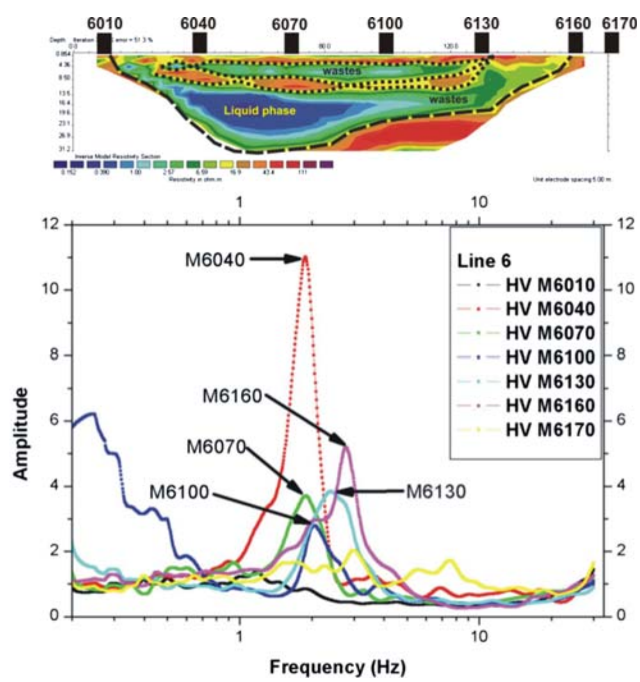

Fig. 9 HVSR measurements along Line 6. The microtremors measurements were carried out in the *black filled rectangles*. In the lower part of the figure, the spectrum of the HVSR measurements is given. The first (*M6010*) and the last (*M6170*) measurements have almost flat response (located at the outcrop of the bedrock), while all the other sites (*M6040-M6160*) have one resonance frequency that appears as the single pick in the spectrum

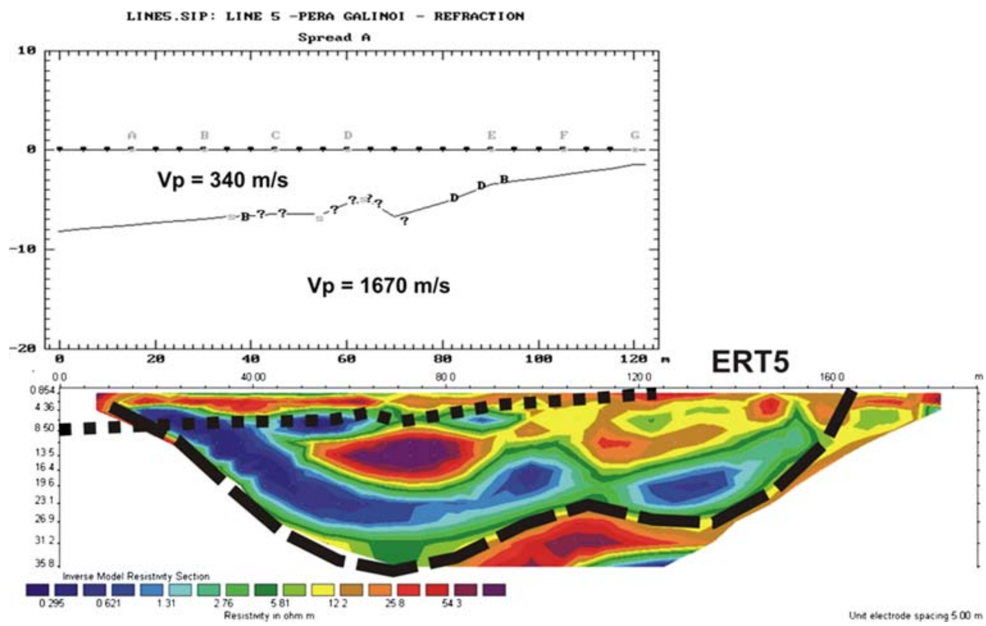

Fig. 10 Comparison of the refraction seismics (*upper*) and the resulted tomographic images from geoelectrical tomography (*lower*) for the same Line 5 profile

flat response (compared to the other locations), since they are located at the outcrop of the bedrock (phyllites). As we move from the limits of the landfill to the center of the waste disposal area, the frequency response changes from flat response (no accelaration/amplitude) to a single peak frequency spectrum. Thus, at all the other sites (sited over the waste deposits) a single peak appears, ranging from 1.88 to 2.99 Hz. From the corresponding ERT measurements (see Fig. 9) the depth of the waste deposits was estimated together with the calculated shear velocities of the waste deposits (Table 3). The estimated V_s model should be confirmed by refraction seismics in order to be precise and reliable by the civil engineers who are responsible for the landfill planning.

