Semi-automatic Mobile System for Detecting Defects in Landfill Liners: Tests in a Pilot Plant at LNEC

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ABSTRACT: The effectiveness of lining systems in service conditions is highly dependent on the performance of geomembranes. However, defects are every-present problem, and for covered geomembranes such as the ones used in landfills, it seems that most defects appear during the placement of the granular material that forms the Primary Leachate Collection System (PLCS). Although some test methods detect and locate defects in geomembrane liners after the placement of the PLCS, they are time consuming and quite expensive. Also, they were mainly developed for simple liner systems consisting of a geomembrane placed over a Compacted Clay Liner (CCL) and, in Portugal, the municipal solid waste landfill liner systems typically consist of a geomembrane placed over a Geosynthetic Clay Liner (GCL), over a CCL. In addition, existing methods were not developed for double liner systems such as the ones generally used in hazardous landfills. A research program aimed at developing a prompt and accurate test method to check geomembrane integrity is in progress. A semi-automatic mobile prototype equipped to record data on the location of defects has been tested in both small and large scale pilot plants. The aim of first pilot plant was to study the resolution and accuracy of the prototype and its response to the water content of materials in contact with the geomembrane. The second pilot plant, constructed at *Laboratório Nacional de Engenharia Civil, I.P.* (LNEC) campus, has been used to study the aptness of the prototype to detect and locate defects in different types of liner systems (simple and double). This paper focuses on the tests carried out at the second pilot plant. Results obtained suggest that the prototype is able to detect and locate defects in different types of liner systems.

1 INTRODUCTION

Landfills are engineering facilities designed and constructed with a barrier system (liner system) intending to assure the protection of the environment. This system includes an active barrier and a passive barrier. The passive barrier comprises a compacted clay liner (CCL) and/or a geosynthetic clay liner (GCL), while the active barrier includes a geomembrane (GM), protected by a geotextile (GTX), and a drainage layer known as Primary Leachate Collection System (PLCS).

The effectiveness of liner systems in service conditions is closely related with the performance of the GM, as it provides the primary barrier to advective and diffusive transport of contaminants.

Unfortunately, despite all precautions regarding manufacturing, transportation, handling, storage and installation, defects in the GM seem to be unavoidable. For covered GMs, such as the ones placed in landfills, it seems that most defects appear during the placement of the PLCS. Indeed, data reported by Nosko and Touze-Foltz (2000) and collected at more than 300 sites from

16 countries, shows that 71% of the damages were caused by stones during PLCS installation. In addition, according to these authors, the number of defects per hectare is about 12.9. A different value is referred by Rollin *at al.* (2002), which indicate a value of 17.4 defects/ha.

A few test methods are available to detect and locate defects in GM liners after PLCS placement, such as the soil-covered GM method and the grid method (permanent). However, these methods present several shortcomings. First, they are time consuming. Second, they are very expensive. Third, they were developed for liner systems consisting of a GM+CCL and, in Portugal, the municipal solid waste (MSW) landfills typically include composite liners consisting of GM+GCL+CCL. Finally, their applicability in landfills with double composite liners (e.g., hazardous landfills) requires further study.

A research programme aimed at developing a test method to assess the integrity of the GM after placement of the PLCS and that overcome the limitations of the existing methods is in progress.

The research programme began with the development of a prototype, equipped to record date on the detection and location of defects and their processing in real time.

The prototype has been tested in two pilot plants, constructed in small and large scale, respectively. The aim of first pilot was to study the resolution and accuracy of the prototype and its response to the water content of materials in contact with the GM. The second pilot plant, constructed at *Laboratório Nacional de Engenharia Civil, I.P.* (LNEC), aims to study the aptness of the prototype to detect and locate defects in different types of liner systems, namely the ones consisting of CCL+GM, CCL+GCL+GM or double composite liners.

This paper focuses mainly on studies conducted at the second pilot plant. It describes the tests carried out and presents the first results obtained. Conclusions are drawn about the suitability of the prototype to detect and locate defects in different types of liner systems.

