THE IMPORTANCE OF PHYSICO-HYDRO-MECHANICAL PARAMETERS AS INDICATORS OF MSW STABILISATION AND THEIR IMPACT ON POST-CLOSURE CARE AND CAP COVER STRATEGIES

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SUMMARY: This paper addresses the Post-Closure Care (PCC) of Municipal Solid Waste landfills and discusses which indicators can be used to monitor long term stability. Waste biodegradation is a complex process, including biochemical, physico-hydrous and mechanical phenomena and the evaluation of its stabilisation has to take into account all three aspects. While important steps have been made on how to characterise the biochemical stabilisation of waste and liquid effluents, very few studies have been conducted so far on old wastes in the fields of (geo)-physics, hydraulics and mechanics. A project called "Paraphyme" has thus been launched, whose main objective is to quantify physico-hydro-mechanical parameters susceptible to serve as direct or indirect indicators of waste stabilisation and criteria for assessing the long-term impact of various scenarios of cap covering (temporary / final cover, semi-impervious / impervious cover, mineral /synthetic cover, etc.).

1. INTRODUCTION

Research studies on old Municipal Solid Waste (MSW) landfills are at the moment less advanced than those dealing with younger waste. Yet, the long-term behaviour and sustainability of landfills is a fundamentally important issue. Indeed, Post-Closure Care (PCC) is compulsory to ensure that a solid waste facility is managed after final closure so that it does not cause a threat to human health and the environment. Legislation and monitoring/reporting protocols for PCC vary significantly between countries. The main regulations and guidelines that serve as a basis of discussion for this study are presented in Table 1.

While most regulations and/or guidelines stipulate that PCC should continue for at least 30 years after closure of a landfill [CEC (1999), US EPA (1998)], this length of time only forms the basis for calculation of landfill charges and financial security. First, the starting point of PCC depends on the definition of landfill closure, which varies according to local regulations: in France, for example, landfill closure is defined at the end of waste disposal, whereas in the Netherlands, it is after capping (Figure 1). A post-operational care period can thus be introduced, which includes both the period before final capping, characterised by important settlements, and the PCC period. Moreover, while all regulations stipulate that PCC can end in the future, be it or not followed by a custodial care period, conditions of this termination are not specified. Custodial care is defined as the de-minimus level of care after completion of a landfill. It includes meeting the end-use of the landfill, maintaining institutional control, controlling public access, satisfying local ordinances and fulfilling other non-MSW land management requirements (Morris, 2008; Tansel et al., 2008). Time needed to move from closure to custodial care depends on waste characteristics, operation techniques and site-specific conditions [Cossu et al. (2007), Scharff et al. (2007)], i.e. on landfill operational history, as presented in Figure 1.

Table 1. Examples of regulations and guidelines applicable to PCC

Country	**Date**	**Authors**	**Title**	**Framework**
USA	1976	U.S. Congress	Resource Conservation Recovery Act - Subtitle C (operation) & Subtitle D (design).	Regulation
USA	1998	US EPA	Solid Waste Disposal Facility Criteria—Technical Manual (Revised).	Guideline
USA	2006	ITRC	Evaluating, optimizing or ending post-closure care at MSW landfills based on site-specific data evaluations.	Guideline
EU	1999	Council of the European Union	Council Directive 1999/31/EC of 26 April 1999 on the landfilling of waste.	Regulation
France	2002	République Française	Arrêté du 9 septembre 1997 relatif aux décharges existantes et aux nouvelles installations de stockage de déchets ménagers et assimilés, modifié en 2002	Regulation
Germany	2007	German BDM für Umwelt	Arbeits-Entwurf einer integrierter Deponie Verordnung.	Regulation
Italy	2003	Repubblica Italiana	Attuazione della Direttiva 1999/31/CE relativa alle discariche di rifiuti.	Regulation
UK	2007	UK EA	Guidance for the landfill sector, Technical Requirements of the Landfill Directive and Integrated Pollution Prevention and Control.	Guideline
New Zealand	2001	Tonkin and Taylor , New Zealand Ministry for the Environment	A guide for the management of closing and closed landfills in New Zealand.	Guideline

