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Lopes and Gomes

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Geotechnical landfill monitoring — adaptations needed

1 **Maria-Lurdes Lopes** PhD, Eng
Full Professor, Department of Civil Engineering, Faculty of Engineering, University of Porto, Porto, Portugal

2 **Cristina Cunha Gomes** PhD, Eng
Senior Engineer, COBA S.A., Lisboa, Portugal

Most monitoring programs implemented in sanitary landfills are based on the principles of geotechnical instrumentation and monitoring of earthworks, such as earth dams, which require custom equipment and installation methods. From 2001 to 2008, the behaviour of two sanitary landfills located in the north of Portugal was monitored using traditional geotechnical instrumentation. The objective of this paper was to highlight the problems encountered with the use of traditional geotechnical instrumentation for monitoring the behaviour of urban solid waste. After a brief description of the instrumentation plan implemented in the two sanitary landfills, for each parameter of the behaviour to be monitored, the reasons for the choice of equipment, the installation method implemented, and the main difficulties encountered and adjustments performed during the work are discussed.

Notation

P_{TA}	Single open-tube piezometer
P_{TAV}	Double open-tube piezometer
ϕ	Diameter

Introduction

The geotechnical component of urban solid waste (USW) landfills requires knowledge about the physical, chemical, mechanical and hydraulic properties of the waste and their variation in time, as well as the use of representative models of the complex and evolutionary behaviour of the waste.

The high heterogeneity of both composition and size of the waste, the variation in time (mainly linked to bio-decomposition processes), the geography (culture, development and industrialisation level, management practices etc.), the multi-phase characteristics, the difficulties of handling waste and obtaining representative samples, the lack of standardised test procedures, as well as the specialised laboratories for their study, add significant constraints to waste characterisation and to the development of proper behaviour models. Moreover, difficulties in simulating *in situ* conditions in laboratory facilities often lead researchers to adopt *in situ* characterisation tests, construct experimental landfills and, especially, monitor existing landfills.

Landfill monitoring programs are mainly based on the principles of geotechnical instrumentation and monitoring of earthworks, including those of earth dams, which require custom equipment and installation methods.

On the other hand, the number of scientific publications on landfill monitoring is relatively scarce and most of them lack details about the equipment used, the installation methods implemented and the main difficulties or limitations encountered (Blengino *et al*., 1996; Coduto and Huitric, 1990; Gotteland *et al*., 1995; Gourc and Olivier, 2005; Jucá *et al*., 1998; Reddy, 2006; Ngambi *et al*., 2001; Sánchez-Alciturri *et al*., 1993; Zekkos, 2011, 2013).

Moreover, the selection of landfill monitoring equipment is usually restricted to those available commercially, which, in general, are not tailored for this type of structure, namely, ability to support the expected high levels of deformation, heterogeneity and physicochemical aggressiveness of the environment.

The behaviour of two landfills located in the north of Portugal (Maia and Santo Tirso) was monitored from 2001 to 2008 using traditional geotechnical instrumentation equipment. Some of the results of that research have been published already (Gomes and Lopes, 2009, 2010, 2011; Gomes *et al*., 2002, 2005, 2013), and some have been submitted for publication.

In this paper, with the aim to highlight some of the peculiarities associated with the monitoring of USW, a brief description of the monitoring plans implemented in the two landfills is presented, the key behavioural aspects to monitor are enhanced and some of the issues involved in the selection of equipment and installation methods are discussed.

Main features of landfill behaviour

General

Landfills are bioreactors where waste undergoes a continuous change in its general properties due to different factors, such as the bio-decomposition processes of organic materials and the degradation of inorganic components.

In this sense, the study of such work requires an adequate characterisation of both the USW deposited (type, quantity and placement conditions) and some parameters associated with the processes developing inside, namely, body of waste temperatures, generated biogas and leachate levels, as well as their physicochemical characteristics, strains and corresponding stress levels.

The temperature of USW is a useful parameter in evaluating the biological activity of a landfill (Shimizu, 1996). In fact, besides the settlement, quality and quantity of the generated leachate and biogas, it is one of the indices used to identify the activity phase of the bio-decomposition processes. Several studies showed that the temperature increases because of the heat generated during the bio-decomposition processes, so it is one of the parameters used to confirm the stabilisation of a landfill (Yoshida *et al*., 1996).

