Magnetic data interpretation in an industrial waste landfill

Alberto Godio
Dipartimento di Georisorse e Territorio, Politecnico di Torino, Italy

Abstract
A magnetic and an electromagnetic survey using low induction equipment were performed on a test site in an industrial landfill; the main goal of the geophysical survey was to check the reliability of data processing techniques for detecting iron masses inside the upper part of the landfill. Physical and chemical characterisations of the test area, performed on some samples, supplied the geophysical investigations. This paper outlines the data processing of the magnetic data, which was mainly based on the solution of Euler's equation to detect near surface magnetic sources, associated with iron concentrations. The results of the magnetic survey delineate the existence of high concentration of ferro-metallic objects; the magnetic behaviour of the waste disposal is affected by the presence both of fine iron materials disseminated in sandy and clayey materials, derived from the cast iron foundry industrial process, and ferro-metallic objects such as drums or parts of heavy machines. Some trenches, excavated in the test area, proved that the magnetic behaviour of the landfill is mainly caused by the high concentration of fine iron materials disseminated in the waste. Therefore, magnetic surveys could be useful tools for detecting zones of high concentrations of iron particles in the landfill; this material can be recovered from the landfill and recycled.

Key words *magnetic survey – Euler's deconvolution – foundry wastes*

1. Introduction

Magnetic surveys for environmental applications are usually employed for a fast and accurate localisation of buried iron objects in waste landfills or to detect buried metallic drums in the investigation of hazardous areas (Tyagi *et al.*, 1983). In most environmental applications, the data processing involves very simple steps for mapping the magnetic data; in many cases, especially in very shallow surveys, a simple evaluation of the maps allows one to localise the main metallic features in the subsoil. Data processing with enhancement procedure can substantially improve the reliability of magnetic surveys: Roberts *et al.* (1990) showed the reliability of upward continuation and of wavelength filtering to reduce the magnetic noise due to shallower metallic objects. In most environmental applications, the quantitative interpretation of the magnetic data using automatic or semi-atomatic procedures (Plouff, 1976; Bhattacharya, 1978; Godson, 1983) may be not reliable because of the effects of strong near surface heterogeneity.

The main aim of this work is to demonstrate the effectiveness of magnetic surveys for site characterisation of an industrial landfill. A preliminary test was carried out on a small cell of the landfill. The magnetic survey is part of a multidisciplinary approach for landfill characterisation through other geophysical methods (electromagnetic techniques), soil sampling and physical and chemical analysis of the materials.

Mailing address: Dr. Alberto Godio, Dipartimento di Georisorse e Territorio, Politecnico di Torino, C.so Duca degli Abruzzi 24, 10129 Torino, Italy; e-mail: godio@vdiget.polito.it

This paper outlines the data processing of magnetic data, which was mainly based on the solution of Euler's equation to detect near surface magnetic sources, associated with iron concentrations in the landfill. Euler's equation allows a fast and semi-automatic detection of the spatial position of the magnetic sources.

The final goal of the research was to check the reliability of the geophysical survey as an aid for detecting a landfill zone with high concentrations of iron particles and delineating the volume of sandy materials, that could be recovered.

2. Site condition

The geophysical test was performed on a small cell of an industrial waste landfill where residues from two iron foundries were landfilled. The landfill was cultivated, starting from 1989 till April 1998, with a total capacity of about 180000 m^3. The maximum depth of the waste disposal is about 15 m.

The first step of the study allowed the establishing of the kind and quantity of wastes produced by the two industrial plants and discharged in the landfill. The most interesting fractions, considering the possibility of an internal recycling, are those of metallic iron wastes and silica sands from the molding and core operations. Each kind of waste was sampled and characterised from a magnetic point of view. Measurements of susceptibility values on samples were carried out using a BISON magnetic susceptibility system model 3101; this equipment is able to measure the magnetic susceptibility of rocks and other materials in the range from 0.00001 to 0.1 cgs units. Higher values can be measured using simple diluition of magnetic with non-magnetic materials. The specimens were sampled from the same materials of the industrial process before being confined in the landfill. The values of susceptibility show a considerable difference according to the sampled material.

The data in table I pointed out that the mere magnetic characterisation could not solve the problem of distinguishing between the different materials in the landfill; due to the special process involved in the foundry, all the samples show a magnetic behaviour for the presence of fine iron disseminated in the materials. Some differences are appreciable between slags (low susceptibility values) and calcium hydroxide; however, very low percentages of these materials are confined to the landfill. It appears to be quite difficult to separate the magnetic behaviour of foundry sand from muddy and clayey materials. On the other hand, the density values are quite similar for the different types of materials; this observation led to the decision to avoid the use of pseudogravity transformation of magnetic anomalies as a tool to improve the reliability of the magnetic data interpretation.