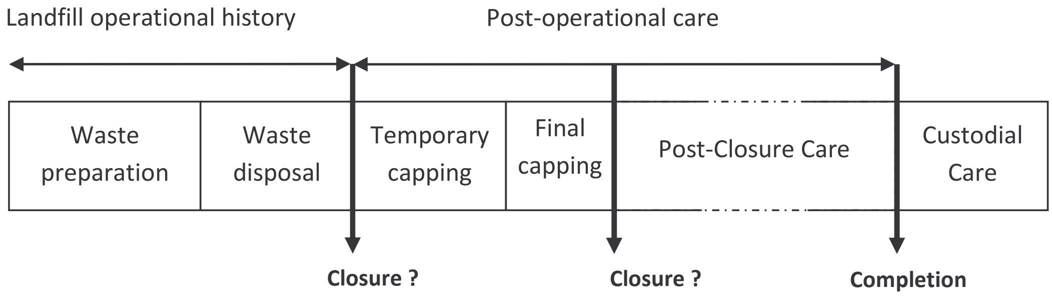


Figure 1. Successive stages of landfill care (adapted from IWWG, 2009).

One of the challenges facing both regulatory entities and the waste management industry is determining when and how to evaluate, optimize and potentially end this PCC period (ITRC, 2006). Two main approaches exist, the first one based on threshold value compliance, and the second one on risk assessment. The German Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, for example, has issued a draft integrated landfill directive (BMU, 2007) that bases assessment of post-closure on the level of waste biodegradation and stability. The main advantage of this approach is that it makes sure that the landfill body is not only biologically stable, but also that it will not be reactivated in the future as a result of unfavourable circumstances (Heyer et al., 2007). According to other authors (Morris and Barlaz, 2008; Morris, 2008), waste stabilisation is yet not a practical strategy, as it is expensive and difficult to monitor. For conventional municipal waste landfills, the period for reaching threshold limits for discharge of leachate into waters is estimated to several hundred years (Ehrig and Kruempelbeck, 2000). The US EPA (US EPA, 1998) consequently points out that assessment of threat may be made at the point of exposure rather than at the source, at least for leachate. ITRC (2006) extends this to the three other elements and recommends the use of performance-base criteria to determine when PCC can end. This allows taking into account possible passive treatment and/or barriers that confine pollution within the waste body. However, this approach has been criticized as it does not plan a potential future failure of either the cover or the bottom liner (Lee, 2004).

In both approaches, the duration of the after-care period is estimated indirectly by means of scenario calculations. To achieve this, it is important that a set of measurements is developed and used appropriately to evaluate the activity in closed landfills in terms of their overall stability and potential threat to human health or the environment (Tansel et al., 2008).

2. HOW TO MONITOR POST-CLOSURE AND EVALUATE THE LEVEL OF STABILITY?

Waste stabilisation is a complex process, including biochemical, physico-hydrous and mechanical phenomena. The evaluation of the level of stability of a landfill must consequently take all three aspects into account.

2.1 Evaluation of the level of biochemical stability of the waste

Several studies have been recently conducted on the definition of an eco-compatible state [Ravelojaona (2005), Stegmann (2008)]. The scientific community agrees to consider a landfill as sustainable if emissions do not significantly modify the quality of the surrounding environmental compartments: air, water and soil. This implies that in order to release a landfill from aftercare, not only the present emissions have to be low, but also the remaining long-term potential. Important steps have been made on how to characterize the biochemical stabilisation of waste and liquid effluents. The most significant indicators to evaluate the quality of the emissions and the achievement of final storage quality are presented in Table 2 (from Cossu et al., 2007).