2 EXPERIMENTAL WORK

2.1 *Prototype*

The prototype developed (Figure 1) comprises the following elements: (1) set of electrical potential measurement electrodes, assembled on a mobile structure; (2) Global Navigation Satellite System (GNSS); (3) embedded data acquisition system and corresponding interface, for connecting with the GNSS; (4) software for processing and displaying the defects located on computer screen; and (5) laptop.

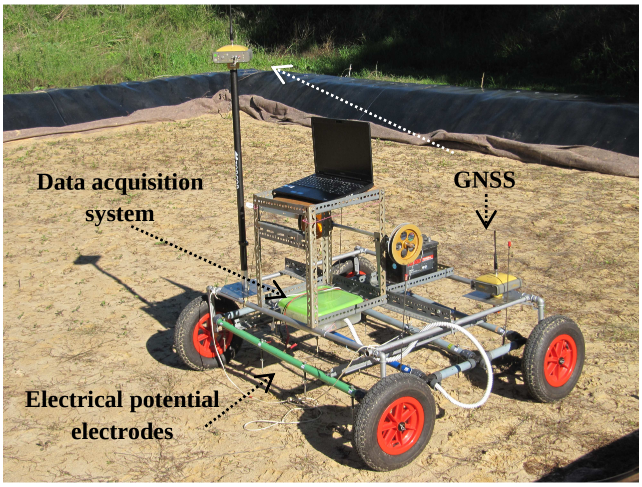

Figure 1. Prototype general view

It should be noted that this prototype is an improved version of the prototype used in tests carried on small scale at *Instituto Superior de Engenharia de Lisboa* (ISEL). The aim of first pilot plant was to study the resolution and accuracy of the prototype and its response in relation to the water content of the materials in contact with the GM. Details about its results were summarised by

Lopes *et al.* (2012) and will not be presented in this paper for the sake of brevity. Similarly, details on preliminary versions of the prototype and on embedded acquisition system can be found, respectively, in Mota *et al.* (2011, 2012) and in Matutino *et al.* (2011).

2.2 *Pilot plant at LNEC*

A large scale pilot plant was constructed at LNEC campus in order to study the suitability of the prototype to detect and locate defects in different types of lining systems. The pilot plant consists of three cells of approximately 10m×10m×1m. Figure 2 presents an overview of cells construction.

Figure 2. Pilot plant construction

Each cell contains a different type of liner system. The lining systems adopted fulfil the minimum requirements specified in the European Directive no. 1999/31/EC on the Landfill of Waste, which is typically followed in Portugal.

According to the European Directive, the lining systems must protect the soil and water (groundwater and superficial water). That protection must be achieved by combining a geological barrier with an artificial sealing layer (usually assumed as a GM).

For MSW landfills, the geological barrier must have a hydraulic conductivity (k) less than 10^{-9} $m.s^{-1}$ and be at least 1 m thick. For hazardous waste landfills, the lining system must consist of an artificial sealing layer plus a geological barrier with $k \leq 10^{-9}$ $m.s^{-1}$ and be at least 5 m thick. If the geological barrier does not fulfil previously the above conditions, other materials may artificially complement it, provided that a technically equivalent protection can be achieved. Moreover, the minimum thickness of the equivalent barrier must be 0.5 m, and must be complemented by a drainage layer (minimum thickness of 0.5 m).

In Portugal, lining systems of MSW landfills typically include an active barrier comprising a drainage layer (≥ 0.5 m) and a high density polyethylene (HDPE) geomembrane, 2 mm thick, and a passive barrier consisting of a GCL over a CCL ($k \leq 10^{-9}$ $m.s^{-1}$, ≥ 0.5 m). Hazardous waste landfills are designed with double lining systems that include two levels of composite liners separated by a drainage layer (also termed in literature as secondary leachate collection system -SLCS or leakage detection system). The aim of this layer is to control the leachate that may flow through the primary liner.

Pilot plant was designed taking into account the lining systems typically used in different landfills in Portugal. Accordingly, cell 1 represents a lining system similar to the ones that have been used in large MSW landfills. Cell 2 simulates a lining system used in small landfills and cell 3 a lining system of a hazardous landfill. Details about cells design can be found in Dores *et al.* (2012).

