Environmental Engineering and Management Journal July 2015, Vol.14, No. 7, 1623-1636
http://omicron.ch.tuiasi.ro/EEMJ/

"Gheorghe Asachi" Technical University of Iasi, Romania

LIQUID INJECTION TO ENHANCE BIOGAS PRODUCTION IN LANDFILLS FOR PRETREATED MUNICIPAL SOLID WASTES - BIO.LEA.R. PROJECT (LIFE+ PROGRAM)

Alberto Godio[1*], Alessandro Arato[1], Fulvia Chiampo[2], Bernardo Ruggeri[2], Martina Di Addario[2], Matteo Fischetti[3], Erica Perissinotto[3]

[1]*Politecnico di Torino, Dipartimento di Ingegneria dell'Ambiente, del Territorio e delle Infrastrutture, 24 Corso Duca degli Abruzzi, Torino, Italy*
[2]*Politecnico di Torino, Dipartimento di Scienza Applicata e Tecnologia, 24 Corso Duca degli Abruzzi, Torino, Italy*
[3]*G.A.I.A. SpA, 48 Via Brofferio, Asti, Italy*

Abstract

The Bio.Lea.R project aims to demonstrate the performance of a landfill for less reactive, biologically treated waste (pretreated organic wastes) compared to a conventionally managed landfill, with regard to both environmental (biogas and leachate production) and economic aspects. The objective is to control the pretreated biodegradable waste through a liquid injection in order to achieve the same biogas quantity in a shorter time than in conventional landfill.
Laboratory and full scale monitoring were performed in order to check the efficiency of the landfill acting as bioreactor. A small-scale lysimeter was set up to simulate in laboratory the biological processes that happen at a bioreactor landfill. The lysimeter consists of a cylindrical reactor filled with waste. The monitoring activity of the geophysical parameters of the landfill is based on network of geophysical sensors to detect the changes in time and space of the electrical conductivity at different depth in the landfill. Electrical conductivity is potentially a good indicator of spatial and temporal changes of liquid content of the waste within, as results of the infiltration process.
Results of the lysimeter experiment have proved the faster production of biogas, with the Methane Potential Yield at 900 days. The current modeling of leachate infiltration is influenced by availability of experimental data which in this case are provided by time lapse monitoring of geophysical parameters. The combination of time-lapse geophysical monitoring, advanced inversion technique and traditional waste sampling techniques provides robust data to evaluate the infiltration process and degradation of waste.

Key words: bioreactor, biogas, geophysical monitoring, sanitary landfill

Received: December, 2014; Revised final: June, 2015; Accepted: June, 2015

1. Introduction

Management of landfills as bioreactors (indicated as "bioreactor landfills" in the following) has been studied and tested since 1970 in the US and has increasingly been spreading world-wide in the last decades (Sanphoti et al., 2006). Bioreactor landfill method aims to speed up the waste biodegradation in Municipal Solid Waste (MSW) landfills by constantly maintaining appropriate waste moisture and, depending on the management configuration, aerobic or anaerobic condition. With respect to the conventional landfill management approach, the following benefits of bioreactor landfills must be considered: i) a quicker stabilisation (10 to 15 years compared to 30 to 100 years with a classical landfilling operation) of biodegradable content can be achieved (Pacey et al., 1999); ii) the

[*] Author to whom all correspondence should be addressed: e-mail: alberto.godio@polito.it

biogas production period can be shortened and the biogas quality increased, thus providing a significant improvement of energy recovery; iii) when a leachate recirculation system is used, the environmental hazard is reduced because the volume of leachate to be treated is reduced, thanks to the liquid retention by the waste matrix (Pohland, 1980; Warith, 2002).

However, *in situ* operations at a bioreactor landfill require careful monitoring and control of the operative parameters due to the great influence of the moisture content on the efficiency of the methanogenic bacteria (Reinhart and Townsend, 1998; Reinhart et al., 2002). The methanogenesis is enhanced by a high moisture content that can be reached by adding water/leachate to the waste. The threshold value of water content, under which no biodegradation activity is observed, ranges from 0.15 to 0.50 kg H_2O per kg of dry waste (DM), while fresh refuse moisture content ranges from 0.25 to 0.65 kg $H_2O \cdot kg\ DM^{-1}$ (Pommier and Lefebvre, 2009). The waste must be maintained at nearly constant water content, especially under temperate climate, where waste disposed in landfill is generally too dry to guarantee the optimal biodegradation. The fluid necessary for obtaining optimal condition can be supplied either by the leachate recirculation or from rain water infiltration (Morris et al., 2003). Moreover, the leachate recirculation tends to uniform the spatial distribution of adapted microflora. As far as an efficient monitoring of the bioreactor is concerned, measuring the liquid distribution all over the landfill is a key issue (Imhoff et al., 2007): the optimisation of leachate injection systems remains a challenging and open problem for bioreactor landfill operators. Laboratory experiments demonstrated the relevancy of a proper calibration of the rate of leachate re-circulation to enhance the waste degradation and increase the biogas production (Hernández-Berriel et al., 2014). Moreover, innovative wells could be adopted to enhance the recovery efficiency of methane, as suggested by Xue et al. (2014).

In such a context, the project Bio.Lea.R. (within the frame of Life+ Program) aims to study a landfill managed as bioreactor, in order to exploit the biodegradable matter at its maximum extent and give the best yields of biogas.

Bio.Lea.R. project has a demonstrative character on full scale, and focuses on two parallel and mutually useful studies:

- at laboratory scale, with a lysimeter filled with waste coming from the landfill under study and managed as bioreactor;
- at landfill scale, with monitoring of the bioreactor activities, in terms of biogas production, and leachate recirculation efficiency and management (recirculation started in January 2014).

Herein we focus on the laboratory results and the main characterisation of the landfill. Particularly, we have designed and installed a network of geophysical sensors capable to explore the changes of electrical conductivity (or resistivity ρ, to say the reciprocal of electrical conductivity) and waste temperature at different depth of the landfill. These parameters can be a good indicator of spatial and temporal changes of liquid content within the bioreactor, as results of the infiltration process. Relationships between resistivity and temperature of leachate, and between resistivity and volumetric water content of waste, can be established by laboratory experiments (Grellier et al., 2005). In such a way, the results of geophysical monitoring collected in the landfill can be converted into water content.

The up-scaling from the laboratory results to the *in situ* properties is based upon the assumption that the properties of the solid waste tested in the laboratory are similar to those of solid waste in the field and that the leachate has the same properties of the leachate within the landfill. Both the assumptions do not have general validity because of the different scale of heterogeneity of the mass of waste and because of the spatial and temporal changes of the leachate properties in the landfill that cannot be controlled (Imhoff et al., 2007).

Electrical Resistivity Tomography (ERT) is suitable to study the complex resistivity distribution (2D and 3D) at large scale (ten to hundreds of meters wide and down to 30 meters deep) and small scale to characterize the waste landfill structure (Bernstone et al., 2000; Meju, 2000). Moreover, ERT is becoming a common tool for studying recirculation experiments in landfills (Acworth and Jorstad, 2006; Guérin et al., 2004; Mondelli et al., 2007; Moreau et al., 2003; Olofsson et al., 2006; Rosqvist et al., 2005). During recirculation process, if leachate content or gas migration creates resistivity changes, ERT can be considered using a time-lapse approach (i.e. repeating ERT survey several times during the injection). On the basis of this background, we designed a monitoring geophysical system, sensitive to the spatial and temporal changes of the liquid within the cell.

In Bio.Lea.R. project, ERT is one of the tools used to study the effects of leachate recirculation, and at the same time its methodological value is evident.