Most PCC programs focus on leachate and biogas production as they are direct indicators of pollution threat and quite easy to measure, provided landfill sites are equipped with a leachate and an active biogas collection system (which may not be the case for some old landfills). However, in case of biodegradation blockage (due to local inhibitors, lack of moisture or oxygen), these methods do not allow the detection of the remaining potential. Mass balance calculations and modelling are thus needed to predict long term emissions. To achieve this, site-specific input data (such as waste characterisation: eluate characteristics, BMP, respiration indexes, stoechiometry) are required but difficult to obtain, as they imply sampling in a highly heterogeneous matrix. Moreover, these indicators bring global information on the level of stability of the global waste body, but are not representative of local heterogeneities (Barlaz et al., 2002). Understanding and quantification of heterogeneities is thus essential (Heimovaara et al., 2008). Geophysical measurement, which is spatially integrating, could allow a better understanding of level of waste biochemical stability. One of the existing geophysical techniques in particular, the induced polarisation, could be promising for the determination of the level of stability of a waste landfill mass during the PCC period. This method consists in the evaluation of the natural electrical potential of the underground, between two non polarisable electrodes. In a landfill, biodegradation processes are reactions of electron transfers that induce gradients of oxydo-reduction potential, to which the induced polarisation method is sensitive. Recent work conducted on a leachate plume near a landfill cell has shown that induced polarisation could be an indicator of the redox condition of the leachate (Girard et al., 2004). Further work is required to apply this methodology to the landfill body. In particular the influence of other parameters should be examined, as induced polarisation is also sensitive to temperature gradients, liquid circulation and ionic diffusion.

Table 2. Comparison of indicators to evaluate the level of biochemical stabilisation.

Phase	Monitoring method	Type of indicator			Advantage		
		Stability indicator	**Mass balance calculation indicator**	**Indicator of pollution threat**	**Direct measure**	**Enables to detect heterogeneities**	**Enables to detect blockage**
Solid phase	RI_4, GB_{21}	X			X		X
	BMP	X			X		X
	TOC	X	X		X		X
	Eluate characteristics	X			X		X
Liquid phase	Induced polarisation	X				X	
	BOD_5/COD	X		X			
	Ammonium	X		X			
Gaseous phase	Biogas production		X	X			
	Biogas composition in particular $(CH_4+CO_2)/N_2$		X	X			

PCC methodology proposal

A multi-parameter approach is recommended:

- ⇨ Characterisation of the emissions through analysis of biogas and leachate production (both quantitatively and qualitatively)
- ⇨ Localization of the heterogeneities using geophysical methods

⇨ Evaluation of the level of solid biodegradation through waste samplings (drillings)

2.2 Evaluation of the level of mechanical stability of the waste body

In order to release a landfill from PCC, mechanical stability has also to be reached. The main mechanical activity of a landfill is settlement. It can be divided into two phases (ADEME, 2005):

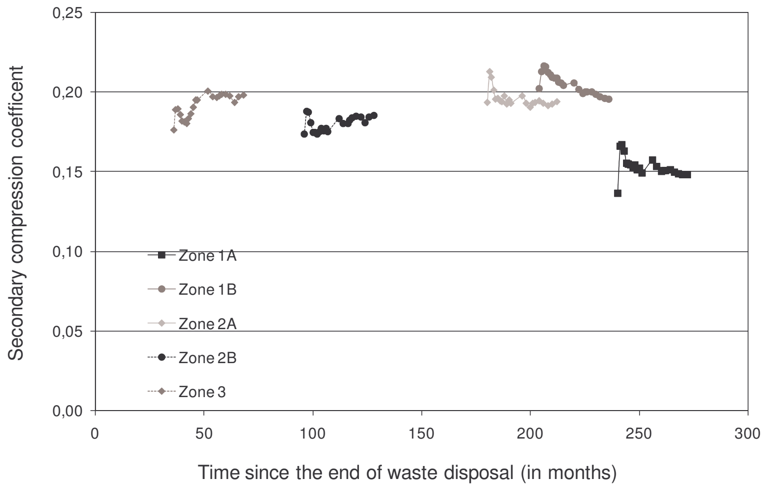
- Primary settlement, which occurs quickly and may be completed shortly after the waste placement, results from compression due to waste overload (from upper waste layers and the cap cover). It typically ranges between 5 and 20 % of the initial waste height (for loads equivalent to 5 m up to 40 m of waste).
- Secondary settlement, which is assumed to be a function of time and independent of compression, results from both mechanical creep (reorientation of the particles) and biodegradation (Gourc et al., 2009). This phenomenon, generally estimated to between 8 and 30 % of the initial waste height, can take place over many years.