3. Data acquisition

On the basis of the preliminary laboratory results, two different geophysical methods were checked on a 50 m × 30 m test cell belonging to

Table I. Laboratory measurements of magnetic susceptibility values of the materials from the foundry.

	Approximate volume in the landfill (%)	Range of susceptibility [10^{-6}] (cgs)	Density (kg/m^3)
Foundry sand (from finish process)	9	8200-8600	1.6
Foundry sand (from furnace)	46	9000-14000	1.2-1.6
Mud and clay	30	2000-6000	1.5
Calcium hydroxide	7	21500-22000	1.3
Refractory slag	8	3200-3400	1.6

the landfill:

– A magnetic survey involving measurements of the total magnetic field and of the vertical gradient of the total magnetic field.

– An electromagnetic survey performed using a conductivity meter operating at low induction number.

Total magnetic field and gradiometric measurements were acquired by using a proton magnetometer EDA Omni Mag/Grad with a sensitivity of 0.1 nT; measurements were performed along sixteen profiles using a 1 m station interval. The sensor for the measure of the total magnetic field was held at 2 m above the soil surface. A 2 m spacing was adopted between the profiles; the profile direction was north to south. The whole area was covered with a total of about 800 measurements in a one day job by two people.

Electromagnetic measurements were carried out by means of the conductivity meter CM-031 (Geophyzica - Czech Republic) operating at low induction number to measure the apparent resistivity values of the subsoil up to 4-5 m deep: data were acquired using both vertical magnetic and horizontal magnetic dipoles on a 2 m × 2 m grid.

Due to the strong magnetic anomalies encountered during the survey (up to 1500 nT), high accuracy of the total magnetic field measured at each station was not very significant; however, according to the high dynamic range of the magnetic anomalies, the stability of the measurements was quite good. A maximum standard deviation less than 5-10 nT was recorded.

The map of the vertical gradient of the total field intensity could refer to the zone of major concentration of iron objects located near the surface. In the following description, only induction magnetisation is considered and no remanent magnetic effects are taken into account.

4. Data processing

In order to verify the effectiveness of the magnetic prospecting on the whole area of the landfill, a preliminary evaluation on the reliability of the data interpretation was performed at the test area. The data processing involved a fast technique, operating on the two-dimensional modelling of the magnetic data:

– Fast and approximate evaluation of the magnetic source depth using the slope method.

– Solution of the Euler homogeneity equation in order to evaluate the spatial position of the magnetic sources; the problem has been reduced to a typically two-dimensional problem and the Euler deconvolution has been applied to the profiling data.

A preliminary determination of the depth of the magnetic sources was performed using the half-slope and straight-slope method as described by Peters (1949) and modified by Rao and Babu (1984). The data interpretation, performed on the whole data set on the north-south profiles, allows a rough estimate of the depth of the magnetic sources, considering vertical contacts, thick dikes and thin sheet. The results are summarised in table II. For vertical contact and thick dike models the results are consistent with the maximum depth of the waste disposal (about 12-13 m), obviously indicating that the magnetic sources are located within the waste disposal.

This data interpretation provides some useful information for the subsequent data processing:

– The best model fitting the data must be searched using vertical contact or thick dike models.

– The depth of the magnetic sources is located approximately between 4 m and 12 m.

4.1. *Euler deconvolution*

The Rao and Babu (1984) method depicted in the previous section is best suited for calculating the depth of isolated anomalies; otherwise, the results showed that the observed magnetic effects can be due to the interference of several magnetic sources.

A simple and fast technique that can be applied for detecting the magnetic sources is Euler's deconvolution method; it can detect the position and depth of a simple body (monopole, dipole, sheet etc.), starting from the observed magnetic data along a single profile or a gridded map. The basic principle of the technique al-

Table II. Depth estimation of magnetic source according to Rao and Babu (1984) for different models.