The cells include several layers, of both soils and geosynthetics. Before presenting the materials used, some comments must be made about the features of the soil used for constructing the CCL (compacted clay liner).

The critical issue of the soil for CCL is the hydraulic conductivity, as previously shown. A value less than 10^{-9} m s^{-1} is required. Construction of a CCL with a $k \leq 10^{-9}$ $m.s^{-1}$ requires the use of suitable soils. It has been considered that the soil ability to achieve a specific hydraulic conductivity depends mainly on soil characteristics and on field compaction procedures.

Concerning the soil characteristics, it has been considered that the soil ability to achieve a specific hydraulic conductivity depends on its plasticity characteristics, water content and particle size.

Plasticity characteristics are quantified by liquid limit (LL), plastic limit (PL) and plasticity index (PI). The PI of the soil is perhaps the single most frequently used indicator of the suitability of a natural soil for use in a CCL. A minimum value around 10% for IP is often recommended (Oweis and Khera, 1998).

Water content refers to the amount of free water contained in a given amount of soil. Its measurement is useful for assessing whether a clay soil needs pre-processing (moisture adjustment or soil amendments) to yield a specific density or hydraulic conductivity.

As regards particle size, a minimum percentage of fines (typically ≥ 50 % passing No. 200 sieve, which has an opening size equal to 75 μm) is usually specified. A minimum of clay (fraction finer than 2 μm) is also sometimes required, such as ≥ 20 to 25 % (Bonaparte *et al.*, 2002).

The geotechnical characteristics of the soil used in the pilot plant for constructing the CCL are summarised in Table 1. As it can be seen, characteristics of the soil used are in agreement with the above mentioned recommendations, except for hydraulic conductivity, which was slightly higher. However, the value indicated in Table 1 refers to a laboratory test carried out using a specimen prepared with a moisture content equal to the optimum moisture content (ω_{opt}) obtained in Proctor test, whereas, according to EPA (1998), the lowest hydraulic conductivity is achieved when the soil is compacted to a water content of 1 to 7% above the optimum moisture content.

Table 1. Characteristics of clayey soil

Percent fines (%)	**Percent clay (%)**	**Atterberg limits**			**Proctor**		**Hydraulic conductivity**	**Classification**
		LL (%)	PL (%)	PI (%)	$\omega_{opt.}$ (%)	$\gamma_{d\ max.}$ ($kN.m^{-3}$)	k_s ($m.s^{-1}$)	Unified Soil Classification System
54.6	18.1	38.1	20.2	17.9	14.7	18	0.7×10^{-9}	CL

Notes: Percent fines = percent passing the USA No 200 sieve (openings of 75 μm); Percent clay = percent finer than 0.002 mm; LL = Liquid Limit; LP = Plastic limit; IP = Plasticity index; ω_{opt} = optimum water content; $\gamma_{d\ max}$ = maximum dry unit weight; k_s = Hydraulic conductivity of the soil; CL = inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays.

With respect to compaction procedures, the clayey soil was compacted at its natural water content, as it was impossible to dry all soil used in the three cells (several tons). Measurements carried out after soil compaction to check the quality of the compaction (Table 2) showed that the water content of the soil was about 3 to 5 % above the optimum moisture content (ω_{opt}) obtained in Proctor test (see Table 1). These values are within the range of moisture contents indicated by EPA (1998) to achieve the lowest hydraulic conductivities, and therefore, a proper in situ value is expected.

Table 2. Results of quality compaction control

Cell	*Moisture-Density Gauge		Sand replacement method		**Oven
	Compaction ratio (%)	Water content (%)	Compaction ratio (%)	Water content (%)	Water content (%)
1	96.6 ± 2.5	13.6 ± 0.5	93	18.2	17.8 ± 0.6
2	97.7 ± 1.4	15.7 ± 0.7	103	19.2	18.2 ± 2.0
3	95.4 ± 2.7	15.6 ± 1.1	95	15.3	19.6 ± 3.6

*10 readings variability with 95% confidence
**5 samples variability with 95% confidence

Some comments must also be made as regards the geosynthetics used in the pilot plant. Several materials with a variety of functions were used, in particular the following ones: a smooth HDPE geomembrane, to act as barrier; a needlepunched GCL, to act as barrier also; two nonwoven geotextiles, to protect the GM against puncturing (the two geotextiles are similar, the difference is that they were provided by different manufacturers); a conductive geotextile over the SLCS in cell 3, to facilitate the detection of defects. Figure 3 presents an overview of geosynthetics used. Details about their design specifications can be found in Dores (2011) and are not included in this paper for the sake of brevity.