For landfill redevelopment after completion (during or after the custodial care period), secondary settlement, which continues for many years after closure, can be problematic from the viewpoint of the integrity of foundations and other elements of structures, but also with regard to the maintenance and operation of post-closure equipment (leachate and biogas collection systems). In particular, differential settlement, which results from non uniform waste placement and biodegradation of the waste, represents the greatest threat to the integrity of new development above the landfill and to the landfill cell itself.

An evaluation of settlements is consequently recommended in the aftercare phase by most regulations or guidelines [Laing et al. (2001); ITRC (2006); UK Environment Agency (2007)]. The aim of this monitoring is mainly to check cap cover integrity and anticipate risk of failure and/or degradation of equipments. Moreover, settlement can be correlated with waste biodegradation (Chakma, 2007). The monitoring of differential settlement has in particular been used to quantify the effect of leachate injection in bioreactor landfills (Vigneron et al., 2007). Settlement, which is a parameter quite easy to measure and relevant if judiciously computed, can thus be a good indicator of the level of the biological stability of waste.

With regard to the determination of PCC termination, some guidelines state that settlement can be considered terminated if its value observed during the last year is less than 5 % of the overall settlement, or if 95 % of the predicted settlement has occurred [Morris (2002), cited in Ravelojana (2005); Malesani (2005)]; and the PCC monitoring of this parameter can thus be stopped. Those two criteria are different, but both should be considered with care. To begin with, the 5 % criteria could be reached long before the end of waste biodegradation. In some cases indeed (lack of moisture in the landfill body or inhibition of the biodegradation), a decrease of the settlement does not necessary imply waste biological stabilisation. Regarding the second criteria, although this approach is interesting, it presents a risk that should not be neglected: it may influence users towards the choice of purely empirical models, such as the model from Asaoka (1978) or from Ling et al. (1998) for example (cited in ADEME, 2005). With such models, a so called “ultimate” settlement is indeed determined based on very few measures. However, as it has been demonstrated (Olivier, 2003) the accuracy of these models is clearly insufficient. Consequently, models such as ISPM [Olivier (2003); ADEME (2005)] that take the whole landfill operation history into account should be preferred. These models must also be used cautiously, with a posterior settlement monitoring. Prediction of the long term settlement, using data derived from vertical displacements collected at the surface of the top cover during a relative short period, could indeed only be possible if the average level of biodegradation of the waste mass could be assessed at the same time (Gourc et al., 2009).

In terms of quality of monitoring, many values for secondary settlement can be found in the literature but the monitoring periods rarely exceed five to ten years: it is indeed sometimes considered that 10 years after the end of waste disposal operations, a major part of the ultimate settlement has already occurred and monitoring can be stopped (Laing et al., 2001). However, settlement can occur over a much longer period, as proved by the example of Montreal landfill, presented in Figure 2: the secondary compression coefficients obtained for five different cells having received similar wastes over a period of 26 years, are remarkably high ($0.15<C_{\alpha\varepsilon}^{*}<0.21$) and stable (Olivier, 2003). These secondary compression coefficients remain constant 20 years after closure (and still pretty high after 23 years). This indicates that mechanical stability is far from being achieved in this particular landfill.



