PREDICTING THE STORAGE CAPACITY OF DEEP LANDFILLS: FERQUES BIOREACTOR CASE STUDY

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SUMMARY: The Incremental Settlement Prediction Model (ISPM), which has been calibrated from a data base gathering some thirty landfills throughout the world, makes it possible to carry out predictions of settlement over periods of 20 to 30 years. With regard to deep landfills, the application of this model has proved very effective for estimating the evolution of waste density and waste storage capacity. After having simulated the operational phasing of Woodlawn landfill (Australia) in 2002, the ISPM model is applied today to Ferques bioreactor project (France). Based on the information available in connection with the geometry of the site, the expected composition of the waste and its mode of treatment (shredding of commercial waste and intensive leachate recirculation), results indicate overall operational densities ranging from 1.08 to 1.39 T/m^3 at the end of construction. Assuming a conservative value of 1.12 T/m^3, an annual storage capacity of 271,000 tons is obtained, representing a surplus of 26,000 tons when compared to the initial operator's estimate. Alternatively, considering a constant storage rate of 245,000 tons/year, the lifespan of the landfill could be extended over 2 years. The optimization of landfill void capacities represents consequently a significant stake for landfill operators.

1. INTRODUCTION

Taking advantage of abandoned mines, American and Australian landfills are frequently being established in former open mines or quarry sites. It is the case of Woodlawn bioreactor landfill, featuring 200 m of depth and a void space of 24 Mm^3, that has been selected by the Australian public authorities to receive the municipal solid waste of Sydney region from 2004 (Figure 1a). A simulation of settlements that will occur during the operational phase was carried out by Olivier et al. (2002), with the objective of forecasting the technical constraints of the landfill in connection with the process of leachate recirculation.

In a context of high demand for dumping space and fewer available sites, European and particularly French landfills are also progressively being designed on the basis of greater depth. In this way, a new landfill established in a quarry site close to Espira-de-l'Agly (France) opened in July 2004. It features a height of between 40 and 60 m, a void capacity of 2.3 Mm^3 and an expected lifetime of 23 years (Environnement Magazine, 2004) (Figure 1b).

Proceedings Sardinia 2005, Tenth International Waste Management and Landfill Symposium
S. Margherita di Pula, Cagliari, Italy; 3 - 7 October 2005

Figure 1. Aerial view of former quarry sites (a) before rehabilitation: Woodlawn (Australia) (b) during rehabilitation: Espira-de-l'Agly (France)

Some 20 km from Boulogne-sur-Mer (France), another landfill project is waiting for operation approval by the French public authorities to receive the non-hazardous solid wastes of the Pas-de-Calais County from year 2007. Taking advantage of a limestone quarry site (Figures 3a and 3b), it would constitute a pilot landfill because of its size (76 m of operation height, a void space of 4.16 Mm^3 to be filled over an operation period initially estimated to 17.3 years) and the technical processes that would be implemented as part of the environmental management policy: delivery of waste by rail, pretreatment (sorting, valorisation of recyclable components and shredding) and recirculation of leachate.

With regard to the hydro-mechanical behaviour of the waste, Ferques landfill confronts a number of technical issues, of which settlements are a major concern for the operator. There is indeed a need to anticipate on waste deformations: related stakes are both economical and environmental including the landfill operational planning and management (phasing of waste placement operation and evaluation of the overall storage capacity).

2. MODELLING OF THE WASTE COMPRESSIBILITY

2.1 Introduction to the ISPM model

The quantitative evaluation of the influence of the various components of settlement is complex. An aspect which complicates the estimate considerably is the fact that the mass of waste is not stored in once but in successive layers. A rigorous representation of waste settlement would attempt to take into account the history of waste placement operation and to add the settlement of the successive layers of waste.

It follows from this the representation of a waste column as a pile of elementary layers, each of them characterized by its own history. This approach was concretized by the development of the "Incremental Settlement Prediction Model" (ISPM) [Olivier (2003), Olivier et al. (2003a), Ademe (2005)] whose application presents, with respect to the traditional models, both fundamental and practical advantages (determination of intrinsic compression ratios, increased reliability of predictions).

2.2 Settlement mechanisms and related phases

Settlement results roughly from four distinct actions (Ademe, 2005):

- <u>Mechanical actions:</u> mainly related to the application of surcharges and involving, as for any granular medium, a rearrangement, a distortion and a reorientation of the different waste constituents. Similarly to certain fine soils (soft clays, peat), these mechanical actions can be prolonged at constant load (creep) during very long periods.

- Biochemical actions: the decomposition of the organic matters involves a mass transfer from the solid phase towards the gas and the liquid phases. Taking into account the poor distribution of water in waste, this loss of solid mass rarely exceeds 20 % after 30 years. A partial disintegration of the structure is caused, accompanied by long term settlement.
- Physico-chemical actions: Actions related to the corrosion of ferrous materials and exceptionally the oxidation or combustion phenomena intervene in a marginal way with respect to biochemical actions. It is a very long process which has the effect of reducing the size of waste constituents and releasing void spaces previously closed.
- Sieving and percolation: the degradation of waste is accompanied, in addition to the loss of mass, by a reduction in the size of waste constituents. This involves the sieving of degraded particles through macro-pores. Although continuous, this mechanism is punctuated by suddenly accelerated phases connected with the collapse of the structure. Water flows accentuate the migration of fine elements through the open voids.