Profile id.	Anomaly position along the profile (m)	Vertical contact depth (m)	Thick dike depth (m)	Thin sheet depth (m)
Line 0 + 0 W	30-40	4.9	6.1	8.2
Line 0 + 2 W	35-40	3.4	4.2	5.7
Line 0 + 4 W	35-40	4.5	5.7	7.6
Line 0 + 6 W	35-40	4.9	6.1	8.0
Line 0 + 8 W	35-40	5.8	7.3	9.7
Line 0 + 10 W	35-40	2.9	3.6	4.8
Line 0 + 12 W	35-40	5.9	7.4	10.0
Line 0 + 14 W	35-40	6.5	8.0	10.8
Line 0 + 16 W	35-40	5.8	7.5	9.7
Line 0 + 18 W	35-40	8.4	10.5	14.0
Line 0 + 20 W	35-40	8.3	10.3	13.8
Line 0 + 22 W	35-40	8.2	10.3	13.8
Line 0 + 24 W	35-40	6.8	8.5	11.3
Line 0 + 26 W	35-40	10.8	13.6	18.0
Line 0 + 28 W	35-40	–	–	–
Line 0 + 30 W	35-40	4.7	5.9	7.8

lows the division of the data set into several windows; the calculation of the solution of Euler's equation is then performed for each window. Each solution provides an estimation of the position of a single magnetic source; the final result is a cross section or a map of all the solutions: these may tend to cluster around a magnetisation of geologic interest. The solutions can be obtained only in the least square sense, due to the inaccuracies in the experimental data.

This technique can be applied to gridded data (3D problems) or along profile data (2D problem); in this application, due to the limited size of the gridded map, only the approach along the profiles has been considered.

A review of the technique using the 2D assumption on the magnetic sources is reported in the paper of Thompson (1982); Reid *et al.* (1990) extended the 2D approach to the 3D interpretation of the magnetic source location. More recently Yaghoobian and Boustead (1993) have introduced the Euler equation to determine non-geological features such as buried ferro-metallic bodies in environmental applications.

According to Thompson (1982), the following relationship between the magnetic field intensity and the horizontal and vertical gradients yields (2D case):

$$x_0 \frac{\partial \Delta T}{\partial x} + z_0 \frac{\partial \Delta T}{\partial z} = x \frac{\partial \Delta T}{\partial z} + N \Delta T(x)$$

where the derivatives or gradients can be measured or evaluated from the data; the unknown quantities of the equation are the coordinates x_0, the distance along the profile, and z_0, the depth of the magnetic source or rather the distance between the magnetic sensor and the source. The N value (structural index) represents the type of sources which best suited the anomaly. The structural index is also a measure of the fall-off rates of the effect of each magnetic anomaly. For instance, a magnetic dipole has a typical structural index $N = 3$, while a narrow 2D dyke has a structural index of $N = 2$. The relationship between the structural index values and the geological features has been discussed by Slack *et al.* (1967), Briener (1973) and Thompson (1982). Yaghoobian and Boustead (1993) discussed the significance of the structural index for magnetic sources in the environmental applications.

The shortcomings and the possibilities of the technique and a numerical implementation of the algorithms were described by Thompson (1982). The approach proposed by Thompson was adopted in this study.

Two important aspects affect the quality of the solution of Euler's equation: the choice of the structural index and the size of the window. Tests performed on synthetic data pointed out that the window size is closely related to the density, the depth and the position along the profile of the solution; the structural index has a physical meaning being linked to the kind of magnetic sources being detected.

The *window size* was set according to the wavelength of the main detected anomalies; if the window size is too large, the final density of the solution is very poor, whereas small windows could produce unreliable solutions. Thompson (1982) suggested a window of 7 samples as a good choice; in the present application the best results were obtained when a window of 11 samples was employed.

The *structural index* refers to the kind of magnetic source, as depicted in table III; the landfill in this cell was filled with horizontal slices: as a logical consequence the dipole or the horizontal monopoles could be the best choice for describing the magnetic sources.

5. Discussion on the results

The results of the magnetic survey are plotted in terms of the total magnetic field and vertical gradient of total magnetic field as shown in figs. 1 and 2a,b.

The results of the 2D interpretation (cross vertical section) by solving the Euler's homogeneity equation can be plotted according to the following criteria: each solution can be depicted by a symbol in a distance/depth diagram; as a rule of thumb, different symbols indicate differ-

Table III. Geological and environmental meaning of the structural index (after Yaghoobian and Boustead, 1997, modified by the author).