Zone	Waste height (m)	Duration of waste disposal (months)	Delay since 1st settlement monitoring (months)	Duration of settlement monitoring (months)
1A	58	60	239	33
1B	67	36	203	33
2A	67	60	179	33
2B	75	84	95	33
3	69	72	35	33

Figure 2. Evolution of $C_{\alpha\varepsilon}$ in the case of Montreal landfill (from Olivier, 2003).

Moreover, settlement monitoring is often initiated with a delay (no data available before or immediately after placement of the cap cover): this may weaken the data extrapolation in order to predict settlement over a longer period (Olivier, 2003). For other old sites, at last, no settlement data is available (Tansel et al., 2007), and landfill cover integrity has to be checked through mass balances (monitoring of leachate production and gas emission) instead of being anticipated through settlement prediction.

Finally, deformations of waste induce also deformation of the (generally) steep lateral slopes of the landfill. Even if slope failure is relatively rare, the deformation of slopes can be critical, including the possible stretching of the liner, failure of the anchorage of the geocomposite system on slope, local problem at the connection with pipes exits and possible tensile cracking of the soil cover at the top, close to the head of the slope, endangering the watertightness of the barrier in this zone. In addition the risk of erosion on slope due to run-off water should be assessed.

PCC methodology proposal

- ⇨ Collection of reliable field data on long term settlements
- ⇨ Correlation of these settlement data with other parameters (hydrous, biochemical or geophysical parameters)
- ⇨ Improvement of the modelling

2.3 Evaluation of the level of physico-hydrous stability of the waste body

At last, the evaluation of the physico-hydrous stability of the waste body is also essential to envisage the termination of PCC. First of all, as waste biodegradation is primarily limited by a lack or excess of water (for anaerobic digestion) and/or by a lack of mobile air (for aerobic degradation) within the landfill body, the characterisation of physico-hydrous properties such as moisture content, porosity and hydraulic conductivity can help determining if there is a risk of biodegradation inhibition.

Additionally, even after stabilisation of its organic matter, the waste continues to present a leaching potential:

- COD values in the leachate may still be in the range of a hundred mg O_2/l, due to the presence of humic acids (Cossu et al., 2007);
- Metals that are bound to the organic or mineral matter can be leached in case of modification of pH, redox or complexation conditions (Feuillade et al., 2000); changes can typically occur in the case of air or water infiltration in the waste mass.

This long term leaching potential is particularly hazardous as it is likely to happen at a time when the bottom drainage layer may be less effective and the cover more permeable, due to mechanical activity of the waste body, as seen previously. For some cell configurations (combination of semi permeable cover and impermeable bottom barrier, for example) leachate can progressively accumulate in the landfill. The saturated zone is intensified with waste biodegradation, as porosity decreases with time. This leachate accumulation, along with a higher risk of bottom barrier leaks, could potentially present serious implications in terms of long term emissions to the groundwater, gas recovery and slope stability (Olivier et al., 2009).

The evaluation of the level of physico-hydrous stability of the waste mass implies determining:

- <u>from an hydro-static point of view</u>: how much leachate is stored within the fine waste matrix and what are the long term leaching risks ?
- <u>from an hydro-dynamic point of view</u>: what is the impact of waste biodegradation and migration of fine particles within the macro-structure on leachate transfer and drainage ?

To assess moisture transfers in a landfill, it is necessary to compute a water balance, as presented in Equation 2 and in Figure 3.