Prediction of ground shaking response at soil sites requires knowledge of stiffness of the soil, expressed in terms of V_s. While it is preferable to determine V_s directly from field tests, it is not often economically feasible to make V_s measurements (using refraction seismics, spectral analysis of surface waves or microtremors measurements) at all locations. Thus, to take advantage of the more abundant penetration measurements, correlations between V_s and penetration resistance (standard penetration test—SPT) are needed. Blow count (SPT-N) and depth (or overburden pressure) are significant parameters in V_s-SPT correlations. The SPT-N is the number of blows required to achieve penetration from 150 to 450 mm. The first increment (0–150 mm) is not included in the *N* value as it is assumed that the top of the test area has been disturbed by the drilling process.

Table 3 Resulting shear velocity from HVSR and ERT

Site	Resonance frequency (Hz)	Depth-to-basement (m)	Shear velocity (m/s)
M6010	Flat response	0	0
M6040	1.88	23	172.96
M6070	1.88	31	233.12
M6100	2.05	22.5	184.5
M6130	2.39	19	181.64
M6160	2.78	0	0
M6170	Flat response	0	0

Thus, it was decided to calculate the V_s model using the a-priori known geotechnical properties of the study area since the mechanical properties of the rocks and the wastes are well known, thanks to the four geotechnical boreholes (Fig. 2, B1–B4) drilled in the landfill (Table 4). The goal of this approach was to acquire a reliable estimate of shear velocity using the empirical formulas found in the literature and concerning similar soil formations and comparable geological conditions (Anagnostopoulos et al. 2003). Thus, the following formulas were selected to estimate the variability of the shear velocity in the landfill.

For non-cohesive soils, the following relationship is proposed by Kalteziotis et al. (1992a, b):

$$V_s(\mathrm{m/s}) = 49.1 \cdot N_{\mathrm{SPT}-N}^{0.502} \quad (1)$$

For non-cohesive sand and clayey and silty sand, the corresponding relationship is (Lontzetidis et al. 1997):

$$V_s(\mathrm{m/s}) = 123.44 \cdot N_{\mathrm{SPT}-N60}^{0.286} \quad (2)$$

Table 4 Geotechnical properties of rocks and wastes in the Landfill

		Wastes	Phyllites quartz	Weathered and fractured phyllites
	Natural moisture-w (%)			14.6
	Dry weight-yd (kN/m^3)			15.8
	SPT	1-1-1	50/7	50/5
Grain size analysis	4	66	73	
	10	54	59	
	40	42	45	
	200	33	34	
Atterberg limits	Liquid limit (LL)	26	29.5	
	Plasticity limit (PL)	21.3	22.3	
	Plasticity indicator (PI)	4.7	7.2	
	Soil classification (U. S. C. S)	SM-GM	SM-GM	
	Gravity Gs		2.7	
	Compression Es (kpa)		2.36	

Finally, for mixed clay–gravels soils, the proposed relationship is given by Lontzetidis et al. (1997):

$$V_s(\mathrm{m/s}) = 192.41 \cdot N_{\mathrm{SPT}-N60}^{0.131} \tag{3}$$

where SPT-N60 is the normalized value for the SPT, corrected for overburden pressures and field procedures. It assumes a standard of 60% of efficiency of the penetration hammer. If there is an uncertainty about the efficiency of the hammer, it can be assumed that $N = N60$ (Skempton 1986; Liao and Whitman 1986).

Applying $N_{\mathrm{SPT\text{-}N/60}}$ equal to 2 (based on the Table 4), we obtained shear velocities varying from 69 to 210 m/s. After all, the estimations of V_s obtained from the application of the empirical relationships (69–210 m/s) with those calculated from the definition of the resonance frequency and the thickness of the upper stratum (wastes) (173–233 m/s) are in very good agreement and can be safely used by the engineers for a detailed estimation of seismic site response analysis and the prediction of seismic displacements of cover sliding (Zekkos 2005) and also to prevent the site from other correlated environmental problems.