Structural index N	Geological model	Cultural model (1)	Objects and structures in the landfill	Number of infinite dimensions
3	Sphere	Tank	Metallic drums	0
2	Kimberlite pipe	Vertical shaft or well	Vertical drums	1 (z)
2	Horizontal cylinder	Tunnel or horizontal shaft	Concentration of iron horizontal structures	1 (x-y)
1	Dyke/Sill	Vertical sheet	Vertical sheet of iron concentration	2 (z and x-y)
0.5	Thick step	Flat sheet	Slab of magnetic material	2 (x and y)
0	Vertical contact	Edge of large tank	Vertical contact between magnetic and non-magnetic materials	3 (x, y, and z)

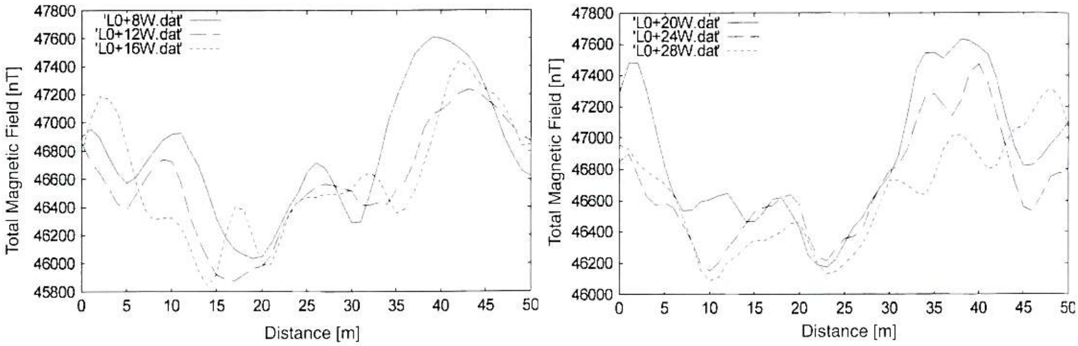

Fig. 1. Examples of magnetic data along the north-south profiles in the landfill (values of the total magnetic field).

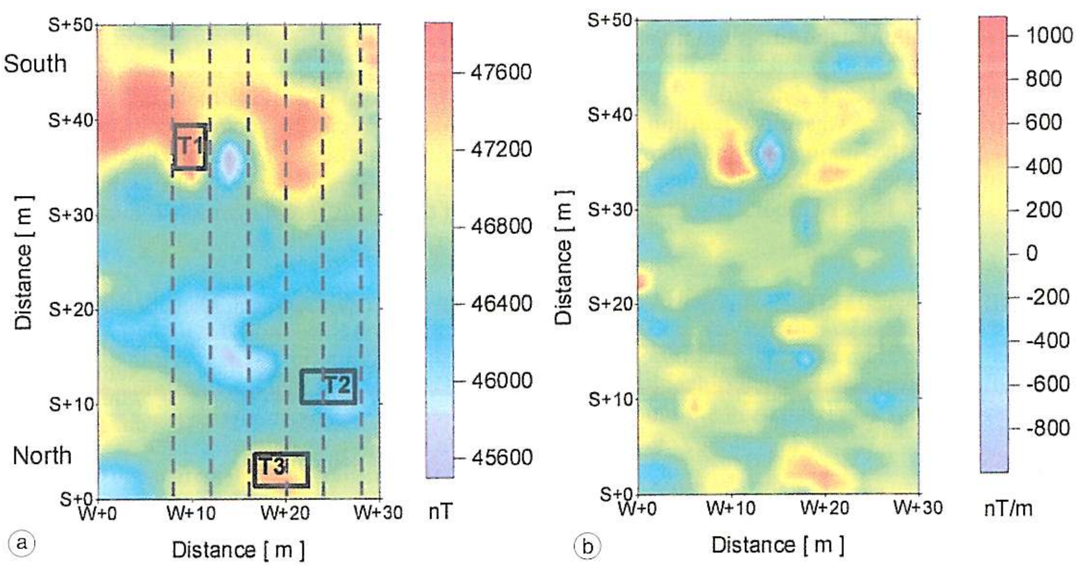

Fig. 2a,b. Maps of the total magnetic field values (a) and of the vertical gradient of total magnetic field (b) ; T1, T2, T3 indicate the position of the trenches excavated after the magnetic survey; the dashed lines indicate the selected profiles for the subsequent data processing.

ent structural indexes of the solutions. The clustering of the solutions can be well represented using a density plot. The cross-section is divided into small pixels, according to the spatial resolution that would be obtained; the number of solutions within each pixel is normalised with respect to all the solutions and the final result is plotted by imaging or contouring the calculated values inside each pixel.