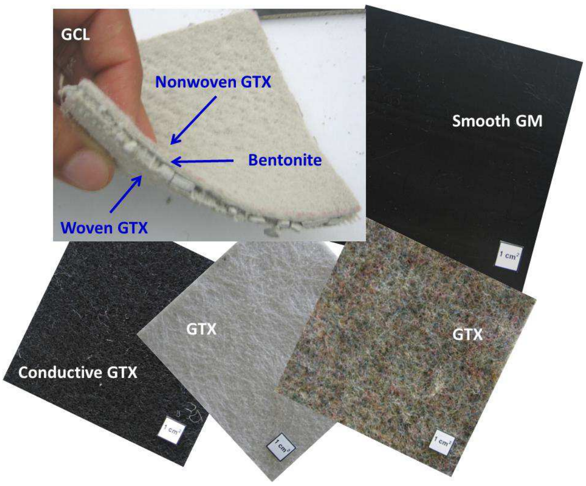

Figure 3. Overview of the geosynthetics used in pilot plant

It should be noted that the geosynthetics were carefully installed, especially the geomembrane, as it is the most important layer of the lining systems. Since seams are vulnerable areas, they were tested as if they were placed in a landfill. Air pressure tests and mechanical tests (peel and shear) were carried out, to assess, respectively, seams continuity and seams strength. Results of these tests showed that the seams were properly made.

The cells comprise the following layers, from bottom to top (Figure 4):

Cell1

- 0.5 m thick layer of compacted clayey soil (CCL) as part of the passive barrier;
- GCL as part of passive barrier (5000g.m^{-2});
- GM as active barrier (HDPE, 2 mm tick);
- GTX to protect the GM against puncturing (polypropylene, 300g.m^{-2});
- 0.2 m thick layer of sand (0.18/2.0 mm), to simulate the PLCS.

Cell 2

- 0.5 m thick layer of compacted clayey soil (CCL) as passive barrier;
- GM as active barrier (HDPE, 2 mm tick);
- GTX to protect the GM against puncturing (polypropylene, 300g.m^{-2});
- 0.2 m thick layer of sand (0.18/2.0 mm), to simulate the PLCS.

Cell3

- 0.5 m thick layer of compacted clayey soil (CCL) as part of the secondary lining system;
- GCL as part of the secondary lining system (5000g.m^{-2})
- Geomembrane (secondary) as part of the secondary lining system (smooth, HDPE, 2 mm thick);
- Geotextile to protect the GM against puncturing (300g.m^{-2}, white);
- 0.15 m thick layer of sand (0.18/2.0 mm), to simulate the SLCS
- Conductive geotextile to facilitate the detection of defects (polypropylene with black carbon impregnation, electrical resistance $\leq 10^5$ Ω,200g.m^{-2});
- Geomembrane (primary) as part of the primary lining system (HDPE, 2 mm tick);
- Geotextile to protect the GM against puncturing (polypropylene, 300g.m^{-2});
- 0.2 m thick layer of sand (0.18/2.0 mm), to simulate the PLCS.