As USW is highly deformable, strains at rupture are very large, which are too much for the other materials present in the landfill: soils, leachate and biogas drainage systems, liners and covers; the deformation behaviour of USW is considered one of the most critical aspects in the proper behaviour of a landfill.

Moreover, the decrease in USW volume during time leads to an increase in landfill capacity. So, the prediction of the total and differential settlement magnitude, the time they arise and the settlement rate are essential to estimate the actual capacity of a landfill and to ensure its proper behaviour. Long-term settlements are also critical to determine the possible reuse of a landfill area.

Settlements of waste are characterised by distinct phases (partially comparable to soils) whose mechanisms are more numerous and complex than those of soil. Based on several studies (e.g. Chen *et al*., 2010; Edil *et al*., 1990; Gourc *et al*., 2010; Landva *et al*., 2000; Manassero *et al*., 1996; McDougall, 2011; Sowers, 1973), these phases are as follows:

(*a*) mechanical actions — distortion, bending, crushing and reorientation of particles, consolidation and creep phenomena (due to USW weight and covers).
(*b*) percolation and entrainment actions — erosion and entrainment of smaller size particles to existing macropores.
(*c*) physical and chemical changes — dissolution of inorganic components by physicochemical actions such as corrosion, oxidation and degradation.
(*d*) bio-chemical actions — biodegradation of organic components resulting in mass transfer from solid to liquid and gas, and in the disintegration or size decrease of solid particles (bio-decomposition).
(*e*) interaction between the above-mentioned mechanisms.

Only mechanical actions are associated with load application. The remaining mechanisms depend mainly on landfill environmental conditions, such as temperature, moisture and aeration, which vary in time depending mainly on the waste bio-decomposition stage. This fact is reflected by the coexistence in the landfill of zones with different temperatures, leachate and biogas production capacities, and different settlement stages (due to mechanical and biodegradation processes).

Thus, analysis of any of the aspects mentioned must be performed considering the life stage of the landfill; a key factor here is knowledge about the construction history of the landfill.

Objectives of the monitoring of the Santo Tirso and Maia landfills

The instrumentation plans implemented in the Maia and Santo Tirso landfills have, as the main objective, the study of the mechanical behaviour of the landfill, particularly the stress-strain-time behaviour and its correlation with age and decomposition phase of the waste (Gomes and Lopes, 2009, 2010, 2011; Gomes *et al*., 2013). Generally, the following aspects, during and after the deposition phase, were analysed: waste body displacements, landfill total displacements (superficial), waste body state of stress and temperature, waste body leachate levels, and landfill construction history.

In the Santo Tirso landfill, the monitoring plan included three areas with wastes of different ages (station A, recent waste; station B, older waste; and station C, ancient waste). When equipment installation started, the deposition of waste at stations B and C had finished, and it was just starting at station A. A detailed report of this research is given by Gomes (2008). In the Maia landfill, the monitoring plan also included three areas (stations R1, R2 and R3) and, at the beginning of the work, any type of waste was deposited.

During the deposition phase (1995 to 2005) of the slope landfill of Santo Tirso (Figure 1), there was daily incoming of waste (about 90% pre-treated). The trench landfill of Maia (Figure 2) is much smaller in size than the Santo Tirso landfill, as it was designed to accept non-treated waste only when the incinerator plant operation was stopped for maintenance (2002 to 2008).

Because of the heterogeneity of the waste, in areas without waste (station A of the Santo Tirso landfill and the Maia landfill) the equipment was installed side by side to minimise the risk of monitoring the behaviour of different types of waste. The pieces

Figure 1. View of the Santo Tirso landfill

Figure 2. View of the Maia landfill

of equipment installed in each waste layer were as follows: four total earth pressure cells, one pore pressure cell, one open-tube piezometer, one magnetic plate associated with one inclinometer tube, and, at the top of the layer, superficial marks to control settlements near the piezometer and the inclinometer. At stations B and C of the Santo Tirso landfill, where waste deposition was already finished, the following were installed (from the top of the landfill): open-tube piezometers, inclinometer tubes with magnetic spiders, and superficial marks to control settlements.