Some interesting clusters of Euler's solution are well depicted in figs. 3 to 5; this would indicate that, starting from the data distribution, many magnetic sources can be detected in a semi-automatic way. Tests have been performed

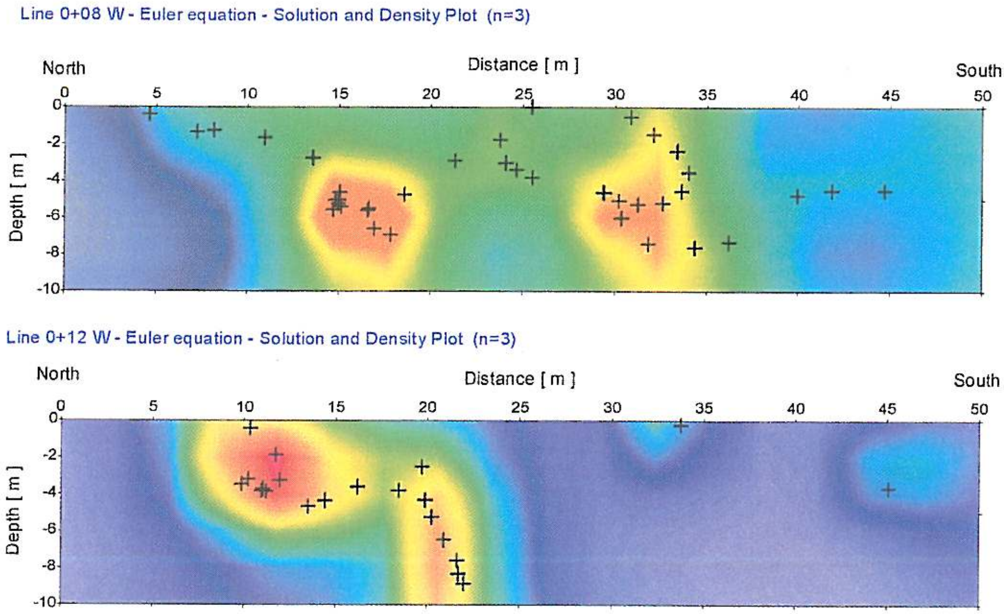

Fig. 3. Solutions of the Euler equation (structural index n = 3) for Line 0 + 08 W and Line 0 + 12 W of the magnetic data; the coloured image shows the density plot of the solutions of the Euler equation.

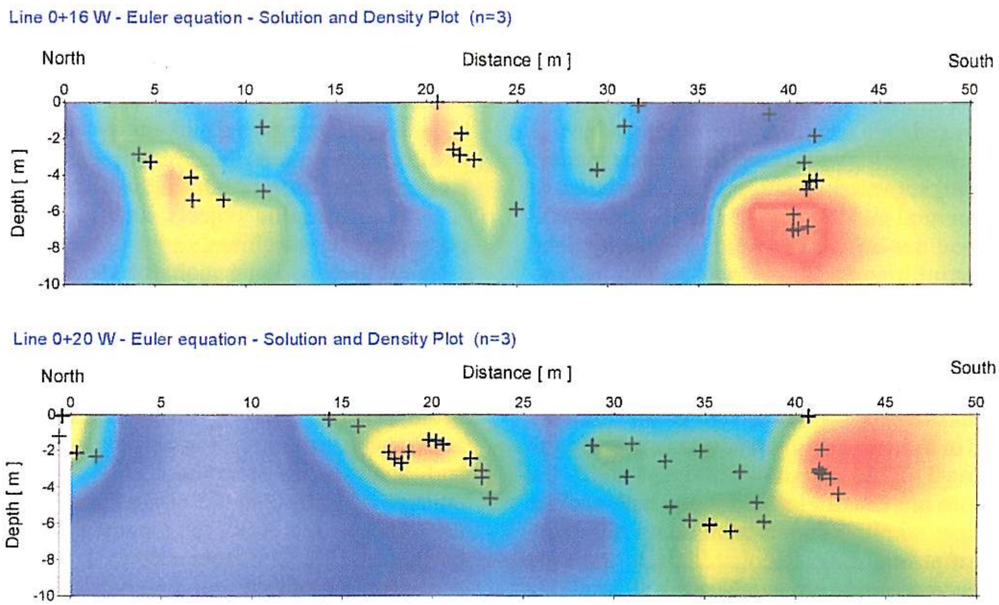

Fig. 4. Solutions of the Euler equation (structural index n = 3) for Line 0 + 16 W and Line 0 + 20 W of the magnetic data; the coloured image shows the density plot of the solutions of the Euler equation.