2. Materials and methods

2.1. The landfill

Cerro Tanaro landfill is located in Northern Italy (Fig. 1) and contains wastes treated with a Mechanical Biological Treatment (MBT), according to the EU Landfill Directive (Directive 1999/31/EC).

MBT reduces the environmental impact of the treated waste, also thanks to the reduction of its moisture and biodegradable fraction; however, the mean waste moisture content is in the order of 20-30% by weight, values unsuitable for the biological processes. In addition, the content of rapidly biodegradable matter is lower since a huge part has been already consumed during the biological treatment itself.

Fig. 1. Plan view of the landfill and position of geophysical profiles for waste characterization (the three images are the location of the vertical boreholes equipped with electrodes for geophysical monitoring)

Thus, low contents of water and rapidly biodegradable matter induce slow biogas production, which implies a longer post-management period.

The landfill is built with two hydraulically independent cells, filled with pretreated wastes. One cell is managed as independent anaerobic bioreactor landfill, in order to shorten and maximize the biogas production. The other cell, managed as conventional landfill, constitutes the comparison term. Each cell is equipped with biogas, leachate and moisture monitoring systems, liquid distribution plant, data transmission system.

2.2. Waste characterization

To characterize the material conveyed to the landfill, at the project starting point, undisturbed waste samples coming from *in situ* well drilling cores and output samples directly after the MBT were collected and analyzed.

The on-site characterization of the waste heterogeneity focused on evaluating the infiltration rate and the liquid distribution within the landfill by integrating drilling and geophysical survey.

2.3. Leachate recirculation and biogas extraction systems

In Cerro Tanaro landfill the leachate recirculation system mainly consists of 8 sub-irrigation rings of 20 m diameter, located at the top of 8 gas extraction wells, below the final waste capping. In addition, 8 horizontal pipes of 10 m length are placed in the zones not reached by the influence areas of the rings, at 0.5 m depth, as well as 4 vertical injection wells where three HDPE pipes reach different depths.

A manually-controlled pumping plant, located at the leachate storage tanks, supports the whole sub-irrigation system. Details on the technologies adopted to inject the leachate in bioreactor landfills are well documented in literature, using vertical wells (Khire and Mukherjee, 2007) or horizontal trenches (Haydar and Khire, 2005). The biogas extraction system consists in 26 vertical biogas wells, perimetral horizontal pipe lines, 8 horizontal rings (10 meters diameter) laid around 8 biogas wells on the top of the landfill and under the capping system.

Through three regulation stations, each well is connected to an energy recovery station where biogas is burnt in order to produce electricity.

2.4. Monitoring of biogas and leachate

Both landfill cells are equipped with the same system for biogas extraction and monitoring (temperature, flow rate, composition by methane, carbon dioxide, oxygen, hydrogen sulphide).

In-line analysis of biogas composition constitutes evidence of the cell response to the leachate recirculation, to verify the effectiveness of the process in enhancing biodegradation. The recirculated leachate is analysed weekly by temperature, pH, electrical conductivity, oxidation-reduction potential (ORP). At the same time, ammonium content and Chemical Oxygen Demand (COD) are analyzed on samples.

In addition, the cell managed as bioreactor is equipped with the system to monitor the leachate recirculation and collect the data about temperature and electrical conductivity measured by the geophysical sensors.

2.5. Laboratory scale tests

In order to simulate the biological processes that happen at a bioreactor landfill, a small-scale lysimeter was set up. The lysimeter consists of a cylindrical reactor (diameter = 0.18 m; height = 0.35 m) filled with waste coming from Cerro Tanaro landfill (Fig. 2).

When the lysimeter was set up, the waste was already 5-years-old (averaged among the different samples), with a mean dry matter content (DM) around 59 % by weight. To completely fill the lysimeter, 3.12 kg of waste were necessary. Given the waste age, just the slowly biodegradable carbon was present, with expected slow degradation kinetics.

The operating conditions in the reactor were optimized to increase the biodegradation:

1) the waste was shredded and the reactor was placed in a thermostatic room (30°C ± 1°C);

2) leachate was recirculated at adequate flow rate (0.1 – 0.7 L min^{-1}) in order to reach the maximum water retention capacity of the waste itself.

To study the degradation process, the following parameters were analyzed:

- *in leachate*: pH, oxidation-reduction potential (ORP), ammonium concentration;
- *in biogas*: flow rate, composition.

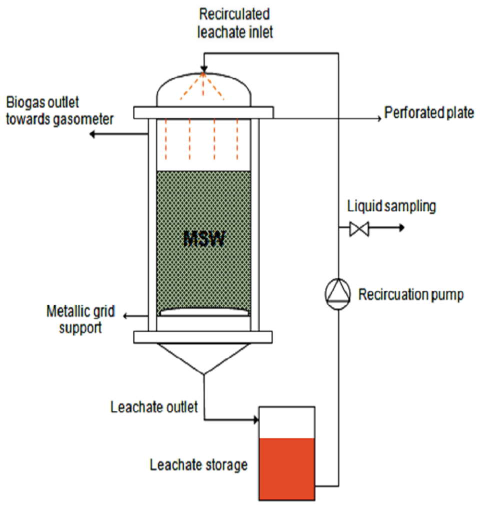

Fig. 2. Lysimeter scheme

2.6. Geophysical characterization

We characterised the electrical behaviour of the landfill by Electrical Resistivity Tomography, along 6 vertical sections. The ERT method is widely applied in environmental study both for monitoring the water infiltration process in landfill (Grellier et al., 2008) and to outline hydrological parameters of the subsoil (Godio and Ferraris, 2005), and to characterise contaminated sites (Godio and Naldi, 2003; Godio et al., 2010). The geophysical investigation has been performed from the surface, with electrodes placed directly on the waste material before the disposal of the final capping. The survey focused on mapping the inner heterogeneity of the landfill, to a depth of about 15 meters and checking the most promising zones for a subsequent hydraulic characterization. We performed 6 ERT profiles aligned as indicated in Fig. 1.

Each profile consisted of 48 in-line electrodes, spaced 2 m, covering a total length of 94 m. Five profiles were parallel between each other, and they were traced with an approximate profile separation of 10 meters.Besides the preliminary geo-electrical characterization of the waste, an infiltration test was carried out in order to estimate the infiltration rate in the uppermost part of the cell. The experiment was carried out on the cell top, before the complete capping of the cell itself, by infiltrating a controlled volume of water from the surface and monitoring the infiltration process, using two cross-profiles of electrical tomography in time-lapse fashion (Arato et al., 2014a).

The test was intended to simulate a rainfall event, as the water was supplied over a 3x5m area through a set of gardening sprinklers. A total volume of 6 m^3 was infiltrated during an infiltration time of about 2 hours. Water resistivity, measured before the test, was 16 Ω·m. The ERT lines, each one set up with 48 electrodes 1 m spaced, were both centered in correspondence of the infiltration area (Fig. 3).

2.7. Geophysical monitoring

The full scale monitoring in the selected landfill was designed to check temperature and humidity evolution at different depths, to be related to leachate infiltration and circulation.

Vertical temperature sensor strings were installed within the landfill along five biogas extraction boreholes. Each string had 5 temperature sensors, with a spacing of 3 m, in order to measure a vertical temperature profile in the depth range between 3 to 15 m from the top of the landfill.

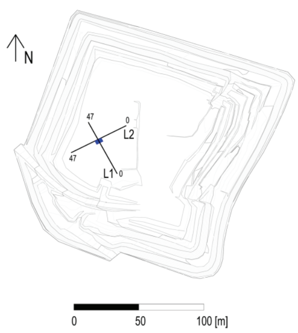

Fig. 3. Position of the two perpendicular profiles (ERT) for the monitoring of the infiltration test from the surface of the landfill

Ten boreholes were specifically installed for geo-electrical monitoring. Each borehole consists of a PVC pipe, with a multi-electrode cable attached along the pipe itself. Each multi-electrode cable has 24 graphite electrodes, 0.6 m spaced, and covers a depth of 13.8 m between the top and the bottom of the landfill, depending on the criticisms occurred during the drilling and completion of the boreholes. All the electrodes were connected by specific electrical cables to a control unit for remote monitoring controlled in real time.