Percolation = Precipitation - Evapotranspiration - Run Off + Groundwater infiltration - Accumulation – Collection (2)

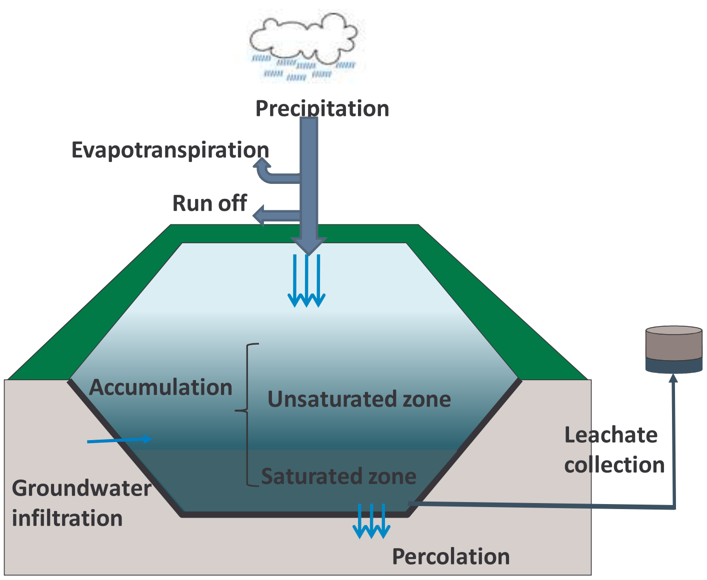


Figure 3. Physical water balance applied to a landfill cell.

Water balance requires a massive collection of data, from the beginning of waste placement operation; this data is rarely available in the case of old landfills. Moreover, in Equation 2, the accumulation term cannot be directly measured. It may nevertheless be non negligible in the case of old landfills, as seen previously, and must therefore be determined through moisture transfer modelling. To adjust these models, the physical properties of waste material are also needed, such as volumetric moisture content, waste porosity and permeability to gas and liquids. However, mechanical properties of waste are not well known, especially for old landfill sites. Models are consequently used with either estimations or laboratory based data, obtained on remoulded waste. A better knowledge of physico-hydrous properties of old landfill is thus required.

Among the methods available to monitor field moisture content and transfer, geophysical measurements may again be interesting. Several geophysical methods allow non-invasive measurements of electrical resistivity, whose temporal variations are, among others, linked to water content, ionic content and temperature:

- Electrical Resistivity Tomography (ERT), based on the measurement of the potential distribution arising when electric current is transmitted to the underground via electrodes.
- Time Domain ElectroMagnetism (TDEM), based on the propagation of electromagnetic waves used in time domain, which can in turn be correlated to moisture content because of the significant differences between the properties of water and other materials.
- Frequency ElectroMagnetism (FEM), also based on the propagation of electromagnetic waves, but in the frequency domain. Contrary to TDEM, which can map deep zones of a landfill, FEM is applied in the upper lift of the underground, i.e. the cover and the superficial waste layer.

While these methodologies have been successfully applied to measure short-term hydrous transfer (ERT in the case of reinjection events for example), their application for long term transfers is more complicated, as several parameters impact waste resistivity. These methods are consequently mostly qualitative (no calibration), due to the heterogeneity and time-evolving properties of the waste matrix. Used along with other more direct techniques (such as drillings for waste sampling), they are however essential to map waste moisture content heterogeneities or distributions [Heimovaara et al. (2008), IWWG (2009)].

PCC methodology proposal

- ⇨ Field data characterisation: moisture content through waste samplings (local determination) and geophysical methods (global determination); porosity and permeability through pumping tests (not remoulded waste)
- ⇨ Laboratory work on in-place waste: porosity and permeability in pilot cells
- ⇨ Modelling
- ⇨ Correlations with water balance.

2.4 Conclusions

While biochemical stability of the waste material has been largely considered, very few studies have been conducted so far on old wastes in the fields of (geo)-physics, hydraulics and mechanics. For example, one would seek in vain rigorous and useful field results on the evolution of waste settlement beyond a period of fifteen years or on the long-term evolution of landfill water balance, particularly in relation to the risk of leachate release from the waste matrix. Little data is thus available on settlements and moreover this data is rarely related to the level of waste biodegradation. Couplings between the different fields are thus required.