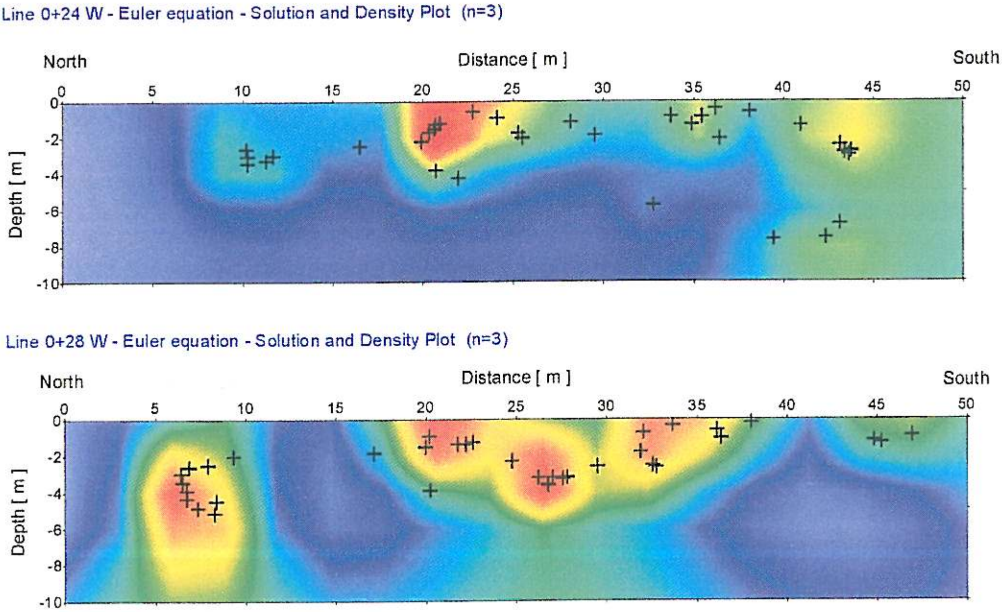

Fig. 5. Solutions of the Euler equation (structural index n = 3) for Line 0 + 24 W and Line 0 + 28 W of the magnetic data; the coloured image shows the density plot of the solutions of the Euler equation.

using different structural indexes; as a final result the structural index of $N = 3$ appears to be the best choice, in terms of clustering of the solutions. High index values seem to have a physical meaning according to how the landfill has been cultivated. However, the best choice of the structural index is a matter of discussion and the good set-up of the value can be defined if other information on the subsoil can be considered.

In the Line 0 + 08 W, two main clusters of the solutions were detected at a depth of 4-6 m; these clusters show the tops of two important magnetic sources. Two magnetic sources are also depicted in the density plot of solution, referring to the Line 0 + 12 W. As shown in figs. 4 and 5, the solutions are usually located in the near surface layers, at no more than 8 m in depth; the presence of strong magnetic materials in the near surface zone could obviously mask any reliable interpretation on deeper structures.

The magnetic sources delineate the existence of ferro-metallic objects that can be found in the landfill; two kinds of ferro-metallic materials can affect the magnetic behaviour of the waste disposal:

– Fine iron materials disseminated in sandy and clayey materials; these materials are derived from the cast iron foundry industrial process.

– Ferro-metallic objects such as drums or parts of heavy machines.

Very high concentrations of small particles of iron in the mud and clay of the foundry wastes could justify the presence of zones with a very high susceptibility contrast. In order to verify the nature of the magnetic sources some trenches were digged in the investigated area; some samples of materials were taken and analysed in laboratory. No appreciable amount of ferro-metallic objects was found in the trenches; therefore, the magnetic behaviour of the landfill is mainly caused by the high concentration of fine iron materials disseminated in the waste.

The dipolar nature of the magnetic source, as determined by Euler's solutions, suggested that the zones of magnetic anomaly are well represented by close masses of accumulation of iron particles. This consideration can be helpful to plan the exploitation activity of the landfill with the aim of recovering iron and sand materials for recycling in the foundry activity.

A more realistic interpretation, starting from these results, can be obtained using 2.5D modelling procedures (*e.g.*, Talwani, 1965), which could define the susceptibility contrast of the materials and delineate the shape of the magnetic sources.

Three trenches were excavated in the test area after the execution of the magnetic survey; the position of the trenches is reported in fig. 2a. A maximun depth of about 6 m was reached in the trench T3; T1 and T2 were excavated until a depth of about 3-4 m. Different samples were taken from the excavated material and measurements of the magnetic susceptibility were performed. The results show a strong dispersion of the measured values, according to the composition of the materials. High susceptibility values (table IV) are encountered in specimens with fractions of calcium hydroxide (very rich in fine iron particles) in trenches T2 and T3. Low susceptibility values were measured in sampled characterised by the presence of sandy material in the landfill levels, close to the surface (T1). The strong magnetic anomaly pointed out by the field survey in the zone of T1 could be explained by the presence of magnetic sources, deeper than the bottom of the excavation.