Seismic refraction interpretation

The time-intercept seismic refraction model for all shots in Line 5 shows a surface layer of variable thickness and low velocity, presumably associated with dry, unconsolidated sediments (Fig. 10). The underlying layer is not clearly differentiated in the data because of the noise in the first arrival travel times due to the high inhomogeneity of the area. Based on the estimated velocity, the second layer is suggested to be composed of saturated unconsolidated wastes. The interface between the two layers is correlated with the interface between the layer of sand/gravels and other weathered materials used to cover the waste layer as is shown in the lower part of Fig. 10.

The results of refraction seismic section are in good agreement with geoelectrical tomography. As an example, the comparison between the resulted tomographic image of Line 5 seismic profile and the 2D resistivity image for the same location is given in Fig. 10. The top layer, having a thickness of approximately 5 m, is a high resistivity/low velocity layer with values ranging between 25 and 50 Ohm.m and 340 m/s, respectively. Below this layer and down to 20 m, there is a low resistivity/high velocity layer with resistivity values ranging between 0.20 and 6.00 Ohm.m and velocity equal to 1,670 m/s, respectively. Since, the theoretical saturated sediment velocity of P-wave is about 1,500 m/s, we could reasonably assume that the velocity of 1,670 m/s corresponds to saturated wastes. This is in agreement with the results of the geoelectrical tomography for the same profile (0.20–6.00 Ohm.m corresponding to conductive leachates).

Conclusions

A feasible study was presented for an integrated investigation of landfill sites using modern techniques. In this study, we have attempted to demonstrate some of the advantages of integrating information from five different approaches. Chemical analyses and laboratory measurements were used for the confirmation of the surface-geophysical results and all these could be successfully used as part of a hydrogeologic assessment of contamination of soil, surface water, and ground water in and around the Fodele landfill in Heraklion, Crete Island.

It was proved that an electrical resistivity imaging survey coupled with terrain conductivity profiles could be successfully conducted across a disused landfill site in order to define the depth extent and geometry of the landfill. These images reveal clearly the geometry of the less electrically resistive (more conductive) waste material sitting within a quarried out structure of more electrically resistive (less conductive) bedrock material. These, along with other imaging line data, enable the estimation of the volume of waste (landfill thickness of 20–35 m).

Both electrical resistivity imaging and electromagnetic ground conductivity techniques were used to locate and monitor the spatial distribution of leachate plumes inside landfill site. Because the electrical conductivity of landfill leachate is often so much higher than that of the natural groundwater, a large contrast in properties is seen enabling the detection of the plume. In our case, the known base of the landfill is drawn on the image and the less resistive leachate is also imaged.

ERT method allows the identification of: (a) the depth and thickness of the buried waste, (b) the presence of leachates (or water), which is a requisite for the active decomposition of the organic waste, and (c) the composition (synthesis) of the waste separating the buried materials into at least four categories: (1) organic waste (OW), (2) saturated in leachates OW (SOW), (3) wastes of mainly inorganic nature with low concentration of OW (LOW) and (4) debris or soil (NOW). If a landfill is adequately scanned by the ERT technology, then it would be possible to predict high-efflux from low-efflux areas within the landfill, estimating for a specific time period, the amounts and nature of the waste that has been piled up.

The determination of some of the dynamic characteristics of the landfill (V_s model and knowledge of the resonance frequencies of site vibration and frequency range of the amplification of ground motion) via HVSR and in situ geotechnical techniques, can be useful for engineering analysis of site slope performance and permanent deformation of the study area due to earthquake loading.

On the other hand, the results from VLF survey were not very precise compared with the electrical tomographic images because of the singularities of the study area (steep topography, difficulty to find the appropriate VLF transmitters and high interference from nearby metals). Contrarily, the seismic refraction model was in good agreement with the inverted geoelectrical profile and could be safely used for confirmation purposes.

The above findings indicate the importance of using an integrated approach of geophysical techniques for acquiring the physical properties of landfills. The employment of different techniques allows the resolution of possible discrepancies and the most accurate description of landfill's characteristics.

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