Selected methods and equipment

Pressure and temperature monitoring

In the deposition areas, the state of stress monitoring was achieved by placing, near the top of some waste layers, total pressure cells (earth pressure cell (EP) in Figure 3) and pore pressure cells (pore pressure cell (PP) in Figure 3). In order to measure the two-dimensional state of stress, the total pressure cells of each set were placed at different orientations (0°, 90°, 45° and −45°).

Concerns arose regarding the uniform distribution of stress on the total pressure cells because of the heterogeneity of the waste and to the presence of elements with different stiffness properties and sizes. On the other hand, the high deformability of the wastes could induce a significant deviation from the cells' initial location (settlements and rotation, the latter being oriented 90° and 45°).

To overcome these concerns, the bigger-size total pressure cells available in the market were selected (vibrant wiring square cells, with an area of $0{\cdot}4 \times 0{\cdot}4\ m^2$ and a reading range from 0 to 700 kN/m^2). To control cell levels, an internal settlement control system with magnetic plates located at the same level as the cells was installed. An electronic uniaxial inclinometer, with a reading range of ±10° (maximum range available), was coupled to each cell oriented 90° and 45° to control the rotation. Vibrating wire temperature sensors, with a reading range from −45°C to 100°C, were coupled to all pressure cells (total and pore pressure cells).

As waste pressures due to biogas can be significant, to control pore pressures two piezometers (one open-tube and the other a vibrating

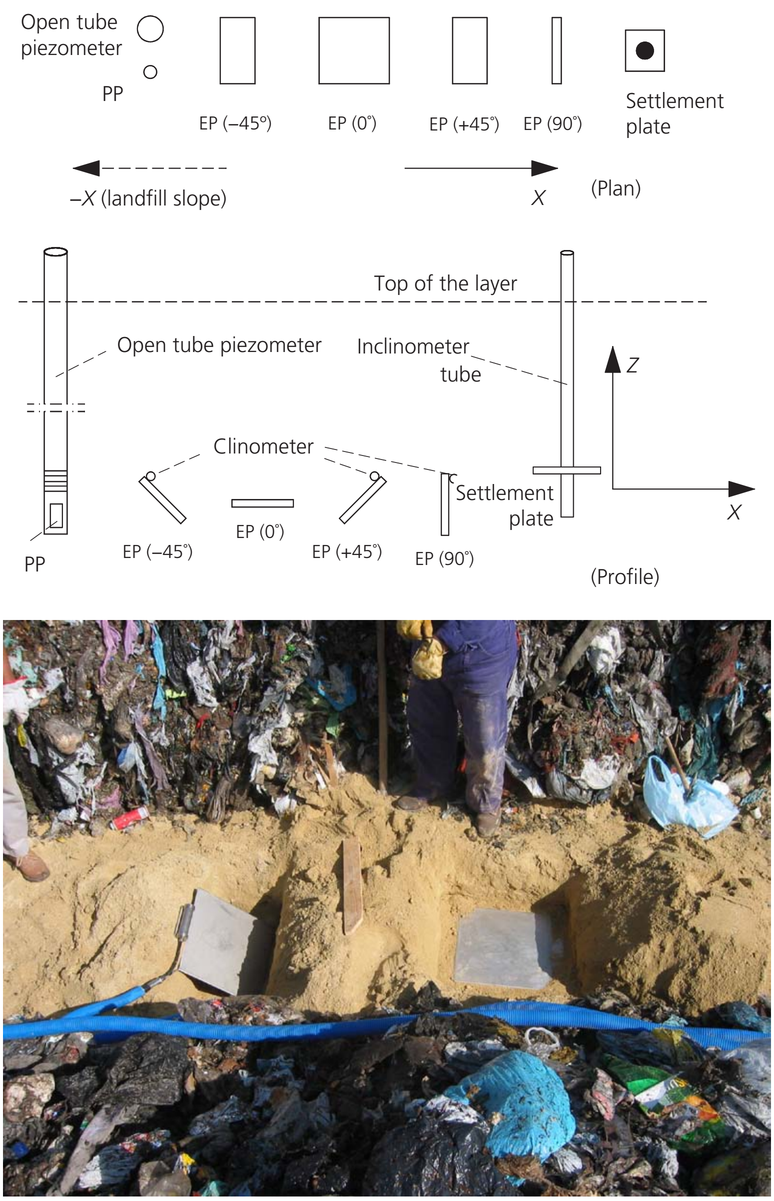


Figure 3. Schematic representation of the instrumentation installed simultaneously in a USW landfill: (a) schematic representation, (b) view. EP, earth pressure cell; PP, pore pressure cell.

wire pore pressure cell) were placed side by side in order to measure the two components of pore pressure (due to leachate and to biogas). In fact, the pressures measured by the vibrating wire piezometer are due to both leachate and biogas, whereas the pressures measured by the open-tube piezometer are only due to leachate, as biogas tends to escape through the top of the equipment.