The results of the electromagnetic survey are depicted in figs. 6a,b and 7a,b, where the maps of the in-phase and resisitivity values of HD mode (horizontal mode) and VD (vertical mode) are plotted.

Table IV. Susceptibility values of waste sampling from trenches in the test cell.

Trenches	Magnetic susceptibility ($cgs \times 10^{-6}$)
T1	3500 - 4000
T2	2000 - 14000
T3	1000 - 20000

These reflect the near surface inhomogeneties of materials in the upper layer of the landfill; great changes in the apparent resistivity values are depicted in the maps. The apparent resistivity maps reflect the near surface lateral variations between the mud and clay (low resistivity) and the sand materials (high resistivity). The in-phase component is sensitive to the presence of magnetic materials in the upper part of the landfill. A quantitative correlation between magnetic and electromagnetic results appears to be difficult because of the different nature of the anomalies: dipolar for the magnetic sources and monopolar for electromagnetic anomalies.

6. Final remarks

A fast approach was employed for processing the magnetic data acquired in an industrial landfill; the technique (Euler's deconvolution) can be successfully used to detect iron masses concentrated in near surface layers of the landfill. The experiment has shown the effectiveness of the method in an environmental application using data with complex magnetic anomalies and in presence of strong gradients. The method also appears to be reliable when there are high level of the magnetic noise due to shallower metallic objects.

This approach allows a fast detection of near surface iron masses and offers a preliminary data analysis before using inversion packages. However, 2D or 2.5D inversion in environmental applications must be handled with care because of the complex nature of the magnetic sources.

The results of the geophysical interpretation showed the good resolution of the magnetic survey to locate waste fractions with high iron metal contents and, on the other hand, the capability of the electromagnetic survey to single out waste fractions, characterised by high resistivity values associated to slag such as moldings and core sands. These observations were validated by the collections of *in situ* samples from the landfill test cell: the wastes were physically and chemically characterised in order to relate the geophysical results to the distribution of the materials in the landfill.

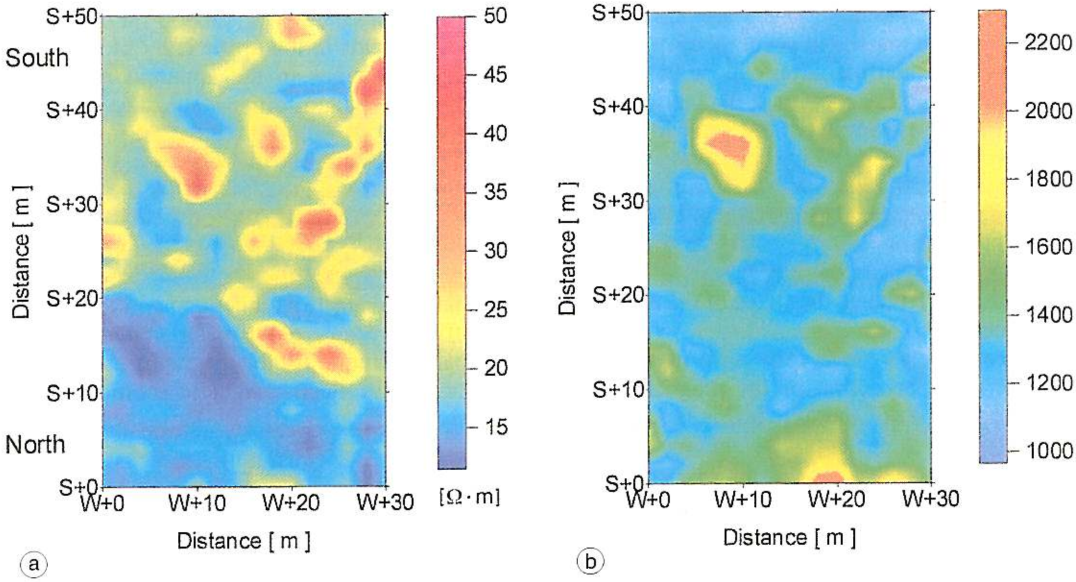

Fig. 6a,b. Maps of apparent resistivity (a) and phase values (b) of the conductivity meter survey using low induction number equipment (CM-031) in the vertical dipole mode.