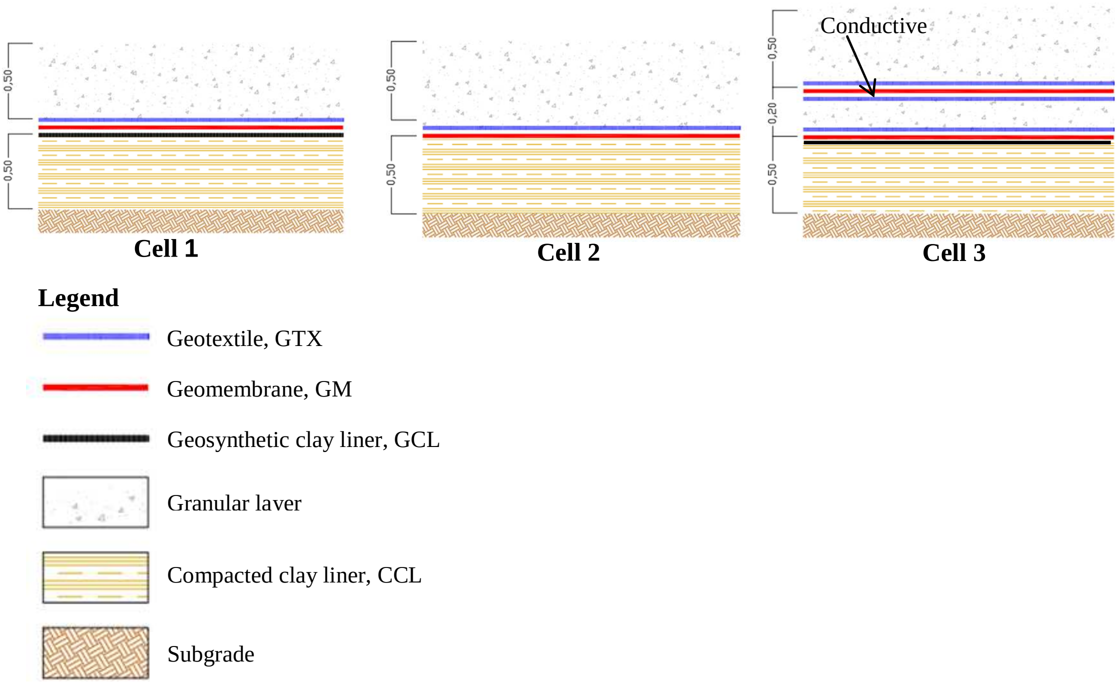

Figure 4. Scheme of the lining systems used in cells 1 to 3 (based on Dores *et al.*, 2012)

2.3 *Defects detection*

The methodology adopted to detect the defects with the prototype is quite similar to the one described in ASTM D7007. It locates defects in the GM by creating an electrical field across the GM and then locating with potential electrodes the points of anomalous electrical potential distribution, where electrical current flows through discontinuities, as Figure 5 schematically shows.

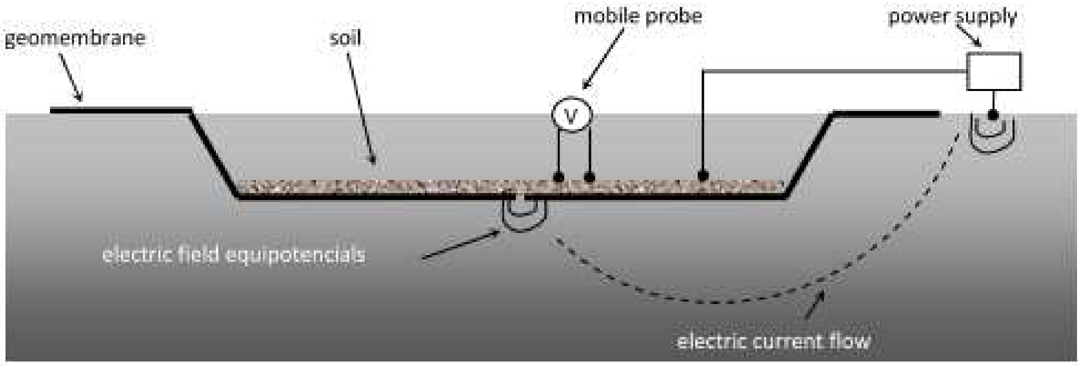

Figure 5. Schematic drawing of the electrical defect detection method (Mota *et al.*, 2011)

In the pilot plant, point-by-point measurements were performed using a 0.3 m dipole configuration (dipole = two electrodes) with automated digital data acquisition. Measurements were conducted along survey lines both parallel and perpendicularly to the source electrodes (Figure 6).

Figure 6. Electrical potential measurements with the prototype

It should be noted that the defects, consisting of a circular hole, 2 mm in diameter, were deliberately made in GM liners. In cell 3 the hole was made in upper GM (primary lining system).