Placement of the selected equipment in the waste was difficult, particularly in the preparation of the surface for installation of the cells, which should be as uniform as possible to allow for proper installation of total pressure cells with different orientations. Firstly, as recommended for soils (Dunnicliff, 1993), a trench with a compacted and levelled bottom was opened, then, with the use of robust metal patterns, cavities were excavated at the bottom of the trench, spaced about 1·0 m and oriented in accordance with the location of the cells to install (0°, 90°, 45° and −45°). The patterns were driven into the waste and then, manually, the waste inside and around the pattern was removed. This method proved unfeasible owing to the difficulties in driving the patterns into the waste and to the change in the anticipated geometry when waste was removed.

After a few more trials, it was decided to fill the bottom of the trench with a 1·0-m-height compacted layer of silty sand soils where the cavities, where each cell should be placed, were excavated. At one end of the trench, two types of piezometers (an open tube and a vibrant wiring) were installed, side by side, as shown in Figure 3. In this case, the installation of the equipment followed the usual procedures in earthworks. Finally, the equipment was covered with about 0·2 to 0·3 m of soils and the remaining volume of the trench was filled with waste. When necessary, one more layer of waste was placed at the top of the trench to achieve a height of 1 to 2 m for the soil and waste materials above the cells, before starting the circulation of the equipment for the spreading and compaction of waste.

From each instrumentation trench, another one was excavated to accommodate the cables toward the data acquisition system. The cables were inserted in corrugated plastic tubes, in order to prevent their damage. Inside the cell trench, the cables were placed loose enough to avoid pulling due to landfill deformations. Outside the landfill, near the data acquisition system, the cables were also protected (buried in a trench or wrapped around with geotextiles) in order to prevent rodent attack and ultraviolet exposure.

The selected methodology led to a homogeneous surface, to minimise the existence of non-uniform stresses and to control the deviations of cell pressure orientations from their original position. Maintenance of the original position of the cells and of the homogeneous surface was confirmed visually, several months later, when accessing a damaged set of cells.

Open-tube piezometers

The open-tube piezometers were installed inside bore drills (stations B and C of the Santo Tirso landfill) or directly in the landfill, as it was rising, near each set of pressure cells (Maia landfill and station A of the Santo Tirso landfill). The piezometer readings were performed with a dip meter and, simultaneously, with a pore pressure cell (vibrating wire piezometer) with a temperature sensor coupled, in order to check for errors in measurements and to record temperatures.

The current method for piezometer installation in soil embankments was used initially. Here, a polyvinyl chloride (PVC) vertical tube (ϕ = 40 mm), with slots in the lower section (length, 0·5 m), wrapped with a geotextile, was installed in a sand bed at the depth to collect data (P_{TA}, Figure 4). At the top of the sand bed, about 0·2 m of silty sand soils was placed and, above it, a sealing layer of bentonite (in piezometers placed inside bore drills).

After the installation of a few of these piezometers, it was found that, in some of them, the presence of biogas was significant, which made it impossible to define the level of leachate, as the rise in biogas level in the piezometer dragged huge quantities of scum (in