As described in Fig. 4, the geophysical monitoring system was designed to perform cross-hole ERT surveys between three pairs of boreholes near three leachate injection-biogas collection stations, plus two isolated vertical boreholes for periodic controls. Since August 2012, monthly we have measured the electrical resistivity along the depth of each borehole. Cross-hole ERT data acquisition was performed in 3 different panels between pairs of boreholes, and the temperature effect on electrical parameters was also checked according to the values measured by the temperature sensor strings.

The permanent system for remote monitoring of the injection has been installed in October 2013, after the complete capping of the cell (Fig. 4). Since then, the switching unit and the control unit were located in a wooden hut; the cabling was performed and controlled to ensure perfect correspondence between electrodes and connectors to the control unit. Preliminary tests were focused to fix some bugs in the electrical connection of the system. In the period November 2013-January 2014, measurements were carried out more frequently (bi-weekly) in order to define a background resistivity model for the stations A, B and C (corresponding to biogas extraction wells CTB107, CTB110 and CTB111, respectively).

The monitoring system has been subjected to an initial step of calibration and start-up, which was based on repeating the electrical surveys at different time periods before starting the leachate recirculation, in order to evaluate the repeatability of the measurements and the stability of the monitoring system. The start-up step referred to the initial monitoring in time-lapse modality of a well-controlled infiltration, limited to injection-extraction station CTB107. A total volume of about 250 m^3 of leachate was supplied to the landfill, with a flow rate of 5 m^3/h. The test began in January 2014 and lasted 5 days.

The leachate had been infiltrated discontinuously for 6-10 hours/day, while cross-hole ERT acquisition had been carried out every 6 hour, to evaluate the sensitivity of the monitoring devices to the humidity changes. The time-lapse ERT inversion (Arato et al., 2014b) was carried out by using R2 finite-element inversion software, (Binley, 2013) which also features the difference inversion algorithm developed by La Brecque and Yang (2001).

The conceptual model of the geo-electrical behavior takes into account that during the subsequent monitoring of the fluid distribution within the bioreactor, the cell is covered by a low permeability capping. The uppermost part of the cell is composed by clay material layer, above a thin layer of drainage material (coarse pebble). These layers form the overburden of the cell with an average thickness of about 0.8 meters; the HDPE liner is disposed above the clay, and hydraulically insulates the cell from the superficial runoff.

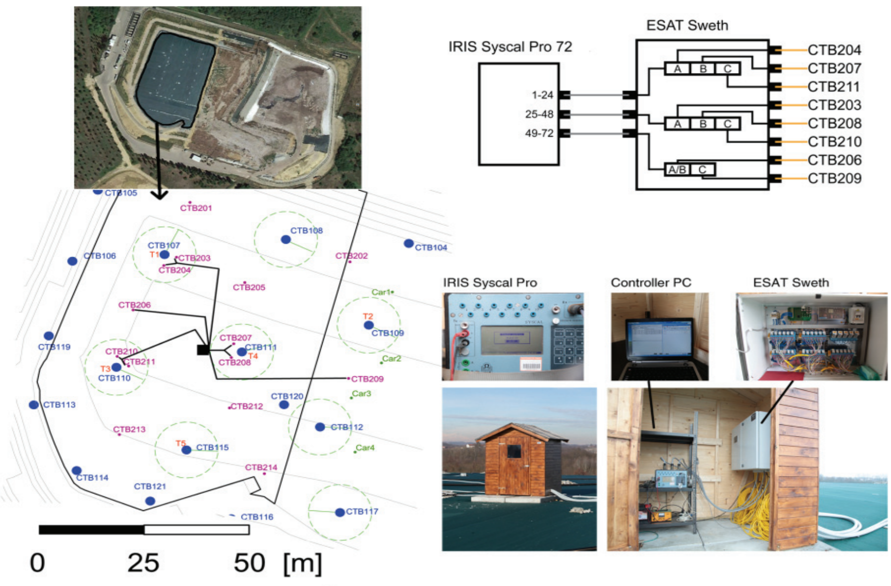

Fig. 4. Map of the cell after the disposal of the final coverage; the black lines on the map refer to the electrical connection between the boreholes (equipped with geophysical sensors) and the remote monitoring system (in the centre of the cell). The acquisition unit (Iris Syscal Pro) is connected to the boreholes through a multiplexer (Esat Sweth); an external PC guarantees the remote control of the unit)

3. Results

3.1. Laboratory tests

3.1.1. Leachate

The chemico-physical parameters measured on leachate samples show values commonly achieved in anaerobic digestion. Among the others, pH, ORP and ammonium concentration are plotted in Fig. 5. pH values are rather constant and around neutrality (except the starting period when the biological system must still adapt), to say suitable for microbial activity, as a whole. ORP shows negative values, typical of the anaerobic systems, even if not so evident.

The ammonium concentration decreases with time, to say it is consumed and after about 60 days its value is negligible.

3.1.2. Biogas

Despite the difficulty in degrading this type of waste, the time needed to reach methanogenesis was reduced and methane production occurred from the 57th day of monitoring. The kinetic model of Gompertz growth equation was used to predict the production of methane which could be obtained in lysimeter (Eq. 1) (Zhu et al., 2009), where: *BM* = cumulative methane yield (NL·kg DM^{-1}); *t* = digestion time (d); *BMP* = methane yield potential (NL·kg DM^{-1}); R_m = maximal daily methane yield (NL·kg DM^{-1} d^{-1}); λ = bacteria growth lag time (d).

$$BM = BMP\,exp\left[-exp(\frac{e\,R_m}{BMP}\left(\lambda - t\right) + 1\right)\right] \quad (1)$$

The experimental data (Fig. 6) allow estimating kinetic parameters and evaluating the degradation trends; the half transformation time ($t_{1/2}$) is 319 days.

The Methane Yield Potential (BMP) can be reached approximately after 900 days; thus, the overall biodegradation kinetics, which is the derivative of the curve, shows higher methane production rate compared to landfill behaviour. It was possible to compare it with values present in the literature. The estimation of BMP equal to 71 NL·kg DM^{-1} agrees with the results of other experimental studies (Mali et al., 2012; Bayard et al., 2009; Sanphoti et al., 2006), that present a rather large range of results (36-185 NL·kg DM^{-1}).

The prediction of biogas production in the landfill is more complex than in lysimeter since there are many different phenomena to take into account, such as waste physical interactions as well as environmental and hydrological ones which can modify the physical and chemical parameters. In addition, the landfill management options and some unpredictable inhibitory phenomena and/or some synergic ones affect the biogas production. The predictive model used in this study was BIO-5 model, which allows getting the biogas production trend for a given landfill (Magnano, 2010). Two cases were simulated with BIO-5 model: conventionally managed landfill (assuming waste moisture equal to 41 % by weight) and the same landfill with leachate recirculation (assuming waste moisture equal to 55 % by weight). Fig. 7 reports the data obtained with these simulations and lysimeter: the positive influence of leachate recirculation is evident.

Considering the biodegradation kinetics, the half-transformation times are approximately 7 years for the traditional landfill, 5 years for the enhanced moisture landfill and 319 days for the lysimeter operation at its maximum water content.