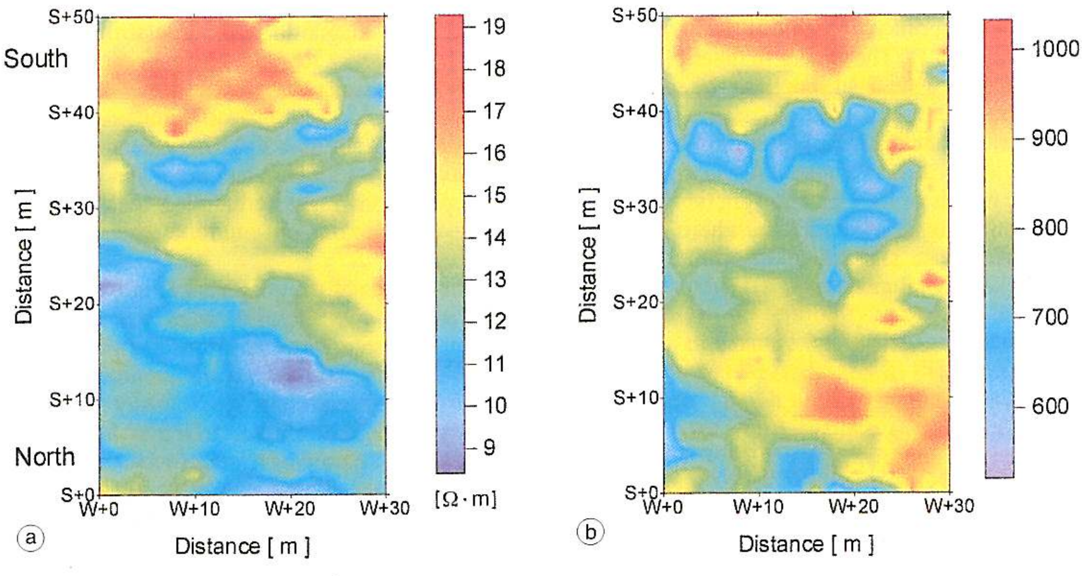

Fig. 7a,b. Maps of an apparent resistivity (a) and phase values (b) of the conductivity meter survey using low induction number equipment (CM-031) in the horizontal dipole mode.

REFERENCES

BHATTACHARYA, B.K. (1978): Computer modeling in gravity and magnetic interpretation, *Geophysics*, **43**, 912-929.

BRIENER, S. (1973): *Applications Manual for Portable Magnetometers: GeoMetrics* (Sunnyvale, CA).

GODSON, R.H. (1983): MAGPOLY: a modification of a three-dimensional magnetic modelling program, *U.S. Geol. Surv. Open-File Rep. 83-345*, pp. 62.

PETERS, L.J. (1949): The direct approach to magnetic interpretation and its practical application, *Geophysics*, **14**, 290-320.

PLOUFF, D. (1976): Gravity and magnetic fields of polygonal prisms and application to magnetic terrain corrections, *Geophysics*, **41**, 727-741.

RAO, D.A. and H.V. BABU (1984): On the half-slope and straight-slope methods of basements depth determination, *Geophysics*, **49**, 1365-1368.

REID, A.B., J.M. ALLSOP, H. GRANSER, A.J. MILLETTS and I.W. SOMERTON (1990): Magnetic interpretation in three dimensions using Euler deconvolution, *Geophysics*, **55**, 80-91.

ROBERTS, R.L., W.J. HINZE and D.I. LEAP (1990): Data enhancement procedures on magnetic data from landfill investigations, in *Geotechnical and Environmental Geophysics*, edited by S.H. WARD, Soc. Expl. Geophys., 261-266.

SLACK, D.W., V.M. LYNCH and L. LANGAN (1967): The geomagnetic gradiometer, *Geophysics*, **21**, 1021-1040.

TALWANI, M. (1965): Computation with help of a digital computer of magnetic anomalies caused by bodies of arbitrary shape, *Geophysics*, **30**, 797-817.

THOMPSON, D.T. (1982): EULDPH: a new technique for making computer-assisted depth estimates from magnetic data, *Geophysics*, **47**, 31-37.

TYAGI, S., A.E.Jr. LORD and R.M. KOERNER (1983): Use of proton precession magnetometer to detect buried drums in sandy soil, *J. Hazardous Materials*, **8**,11-23.

YAGHOOBIAN, A. and G.A. BOUSTEAD (1993): Object delineation using Euler's homogeneity equation: location ad depth determination of buried ferro-metallic bodies, in *Symposium on the Application of Geophysics to Engineering and Environmental problems*, SAGEEP '93, Orlando, vol. 2, 613-632.