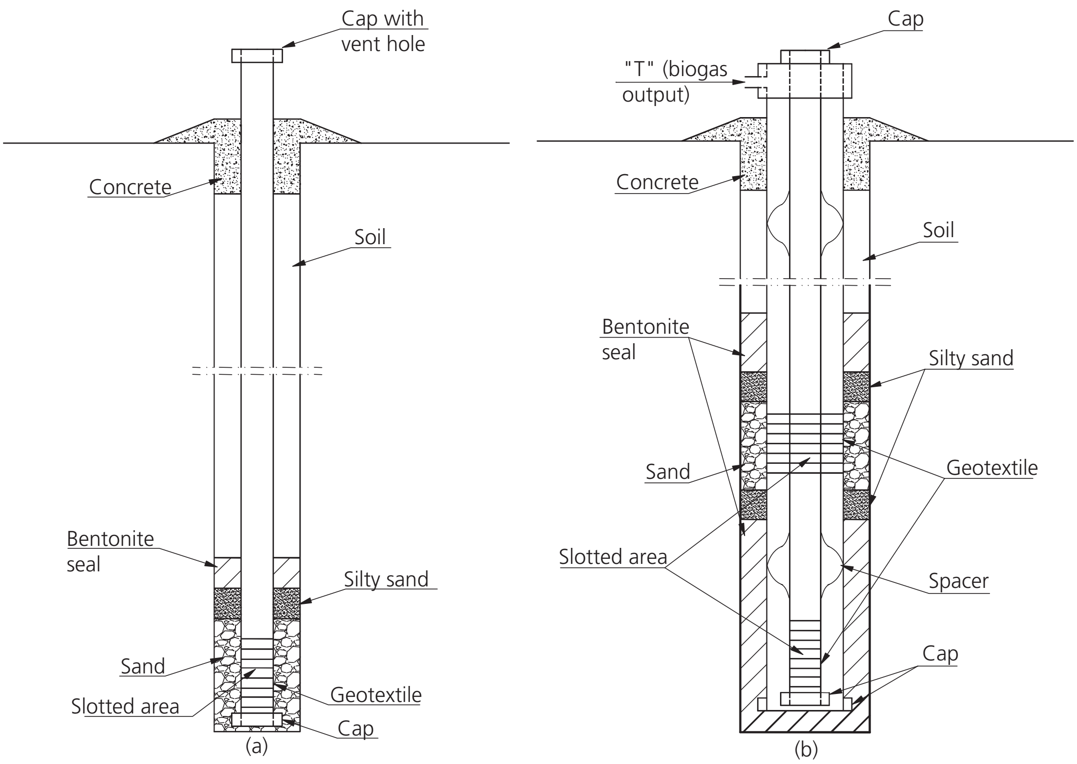


Figure 4. Open-tube piezometer scheme: (a) single (P_{TA}), (b) double (P_{TAV})

some cases up to the top of the piezometer), resulting in the closure of the water meter circuit, as soon as the scum reached it. Several methods were tested, without success, to remove the scum, namely, air pressure injection, just before the readings.

It was decided to change the scheme of the piezometer in order to make it possible to separate the gaseous and the liquid fractions. The new piezometers, named double or vectorial (P_{TAV}), which were similar to P_{TA}, were introduced inside a larger PVC tube (ϕ = 90 mm), with a slotted section at a higher level than that of P_{TA} (Figure 4).

Leachate and biogas go through the slotted section at high levels; the biogas rises along the space between tubes and exits through the top, and, meanwhile, the leachate goes through the thinner tube through the slotted section at the lower level. Readings of leachate level were taken from the thinner tube.

Installation of the piezometers directly in the landfill (station A) followed a similar methodology, with the difference that they were placed inside a cylindrical hole opened at one end of each cell pressure trench.

Inclinometer tube with spiders or magnetic plates

In all the stations of the two landfills, inclinometers were installed to register the displacements of the waste body. Where waste was deposited, inclinometer tubes and magnetic spiders were installed in bore holes; elsewhere, the base of the inclinometer tube was fixed first, and then, as the landfill was rising, inclinometer tubes were added and associated magnetic plates were installed.

Some of the main problems encountered with the installation of the equipment were as follows: the tube flexibility, which guarantees its integrity even under the high total and differential settlements foreseen; the fixing of the inclinometer base, which cannot be moved after installation; the huge settlements foreseen, which implies the use of special telescopic connections or other systems compatible with those settlements; the connection of spiders and plates to the tubes and to the landfill in order to monitor the real settlements of the landfill; the filling material of the space between the tube and the hole lateral surface, which should have similar stiffness as the waste to guarantee the availability of data.