3 RESULTS AND DISCUSSION

Figure 7 shows the electrical potential field obtained with measurements performed with the potential electrodes installed parallel and perpendicular to the source electrodes at cell 2. As it can be seen, the electrical potential field is quite constant, in the range -100 to +100 mV, except near the defect. In this area, a high gradient in the electrical potential field was found (between -200 and +200 mV). Although both measurements (parallel and perpendicular directions) show a gradient near the defect, the most significant was obtained in the direction parallel to the source electrodes.

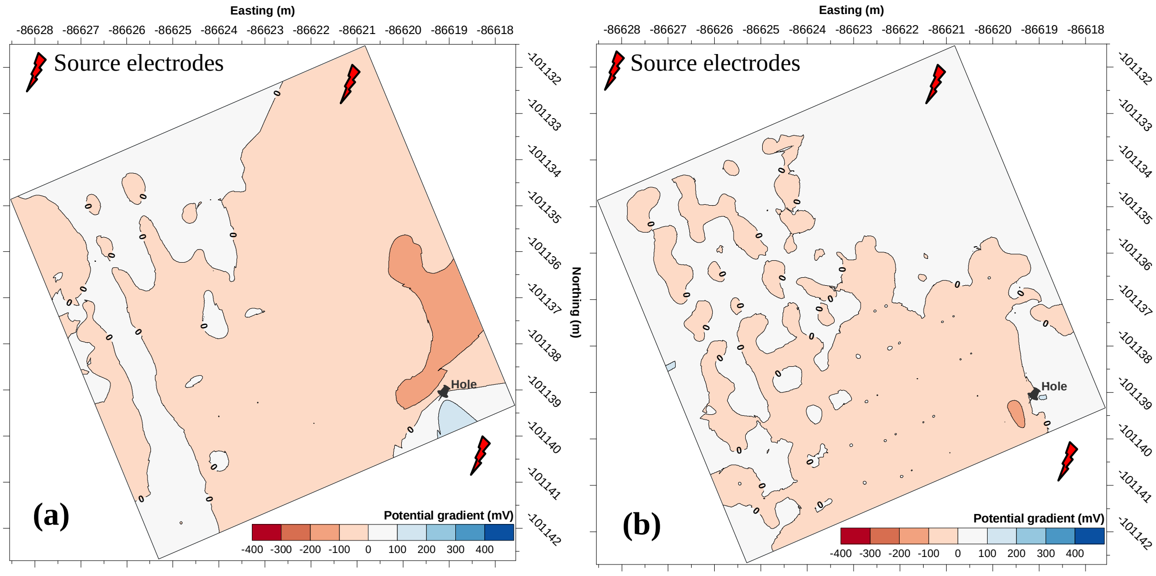

Figure 7. Electrical potential field: (a) measurements parallel to the source electrodes; (b) measurements perpendicular to the source electrodes

Similar results were obtained at cell 1. They are not included in this paper for the sake of brevity. Tests on cell 3 are still in progress and will be presented in a near future. Nevertheless, results obtained until now for cells 1 and 2 suggest that the prototype is able to detect and locate the defects in different types of lining systems.

Some problems were identified in the prototype, which are being solved. Of note is the need for improving robustness. This issue was already addressed and an upgraded version of the prototype is being constructed.

4 CONCLUSIONS

This paper presented and discussed experimental work performed in a large scale pilot plant constructed at *Laboratório Nacional de Engenharia Civil, I.P.* (LNEC) to study the suitability of a prototype to detect and locate defects in different types of landfill liner systems. Another goal of the experimental work was to identify and overcome the potential drawbacks of the prototype, before producing test equipment to be used in landfills.

Results obtained from the pilot plant are encouraging. The prototype has been able to detect and accurately locate the defects deliberately made in the geomembrane barrier of the different liner systems.

Problems found in the prototype were addressed, and an upgraded version is under construction. This version will be tested, not only in the pilot plant, but also in a landfill, before final launching. Nevertheless, the developments already made with the existing prototype suggest that progress may have been made in defect detection.

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