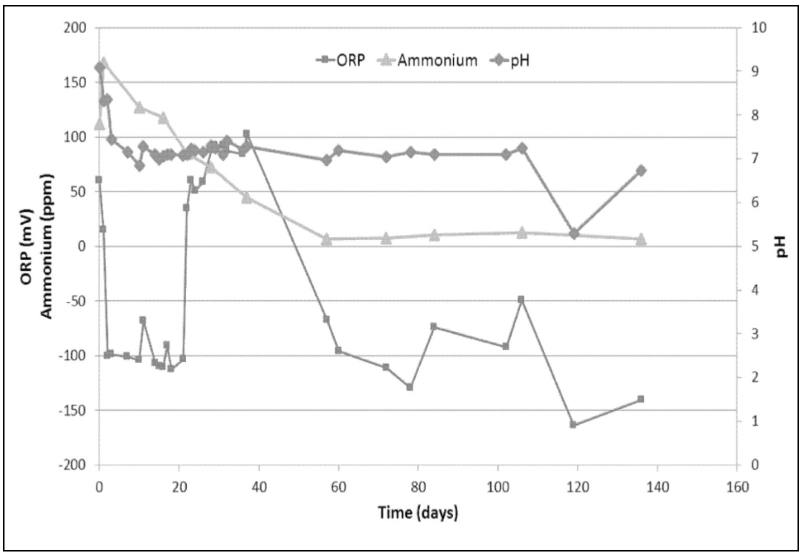

Fig. 5. pH, ORP and ammonium concentration in leachate recirculated in the lysimeter

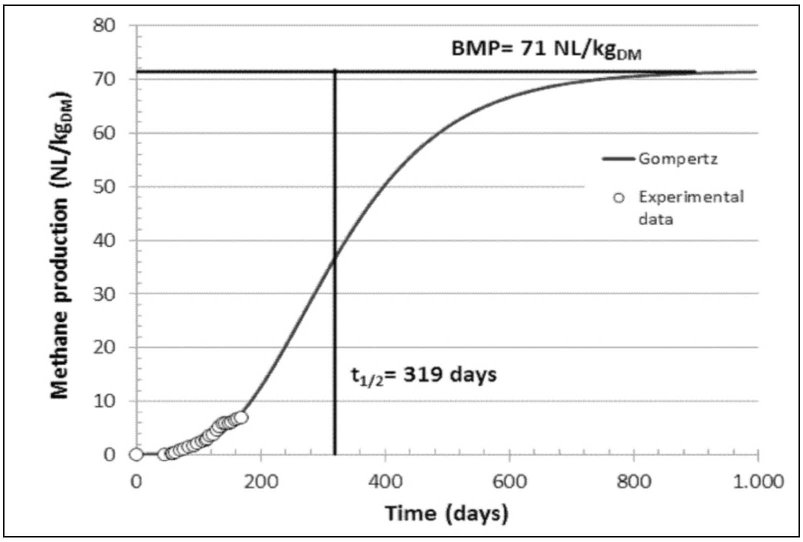

Fig. 6. Cumulative methane yield in the tested lysimeter

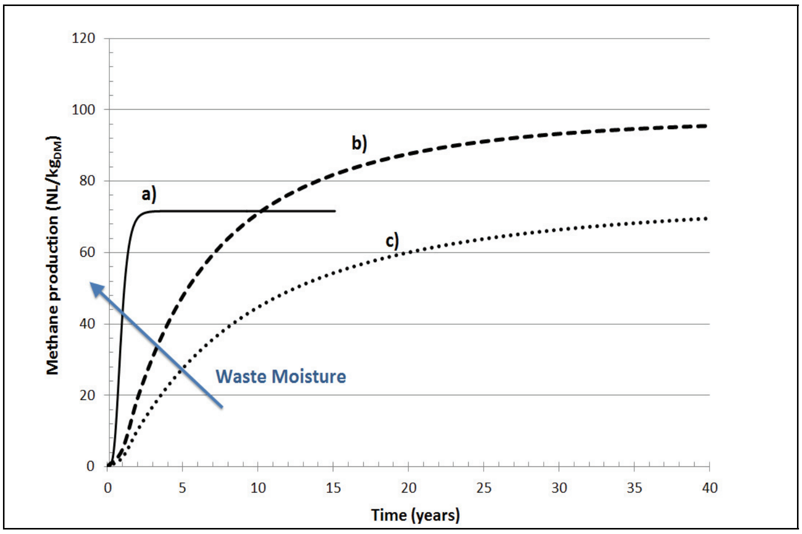

Fig. 7. Comparison of cumulative methane yield in: a) the tested lysimeter; b) landfill with leachate recirculation; c) landfill without leachate recirculation

3.2. Recirculated leachate

The weekly analyses done on landfill leachate have evidenced the wide range of the measured parameters, namely:

- temperature: 10-30 °C;
- pH = 7.8-8.7
- ORP = (-252)-(-52) mV
- electrical conductivity = 7825-32890 μS·cm^{-1}
- COD = 5280-18380 mg·L^{-1}
- ammonium concentration = 737-3730 mg·L^{-1}.

The wide spectrum of each parameter demonstrates the huge heterogeneity of the leachate, which can be influenced by season, and weather.

3.3. Small scale test

A "cube-scale" controlled infiltration test has been carried out in October 2014, in order to analyze the small-scale behavior of the waste under re-circulation and to try to understand the dependence of the resistivity on the waste moisture content. A single cube of pretreated waste (1.5 m^3 in volume and mass around 1400 kg) has been equipped with 24 electrodes for apparent resistivity measurements, to follow the evolution of geo-electrical properties of a cycled infiltration experiments. The test started infiltrating 600 L of tap water (conductivity = 800 μS·cm^{-1}), in 3 hours. From the bottom of the cube, 300 L of liquid were collected into two PVC containers. Water was supplied from the top of the cube, through a regular grid of holes, as shown in Fig. 8. In-flow liquid volume has been measured with a flowmeter, while out-flow volume has been measured by taking manual measurements of liquid height in the containers. The filtrated liquid has been progressively recirculated for 5 days, with the aim of following the evolution of electrical resistivity under this wetting process. Water conductivity has been measured with a multi-sensor probe.

The out-flow volume of leachate at the end of the test (after 5 days), was around 150 L, meaning that more than 400 L had been retained by the waste. The results of the small scale experiment are shown in Fig. 9: the in-flow and out-flow volumes versus time are reported at the top; the specific fluid conductivity values are reported over the same time-scale (in the central plot); the evolution of apparent resistivity measured between electrodes at the top face of the cube is plotted on the bottom plot.

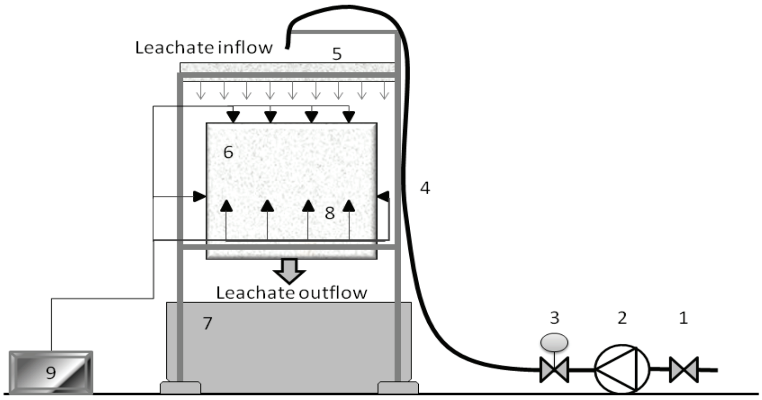

Fig. 8. Experimental set up of a single cube of pretreated waste for the small-scale re-circulation test and resistivity monitoring: 1) closure valve, 2) pump, 3) regulator valve, 4) delivery pipe, 5) distribution grid, 6) waste, 7) collecting tank (discharge), 8) electrodes, 9) acquisition unit for resistivity monitoring