Plastic acrylonitrile butadiene styrene tubes (ϕ_{ext} = 69·85 mm) were used, as they are more flexible, even at high temperatures, and more chemically resistant than PVC, aluminium and glass fibre. Even so, in some cases, the tubes broke (particularly those placed at the same time as the waste), usually at depths corresponding to the transition of the layers. Even in the cases where tube failure did not occur, their deviations from the initial position were significant and irregular along the length, and, in some cases, the cylindrical shape of the tube changed to oval owing to the high temperatures of the surrounding environment. As a result, and because of the risk of blockade of the reading torpedo, the monitoring of internal horizontal displacements was disregarded. Inclinometer tubes were only used to control vertical settlements based on the position of magnetic plates and spiders. When the access to the base-fixed reference was lost, the location of magnetic plates and spiders was defined in relation to the top of the inclinometer tube, which required a topographical survey at each reading time.

Fixing the base of the inclinometer tubes raised some difficulties, particularly where wastes were deposited. Different installation methodologies were used (Figure 5):

(*a*) Maia landfill — As the landfill bottom was plane and drainage and liner systems were built, a concrete foot above the base lining system was constructed, with a high-density polyethylene (HDPE) tube (ϕ = 200 mm) welded at the centre; the inclinometer tube was then placed and fixed inside that tube.

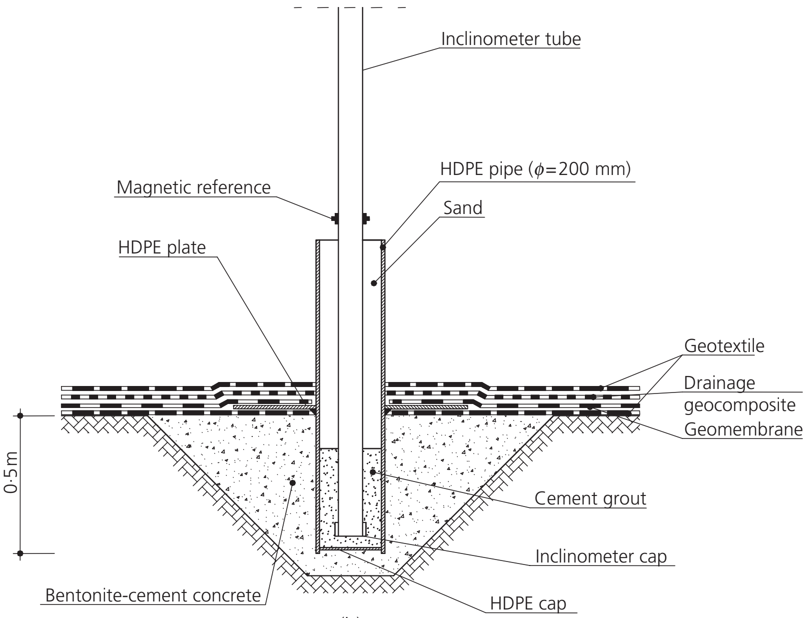
(*b*) Areas without waste in the Santo Tirso landfill (station A) — as the bottom of the landfill was, in this area, inclined and the base lining system was built, this system was cut and a hole with about 0·5-m depth was opened; inside this hole a HDPE tube (ϕ = 200 mm) was fixed with bentonite-cement mortar, then the inclinometer tube was placed and fixed inside that tube; finally, the base lining system was rebuilt.

(*c*) Areas with waste in the Santo Tirso landfill (stations B and C) — the inclinometer tubes were installed in bore holes that crossed the base lining system and penetrated about 1 m into the foundation (with a lower drill, ϕ = 100 mm); fixation of the foundation was done by bentonite-cement grouting (with pressure slightly lower than the weight of the overlying waste); then the section just above it, including the base lining system, was isolated and fixed (by gravity grouting) with a bentonite-cement dense paste.

At first, the connections between tubes were done using 30·5-cm-length junctions (with a minimum overlapping) and 1·5-m-length tubes, in order to increase the number of junctions of the inclinometers so as to increase their capacity to adapt to the waste vertical movements. As it was found impossible to maintain the sequence (tubes, junctions and spiders) properly fitted, the methodology was disregarded. The integrity of the sequence required junctions riveting strong enough to support the weight of all sequences, on one hand, but weak enough to fail easily and allow the tubes to follow the waste settlements, on the other hand. Friction between junctions and tubes was found to be too high, which could imply that settlement inclinometer readings in the landfill were not correct. To overcome these difficulties, longer-length tubes (length, 3 m) with fixed junctions (closed junctions properly riveted) were used. The spiders (with a magnetic ring internal diameter slightly bigger than the external diameter of the tubes) were installed just below the junctions, allowing their free sliding along the tube.