3. PRESENTATION OF THE "PARAPHYME" PROJECT

The French Environmental Agency (ADEME) has launched in 2008 a call for project proposals about landfill Post-Closure Care. Five projects were selected amongst which the so-called "Paraphyme" project. The main objective of the Paraphyme project, in relation with the process of waste stabilisation, is to quantify physico-hydro-mechanical parameters susceptible to serve as direct or indirect indicators of waste stabilisation and criteria for assessing the long-term impact of various scenarios of cap covering (temporary / final cover, semi-impervious / impervious cover, mineral /synthetic cover, etc.).

3.1 Presentation of pilot landfills

Experiments involve four pilot landfills expected to become an observatory on PCC, supplemented by four other sites covering a large range of configurations with regard to the morphology of landfill sites, the climatic conditions, the composition and age of the waste (up to 29 years) and the types of cap covers in place, as detailed in Table 3.

Table 3. Main characteristics of the landfill sites.

Landfills	Number of closed cells	Operation		Waste age (years)		Maximum waste height	Cap cover type*
		Start	End	Min	Max		
Site 1	1	1993	2006	3	16	20 – 22 m	Type 1 + 2
Site 2	3	1998	2006	2	11	20 m	Type 4
Site 3	2	1887	2001	8	12	25 m	Type 3
Site 4	1	1988	Open	0	21	30 m	Type 2 + 4
Site 5	13	1980	2004	5	29	12 – 22 m	Type 2
Site 6	14	1981	2007	2	28	15 -17 m	Type 1
Site 7	10	1991	2008	1	18	14 m	Type 1 + 3 + 4
Site 8	11	1978	2004	4	29	20 m	Type 1

** Type 1 : Mineral semi impervious; Type 2: Mineral impervious; Type 3: Mineral / Synthetics semi impervious; Type 4: Mineral / Synthetics impervious.*

3.2. Presentation of the R&D program

The R&D program will test the PCC monitoring methodology proposed earlier for biochemical, mechanical and physico-hydrous stability determination. It includes the following association of measurements, as summarised in Table 4:

- on a global scale (cell by cell): measurement of biogas production, analyses of leachate composition, hydrous balance and localization of waste heterogeneities;
- on an intermediate scale (waste column): measurements of settlement;
- on a local scale (carried out on waste samples, on-site or in laboratory): moisture content, permeability tests as well as biodegradation potential tests on solid matter, control of cover integrity.

The coupling of these parameters and the cross-comparison of the results obtained will enable us to determine the most appropriate ones, based on economical, technical and practical criteria. In addition, the evaluation of the integrity of the different types of cover, associated with the level of waste stability will enable us to set up a list of proposals for a better landfill management.

Table 4. Parameters monitored in the PARAPHYME project.

Type of parameter	Parameter	Scale	Monitoring method
Biochemical parameters	Biogas production and composition	Landfill site	- Flowmeter, gas analyser
		Modelling	- Biogas generation model
	Leachate composition	Landfill site	- Sampling of leachate for biochemical analyses
	Waste residual biodegradation potential	Landfill site	- Induced polarization (geophysical method)
		Laboratory	- Waste sampling (drillings) and analysis (BMP, etc.)
Hydro-physical parameters	Waste heterogeneity	Landfill site	- Geophysical measurement (ERT / TDEM / FEM)
	Moisture content	Landfill site / Laboratory	- Waste sampling through drillings - Neutron probe on sampled waste
	Porosity, hydraulic conductivity	Landfill site	- Pumping tests (non remoulded waste)
		Laboratory	- Pilot tests on sampled waste (remoulded waste)
	Hydrous transfers	Landfill site	- Hydrous balance - Neutron probe
		Modelling	- Modflow, Comsol softwares
Mechanical parameters	Settlements	Landfill site	- Historical data analysis
		Waste column	- Geodesic levelling
		Modelling	- ISPM model
	Covers	Landfill site	- Control of cover integrity

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