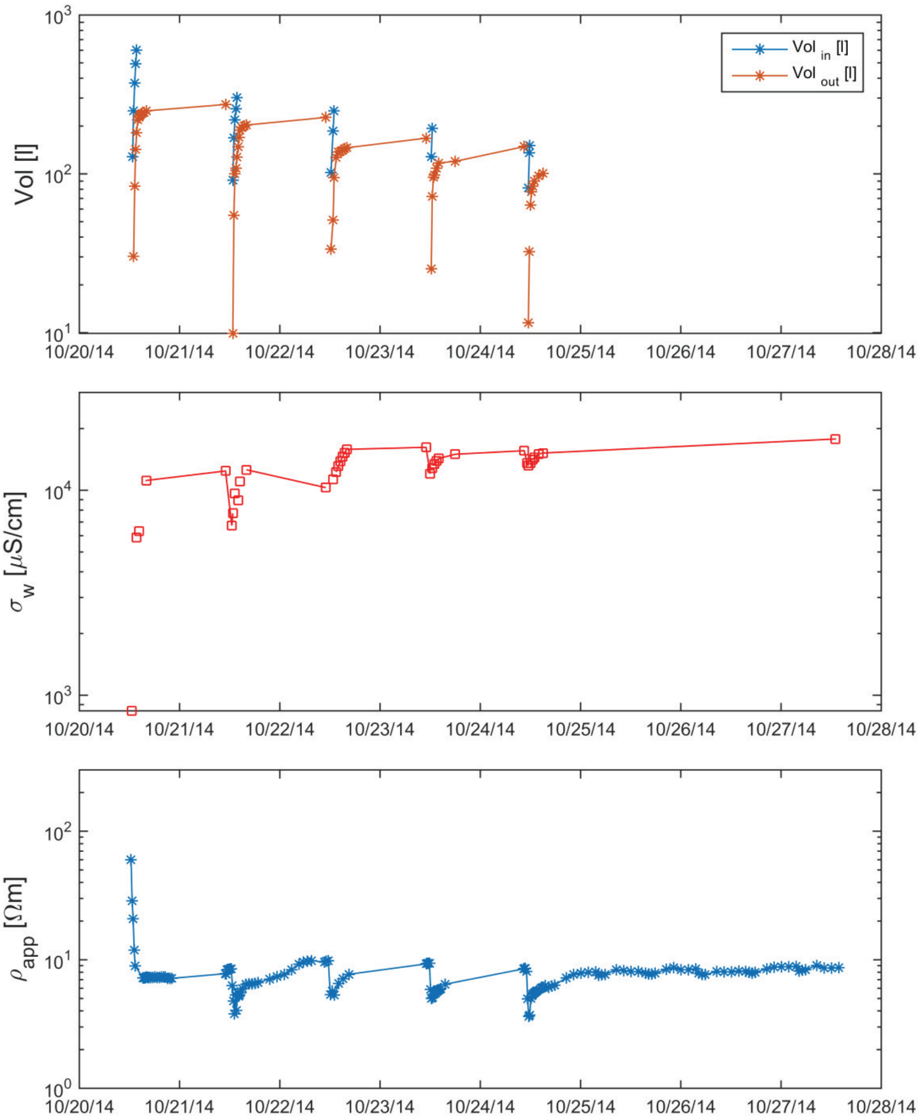

Fig. 9. “Cube-scale” test: in-flow and out-flow volumes (top); fluid conductivity of the recirculated fluid (center); apparent resistivity measured with the quadripole at the top of the cube (bottom)

3.4. Geophysical characterization

The electrical resistivity characterization refers to five parallel vertical sections in the Western sector of the landfill, along SW-NE direction, plus one diagonal section along SE-NW direction. According to the electrical characteristics of the landfill and the electrode spacing, a maximum depth of investigation of about 10-12 meters was reached. This is enough to characterise the waste material down to the bottom of the cell.

The results of the electrical characterisation points out a portion of the landfill of with a rather homogeneous electrical response (Fig. 10). Particularly, we observe:

- the presence of upper layers of waste material up to a depth of about 3-5 meters characterized by resistivity values in the range 20-50 Ω·m;
- at greater depth a slight decrease of the resistivity values, that are in the range 2-5 Ω·m.

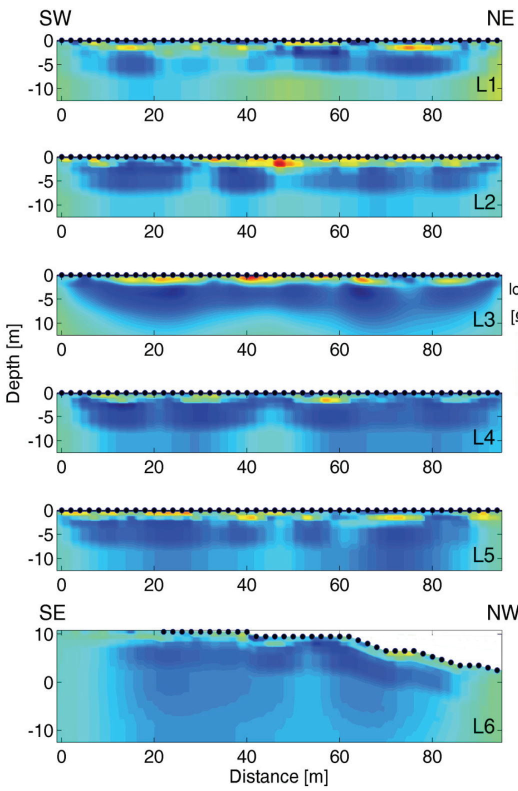

Fig. 10. Electrical resistivity distribution along several transects of the landfill (see Fig. 1 for positioning)

The results of the surface infiltration test, monitored by using time-lapse ERT, are shown in Fig. 11. The panels on the left are referred to Line 1, while the panels on the right are referred to Line 2. The top row reports the background resistivity distribution while the other panels are related to subsequent relative resistivity differences, with respect to the background values, at five time steps (t_0=background; t_1=0-0.5 hours; t_2=1-1.5 hours; t_3=2-2-5 hours; t_4= 4-4.5 hours; t_5=24-24.5 hours. Times are referred to the start of the irrigation).

Based on the results of the time-lapse monitoring of the infiltration test, we pointed out that:

- the infiltration proceeded very fast, according to an initial horizontal spreading in the upper surface layer (1-2 meters) and then moving downwards;
- the vertical movement of the flow follows some preferential pathways, due to the high waste anisotropy; indeed the water creates an elongated plume along Line 1 direction, as it is clear from the negative difference anomalies in correspondence with the infiltration area;
- a preferential zone of fluid accumulation (low electrical resistivity) is observed at the depth of about 4-6 meters; this means that a relevant substrate at low permeability has been reached by the vertical flow and the infiltration will proceed downward very slowly.

An example of monitoring of electrical resistivity in cross hole configuration is plotted in Fig. 12. The left panel refers to the vertical resistivity section between the wells CTB203-CTB204 (monitoring station A) and, on the right, the vertical section between the wells CTB210-CTB211 (monitoring station C). In the uppermost part of the sections, we pointed out resistivity values around 50-60 Ω·m, which are in accordance with the preliminary measurements shown in Fig. 10: resistivity tends to gradually decrease with depth, and at 6-8 meter depth, a very conductive zone is detected (resistivity less than 1 Ω·m).