Installation of the inclinometer tubes simultaneously with the landfill rise followed a similar methodology. In this case, riveting of the junctions was not needed, and instead of spiders, magnetic

(a)



(b)

Figure 5. continued overleaf

plates (composed of a ring with similar characteristics to those of spiders associated with a PVC plate with an area of $0{\cdot}3 \times 0{\cdot}3\ m^2$) were used. To protect the plate and to maintain a regular and horizontal surface and a good contact over all the plate area, a layer of silty sand soils was placed at the base and at the top.

Usually, installation of inclinometer tubes in bore holes requires filling the space between the tubes and the hole lateral surface with cement grouting (with or without additives) with similar stiffness as the surrounding material in order to obtain spider readings that reflect the surrounding environment movements. Because of the high deformability of the waste, it was considered inappropriate to use cement grouting to fill that space. As an alternative, different materials were tested (waste, plastic spheres with small diameter, soils, etc.), and it was decided to use a mixture of waste (with bigger-size elements removed) with plastic spheres with small diameter. This mixture was introduced in small quantities and compacted with a steel cylinder with a small diameter, hung by a rope, from the top of the bore hole. This work requires great expertise and appropriate control of the spider positions to prevent the twisting of waste strips on spider rods, damage to or the premature opening of the spiders by the steel cylinder. Opening of the magnetic spiders was done sequentially, when the level of filling reached the position of each spider.