These values are in good agreement with the stratigraphic column of the boreholes, indicating the presence of dry waste up to 4-6 meters in depth and wet waste at greater depth. The resistivity heterogeneities around the electrodes come from the extremely complex material which is in place, and could even be caused by the presence of organic material and inert separating the pretreated wastes. Moreover, the resistivity gradient with depth is strongly affected by temperature effect: it should be noted that a decrease of about 2 % of resistivity values is expected for an increase of 1 Kelvin degree. We observe an average temperature of about 45 °C, starting from a depth of 4-6 meters from the top of the landfill, which could be partially responsible of the very low resistivity values pointed out at greater depth in the landfill.

The results of the time-lapse monitoring of the first recirculation test are shown in Fig. 13a, 13b. The Figures are organized in rows of resistivity difference panels, covering four days of the test, each day is described in a single row. Following the background resistivity, it is clear how the leachate recirculation affects the resistivity measurements. The most influenced zone is the shallow layer, down to 4 m depth. As the volume of infiltrated leachate increases, the resistivity differences with respect to the background increase, because of the wetting induced by the leachate migration. Furthermore, the resistivity contrasts between the different waste layers are enhanced too. The last panels of the bottom row refer to the fifth day of the test, when recirculation had been stopped. Resistivity contrasts tend to reduce, as the system starts to return to background conditions.

4. Discussions

Experimental simulation of bioreactor landfill showed that leachate recirculation gives its benefits even in the case of waste with low biodegradable content. Despite the difficulty in degrading this type of waste, thanks to the increase of moisture content, it is possible to reduce the time needed to reach methanogenesis. Gompertz equation allowed us to build a predictive curve of methane evolution for the experimental conditions.

By comparing the experimental ones, it can be noted that the biodegradation is strongly affected by the moisture content: the quantity of retained water in the refuses affects positively the Methane Yield Potential as well as its rate. Modeling of biogas production is fundamental in such a context, because it allows predicting the biogas production in a long term (decades of years), necessary to mineralize the waste.

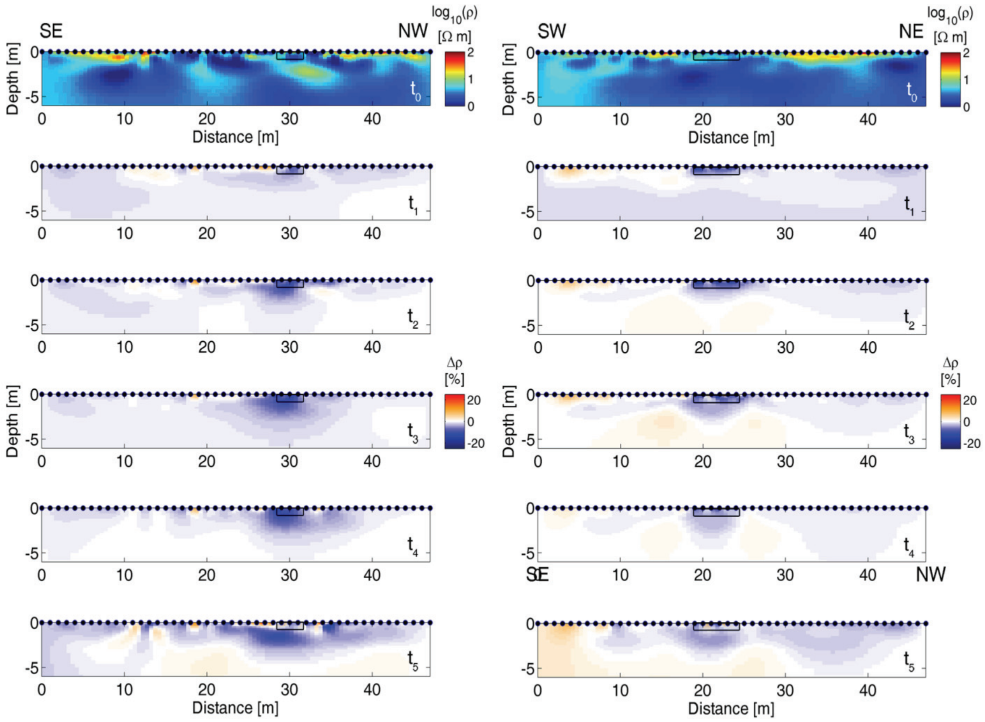

Fig. 11. Relative differences obtained by inversion of resistance data at time-lapse steps (compared to the corresponding background data); the experiment refers to an infiltration test of 6 m^3 of water, infiltrated from the top of the landfill

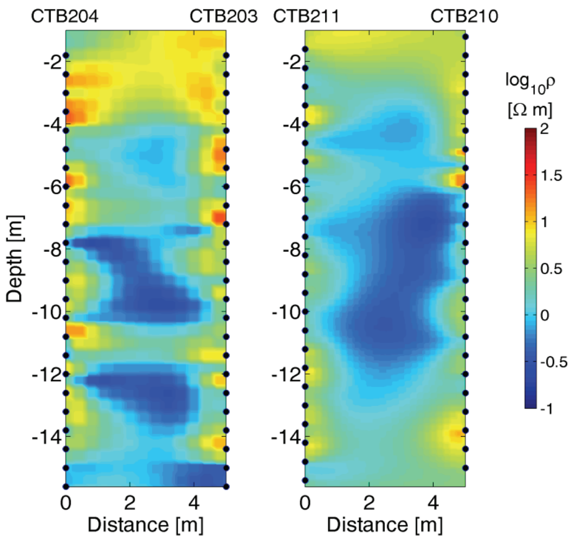

Fig. 12. Background resistivity distribution along two vertical sections of the landfill; section A (left) and C (right)

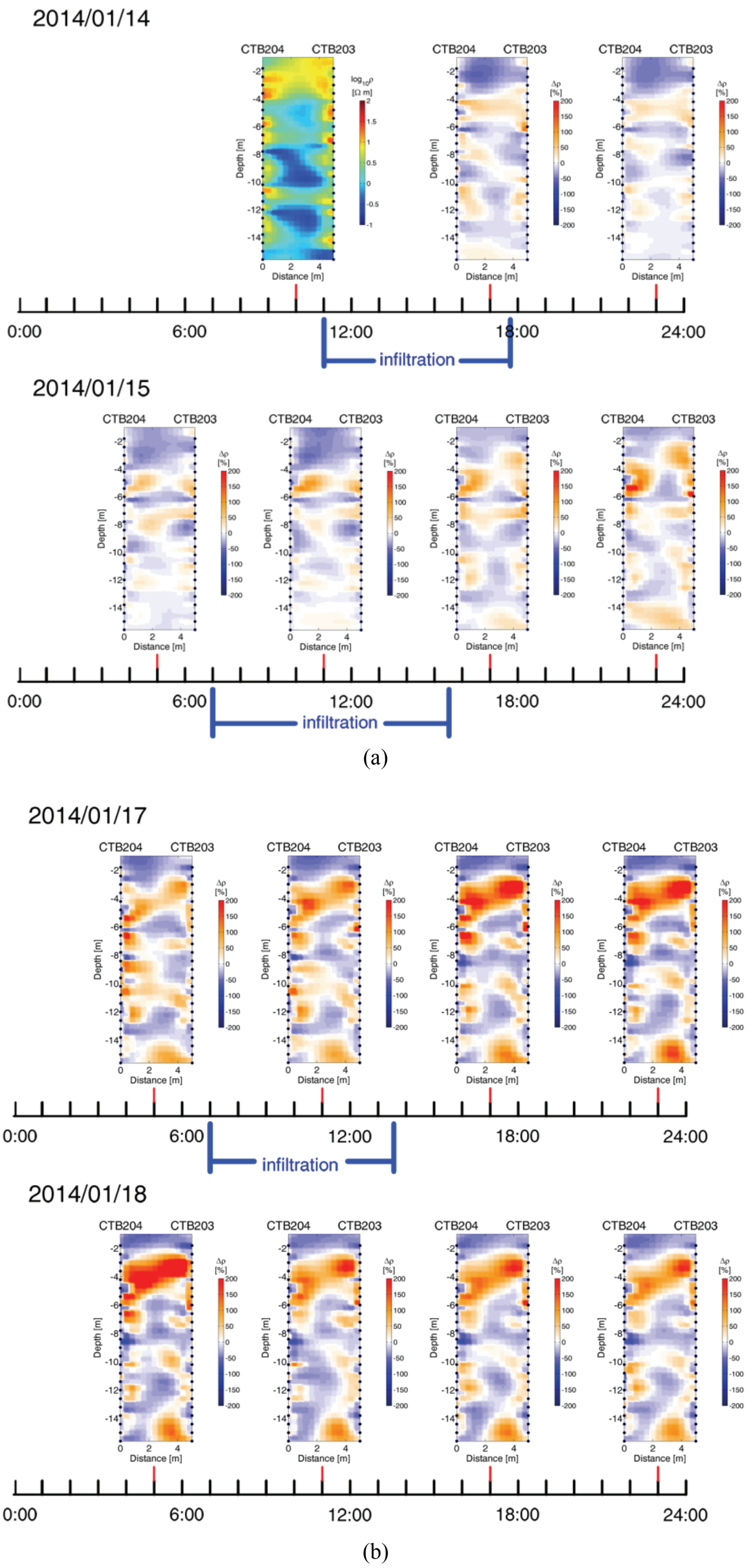

Fig. 13. Time-lapse geo-electrical monitoring of a pilot re-circulation test, at boreholes CTB203-CTB204: (a) background resistivity image and first two days of infiltration; (b) end of the infiltration and redistribution phase

The preliminary characterisation and the set up of the monitoring system were focused to check the sensitivity of geophysical methods to monitor dynamic processes in a heterogeneous medium and assess the efficiency of the landfill working as bioreactor. The geophysical characterisation aimed to point out the electrical response of the landfill and the sensitivity of electrical tomography to detect the infiltration and the volume affected by leachate recirculation. According to our experience, this is the first attempt of monitoring long-term behaviour of the bioreactor landfill by using geophysical sensors permanently installed within the wastes. This required great care in designing the monitoring devices in order to warrant long life to the monitoring system: high temperature resistant cables and graphite electrodes were installed to preserve the devices against effect of high temperature and corrosive environment.

In the cube-scale test, the dependence of the observed resistivity on the fluid content in the waste is well demonstrated: the resistivity dramatically drops down when the wastes are being hydrated, as the fluid is supplied and filtrates through the solid mass. The fluid specific conductivity (observed at the leachate outflow) follows an opposite trend, as it increases due to increasing of dissolved solid content. It is therefore realistic to observe a sharp changes of electrical resistivity during the infiltration (after few hours or days), while the prediction of electrical behavior at long term still remains a challenge.

In the mature waste mass throughout the landfill, the geo-electrical response is related to changes in the chemistry of the pore fluids. Particularly, in porous material the electrical resistivity is mostly affected by temperature (Campbell et al., 1948) and volumetric fluid content (Archie, 1942). In such a context, we observe low resistivity values all around the cell, with an abrupt decrease at deeper level; this agrees with an increase of temperature and moisture content with depth.

In steady-state condition, without infiltration, the surface layers of landfill waste (just below the capping) are the part of the landfill waste where oxygen and bacterial supply are abundant, with quicker decomposition than in the deeper parts: the bulk resistivity of this oxidized zone points out a relative increase with time, because of the organics for microbial degradation become depleted in supply and much of the soluble elements have been removed.

It may thus be relatively more resistive in comparison with the clay cap and the underlying zone of incomplete waste decomposition. The bulk resistivity of the waste at deeper level may have only been partially decomposed under anaerobic conditions thus leading to different physical properties. The lower part of the waste deposit contains a zone dominated by relatively incomplete leaching and therefore exhibits relatively low bulk resistivity.

During infiltration, the time-lapse electrical resistivity panels point out relevant changes of the electrical properties with time up to a depth of about 6-8 meters, with changes of increase and decrease of bulk resistivity. The water flux through the top of the landfill affects its resistivity characteristics: a highly conductive fluid like leachate can influence the electrical behavior of a medium in different ways. Theoretically, higher fluid content implies a reduction of resistivity, but anomalous electrode polarization phenomena can arise in such conditions. Electrodes can be themselves a source of polarization effect; this effect can be difficultly removed from the measurements and produces artifact in resistivity distribution. Thus, in such a harsh environment, only qualitative explanation of the infiltration processes can be given but, nevertheless, the zone impacted by the leachate flow can be delineated.

A fast vertical infiltration rate is expected in the uppermost zone, because of the high permeability of the detritus coverage mixed with low-compacted wastes. At deeper levels, a decrease of waste permeability is expected. On the other hands, the main drawbacks related to an efficient infiltration from the top of the cell are related to the relevant lateral spreading of the infiltrated water, as pointed out by the infiltration tests. This could lead to a non-uniform distribution at deeper level of leachate within the waste, partially reducing the efficiency of the enhancement of biogas production.

5. Conclusions and future activities

Leachate infiltration in landfills is a complex process and detailed information on the flow characteristics are needed to provide fundamental understanding of the processes involved for prediction of biogas production. We are analyzing the complexity of processes by integration of laboratory tests on waste samples and geophysical characterization and monitoring in the landfill: the final goal of Bio.Lea.R. project (Life+ Program) is to demonstrate the improvement of biogas production by leachate recirculation in a landfill for MBT wastes.

First results at laboratory scale have proved the faster production of biogas, with the Methane Potential Yield at 900 days. The current modeling of leachate infiltration is influenced by availability of experimental data which in this case will be provided by time lapse monitoring of geophysical parameters.

The combination of time-lapse geophysical monitoring, advanced inversion technique and traditional waste sampling techniques provide robust data to generate a consistent structural framework of the landfill as well as experimental results on the infiltration process and degradation of waste. Experiments at different scales and environmental conditions, to say lysimeter and landfill, point out the processes that are involved in biodegradation. This leads to advanced characterization of biodegradation and prognosis of local process development. The data of biogas production and emission of the two cells (with and without re-circulation of leachate) will be compared to define optimal conditions of liquid recirculation/distribution to reduce and concentrate the biogas production period. In this way, the project is useful for future implementations of non-hazardous landfills managed as bioreactors. The re-circulation of leachate is another positive solution to reduce the environmental impact of effluents of waste landfilling (Şchiopu et al., 2012; Şchiopu and Ghinea, 2013)

The project can warrant a more efficient biogas extraction and consequently lower methane losses in the environment.The methane exploitation to produce electricity is another positive aspect, in view of fossil fuel substitution.

Acknowledgements
This work has been performed in the framework of the Project Life+ "Full scale use of liquid injection, for innovative control of waste moisture to enhance biogas production in pretreated waste landfill" (LIFE09 – ENV/IT/000101).

References

Archie G.E., (1942), The electrical resistivity log as an aid in determining some reservoir characteristics, *Petroleum Transactions of AIME*, **146**, 54–62.

Acworth R.I., Jorstad L.B., (2006), Integration of multi-channel piezometry and electrical tomography to better define chemical heterogeneity in a landfill leachate plume within a sand aquifer, *Journal of Contaminant Hydrology*, **83**, 200-220.

Arato A., Agostini A., Godio A., (2014a), *Geophysical Characterization and Monitoring of a Landfill Working as a Bio-Reactor,* Near Surface Geosciences Conference, Athens 2014, on CD.

Arato A., Godio A., Sambuelli L., (2014b), Staggered grid inversion of 2D cross-hole resistivity data, *Journal of Applied Geophysics*, **107**, 60–70.