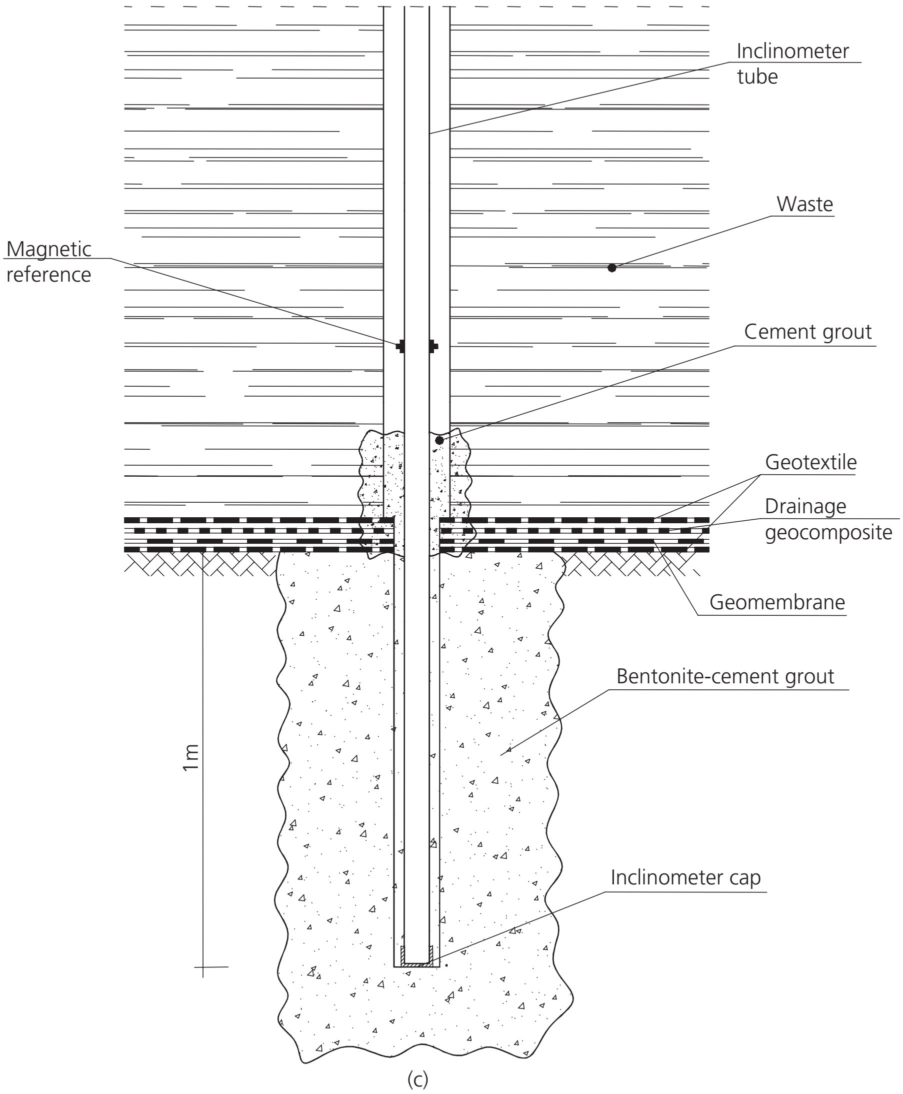


Figure 5. Fixing of the inclinometer base: (a) Maia, (b) station A (Santo Tirso), (c) stations B and C (Santo Tirso)

Equipment long-term behaviour

The total number of equipment installed at the Santo Tirso landfill was 198 (162 at station A and 36 at stations B and C) and 101 at the Maia landfill (Table 1).

During the 7 years of landfill-behaviour monitoring, each equipment was damaged at stations B and C of the Santo Tirso landfill (areas where the deposition of waste had already finished when the research started). However, at station A of the same landfill, where equipment was installed as the landfill was rising, about 26% of the equipment was damaged at the end of the research (Table 1). A worst situation was observed at the Maia landfill, where about 57% of the monitoring equipment was damaged at the end of the research.

The small size of the Maia landfill and the change in the exploitation method during time were the main reason for the increased number of damaged equipment in this landfill. At the Santo Tirso landfill, a thunderstorm was the cause of the damage to a high number of total earth and pore pressure cells and of temperature sensors.

Considering the results presented in Table 1, it can be concluded that the use of traditional geotechnical monitoring equipment in finished waste deposition landfills is possible; however, the behaviour parameters analysed were limited. On the other hand, the use of traditional geotechnical monitoring equipment in a landfill that is still rising is questionable, particularly magnetic plates, inclinometer pore pressure cells and pressure cell inclinometers.

Despite the high number of damaged equipment, the objective of the research was achieved, especially at the Santo Tirso landfill (Gomes, 2008; Gomes and Lopes, 2009, 2010, 2011; Gomes *et al.*, 2002, 2005, 2013).

Landfill	Santo Tirso		Maia	Cause
Station	A	B and C	R1, R2, R3	
Equipment	Installed/(un)damaged			
Total pressure cells	28/11	—	22/16	Thunderstorm, landfill exploitation or failure
Pore pressure cells	7/4	—	6/3	Thunderstorm, landfill exploitation or failure
Open tube piezometers	8/2	13/0	6/6	Broken with landfill rise
Inclinometers	5/3	2/0	3/3	Broken with landfill rise
Magnetic plates	7/7	—	9/9	Access lost (6); failure (1)
Magnetic spiders	10/1	8/0	—	Access lost
Superficial marks	41/1	13/0	11/1	Equipment circulation
Temperature of sensors: °C	35/12	—	28/10	Thunderstorm or failure
Pressure cell inclinometers	21/11	—	16/10	Failure or outside reading range
Total	162/52	36/0	101/58	

Table 1. Equipment installed and corresponding damage

Concluding remarks

The objective of this paper was to address the difficulties associated with the use of traditional geotechnical monitoring equipment in urban solid waste landfill and to determine how to adapt such equipment in this setting.

During installation and 7 years of operation, several pieces of equipment were damaged due to

(*a*) waste deposition simultaneously with equipment installation, mainly at the Maia landfill; because of its small size, maintenance and deposition works were done very close to the instrumented areas; the monitoring of geotechnical works during its construction was a delicate operation and usually led to failure of some equipment; this situation was worse in the case of landfills with medium adverse restrictions and with lower quality control of waste deposition in relation to current earthworks.

(*b*) high landfill deformations and the lack of specific monitoring instruments in the market.

(*c*) environmental, physical and chemical aggressiveness and, again, the lack of specific monitoring instruments in the market.

(*d*) external causes, such as rodent attack (damage to electrical cables), thunderstorms (damage to data acquisition systems and, in the case of the Santo Tirso landfill, to all electronic sensors installed).

(*e*) limited experience of the technical teams in monitoring this particular type of work and to the scarcity of available literature on the subject, which had led to the systematic use of trial-and-error methods and to the constant adaption and improvement of procedures.

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