Bayard R., Benbelkacem H., Zhang Y., Gourdon R., (2009), *Impact of leachate Injection Modes on Landfill Biogas Production*, Proc. Sardinia 2009, 12th Int. Waste Management and Landfill Symposium, S. Margherita di Pula, Cagliari, 5-9 October 2009, on CD.

Bernstone C., Dahlin T., Ohlsson T., Hogland W., (2000), DC-resistivity mapping of internal landfill structures: two pre-excavation surveys, *Environmental Geology*, **39**, 360-371.

Binley A., (2013), R2 free resistivity inversion software, Version 2.7.

Campbell R.B., Bower C.A., Richards L.A., (1948), Change of electrical conductivity with temperature and the relation of osmotic pressure to electrical conductivity and ion concentration for soil extracts, *Soil Science Society of America Proceedings*, **13**, 66–69.

EC Directive, (1999), Council Directive 1999/31/EC of 26 April 1999, on the landfill of waste, *Official Journal of the European Communities*, **L 182**, 1-16.

Godio A., Naldi M., (2003), Two dimensional electrical imaging for detection of hydrocarbon contaminants, *Near Surface Geophysics*, **1**, 131-137.

Godio A., Ferraris S., (2005), Time lapse geophysics for monitoring an infiltration test in vadose zone, *Bollettino di Geofisica Teorica e Applicata*, **46**, 201-216.

Godio A., Arato A., Stocco S., (2010), Geophysical characterization of a NAPL-contaminated site, *Environmental Geosciences*, **17**, 141-162.

Grellier S., Bouyé J.M., Guérin R., Robain H., Skhiri, N., (2005), *Electrical Resistivity Tomography (ERT) Applied to Moisture Measurements in Bioreactor: Principles, in situ Measurements and Results,* International Workshop Hydro-Physico-Mechanics (HPM) Landfill, 21- 22 March, Grenoble.

Grellier S., Guerin R., Robain H., Bobachev A., Vermeersch F., Tabbagh A., (2008), Monitoring of leachate recirculation in a bioreactor landfill by 2-D electrical resistivity imaging, *Journal of Environmental and Engineering Geophysics*, **13**, 351-359.

Guérin R., Grellier S., Robain H., Bobachev A., Vermeersch F., (2004), *Monitoring of Leachate Recirculation in a Bioractor by Electrical Resistivity Tomography*, 66th EAGE Conference & Exhibition, Paris, 7-10 June 2004, On line: http://www.earthdoc.org/publication/publicationdetails/?publication=2445.

Haydar M.M., Khire M.V., (2005), Leachate recirculation using horizontal trenches in bioreactor landfills, *Journal of Geotechnical and Geoenvironmental Engineering*, **131**, 837-847.

Hernández-Berriel M.d.C, Mañón-Salas M.d.C., Buenrostro-Delgado O., Sánchez-Yáñez J.M., Márquez-Benavides L., (2014), Landfill leachate recirculation. Part I: solid waste degradation and biogas production, *Environmental Engineering and Management Journal*, **13**, 2687-2695.

Imhoff P.T., Reinhart D.R., Englund M., Guerin R., Gawande N., Han B., Jonnalagadda S., Townsend T.G., Yazdani R., (2007), Review of state of the art methods for measuring water in landfills, *Waste Management*, **27**, 729–745.

Khire M.V., Mukherjee M., (2007), Leachate injection using vertical wells in bioreactor landfills, *Waste Management*, **27**, 1233-1247.

La Brecque D.J., Yang X., (2001), Difference inversion of ERT data: a fast inversion method for 3-D in situ monitoring, *Journal of Environmental and Engineering Geophysics*, **6**, 83–89.

Magnano E., (2010), *Landfill Gas* (in Italian), EPC Libri, Rome, Italy.

Mali S.T., Khare K.C., Biradar A.H., (2012), Enhancement of methane production and bio-stabilization of municipal solid waste in anaerobic bioreactor landfill, *Bioresource Technology*, **110**,10-17.

Meju M.A., (2000), Geoelectrical investigation of old/abandoned, covered landfill sites in urban areas: model development with a genetic diagnosis approach, *Journal of Applied Geophysics*, **44**, 115-150.

Mondelli G., Giacheti H.L., Boscov M.E.G., Elis V.R., Hamada J., (2007), Geoenvironmental site investigation using different techniques in a municipal solid waste disposal site in Brazil, *Environmental Geology*, **52**, 871-887.

Moreau S., Bouye J.M., Barina G., Oberty O., (2003), *Electrical Resistivity Survey to investigate the influence of Leachate Recirculation in a MSW landfill*, Proc. Sardinia 2003, 9th Int. Waste Management and Landfill Symposium, S. Margherita di Pula, 6-10 October, Cagliari, Italy.

Morris J.W.F., Vasuki N.C., Baker J.A., Pendleton C.H., (2003), Findings from long-term monitoring studies at MSW landfill facilities with leachate recirculation, *Waste Management*, **23**, 653-666.

Olofsson B., Jernberg H., Rosenqvist A., (2006), Tracing leachates at waste sites using geophysical and geochemical modelling, *Environmental Geology*, **49**, 720-732.

Pacey J., Reinhart D.R., Hansen D.L., Townsend G.T., Johnson W.H., (1999), *Landfill Bioreactor – an Innovation in Solid Waste Management*, 22nd Annual

LFG Symposium, SWANA, Lake Buena Vista, 23 March 1999, 171-178.

Pohland F.G., (1980), Leachate recycle as landfill management option, *Journal of the Environmental Engineering Division-Asce*, **106**, 1057-1069.

Pommier S., Lefebvre X., (2009), *Impact of Moisture Content on the biodegradation of Heterogeneous Solid Waste: simulation by a New Modelling Framework*, 3rd International Workshop "Hydro-Physico-Mechanics of Landfills", 10-13 March, Braunschweig, Germany.

Reinhart D.R., Townsend T.G., (1998), *Landfill Bioreactor Design & Operation*, Lewis Publishers, New York, USA.

Reinhart D.R., McCreanor P.T., Townsend T., (2002), The bioreactor landfill: Its status and future, *Waste Management & Research*, **20**, 172-186.

Rosqvist H., Dahlin T., Lenhé C., (2005), *Investigation of Water Flow in a Bioreactor Landfill using Geoelectrical Imaging Techniques*, Proc. Sardinia 2005, 10th Int. Waste Management and Landfill Symposium, S. Margherita di Pula, Cagliari, 3-7 October 2005, on CD.

Sanphoti N., Towprayoon S., Chaiprasert P., Nopharatana A., (2006), The effects of leachate recirculation with supplemental water addition on methane production and waste decomposition in a simulated tropical landfill, *Journal of Environmental Management*, **81**, 27-35.

Şchiopu A.M., Ghinea C., (2013), Municipal solid waste management and treatment of effluents resulting from their landfilling, *Environmental Engineering and Management Journal*, **12**, 1699-1719.

Şchiopu A.-M., Piuleac G.C., Cojocar C., Aposto I., Mămăligă I., Gavrilescu M., (2012), Reducing environmental risk of landfills: Leachate treatment by reverse osmosis, *Environmental Engineering and Management Journal*, **11**, 2319-2331.

Xue Q., Liu L., Chen Y., Wang J. (2013), Investigation of the recovery efficiency of methane using vertical wells operating in landfills, *Environmental Engineering and Management Journal*, **12**, 1855-1859.

Warith M., (2002), Bioreactor landfills: experimental and field results, *Waste Management*, **22**, 7-17.

Zhu B., Gikas P., Zhang R., Lord James J.B., Li X., (2009), Characteristics and biogas production potential of municipal solid wastes pretreated with a rotary drum reactor, *Bioresource Technology*, **100**, 1122–1129.