The actions of the above mechanisms are superimposed in a complex way. Nevertheless, they can be represented schematically by two distinct components:

- a primary (instant) settlement component assumed solely function of the increasing vertical load induced by the self-weight of overlying layers of waste and the cap cover. The thickness and initial density of elementary layers of waste being systematically defined after compaction, primary compression does not account for the instantaneous settlement resulting from waste compaction.
- a secondary (delayed) settlement component assumed independent of the load and continuing during several decades. It results primarily from the decomposition of the organic matter, the collapse of the structure and the sieving of fine particles.

2.3 Compression of an elementary layer of waste

Experimental tests of compression on various representative samples of household waste (1 m^3) under laboratory conditions have highlighted that primary and secondary settlements can be represented by logarithmic relationships function respectively of load and time [Olivier (2003)].

Considering an elementary layer of waste of index (i), assumed non-saturated at all times, the primary settlement Δh_i^p relating to this layer is described by analogy with the theory of Terzaghi (1943). It starts when the surcharge σ_i applied at the top of layer (i) exceeds the pre-consolidation stress σ_{ci} due to compaction.

$$\frac{\Delta h_i^p}{(h_i)_0} = 0 \text{ in over-consolidated conditions } (\sigma_i \leq \sigma_c) \qquad (1)$$

$$\frac{\Delta h_i^p}{(h_i)_0} = C_R^*.\log\frac{\sigma_i}{\sigma_{ci}} \text{ in normally consolidates conditions } (\sigma_i > \sigma_c) \qquad (2)$$

where $(h_i)_0 = h_0$ represents the initial layer thickness (immediately after compaction), C_R^* the primary compression ratio intrinsic to the waste, $\sigma_{ci} = \sigma_c$ (kPa) the pre-consolidation stress resulting from compaction and σ_i (kPa) the surcharge applied at the top of layer i resulting from the weight of overlying waste layers and the cap cover.

Considering the same elementary layer (i), the secondary settlement Δh_i^s starts at the end of placement of the layer of waste and is described by analogy with the Buisman law (1936) by:

$$\frac{\Delta h_i^s}{(h_i)_0} = C_{\alpha\varepsilon}^* . \log \frac{\tau}{\tau_i} \tag{3}$$

where $C_{\alpha\varepsilon}^*$ represents the secondary compression ratio intrinsic to the waste, τ_i the duration of construction of layer i and τ the time taken since the beginning of construction of layer i.

The actual thickness h_i of layer (i) is derived from Equations 2 and 3 by subtracting primary and secondary settlements to the initial thickness h_0:

$$h_i(t) = (h_i)_0 - \Delta h_i(t) = h_0 - [\Delta h_i^p(t) + \Delta h_i^s(t)] \tag{4}$$

Now, by disregarding the reduction of waste mass resulting from biodegradation, one can apply the principle of mass conservation to layer (i) and derive its "operational density" ρ_i at time t:

$$\rho_i(t) = \frac{(\rho_i)_0.(h_i)_0}{h_i(t)} = \frac{\rho_0}{1 - \frac{\Delta h_i(t)}{h_0}} \tag{5}$$

where $(\rho_i)_0 = \rho_0$ (T/m^3) represents the initial waste density immediately after compaction.

2.4 Compression of the overall waste body

At the scale of a waste column, compaction is assumed to affect only the upper layer of waste as a result of rapid lateral spreading of stresses with depth. Primary and secondary settlements (Δh_i^p and Δh_i^s) relating to the different layers of the column are added to obtain the total settlement w_n of the column (composed of n layers) at time t:

$$w_n(t) = w_n^p(t) + w_n^s(t) \tag{6}$$

where: $w_n^p(t) = \sum_{i=1}^n \Delta h_i^p(t)$ and $w_n^s(t) = \sum_{i=1}^n \Delta h_i^s(t)$

Consequently, the overall height H_n of the column (cap cover excluded) can be expressed, as follows:

$$H_n(t) = nh_0 - w_n^p(t) - w_n^s(t) \tag{7}$$

Now, in order to derive the "overall operational density" $\bar{\rho}$ characterizing the overall mass of waste stored (the signification of $\bar{\rho}$ is purely economical since it does not account for the loss of mass resulting from the biodegradation process), let us assume entire mass conservation during the complete operation period. Given a certain waste layer (i) in an open out excavation, conditions of loading and age are sensibly identical across its surface (Figure 2). Consequently, the operational density ρ of the waste is also approximately constant ($\rho = \rho_i$). It is therefore possible to derive the overall operational density relating to the overall waste mass from the net storage volumes V_i (derived from the surveyor's calculations as detailed in Table 1):

2.5 Application of the ISPM model during construction

In the specific case which consists in evaluating settlements from the very start of construction of the waste column, the prediction method is based on the pre-calibration of primary and secondary compression ratios C_R^* and $C_{\alpha\varepsilon}^*$. As part of a research program on settlement supported by the French Environmental Agency (ADEME) since 1996, ten French landfill sites have been instrumented providing the premises of a data base. As the influence of certain parameters could not be tested considering solely landfills established in France, an international observatory has been developed in parallel composed to date of thirty sites located on 4 continents. In addition, calibration tests were also conducted on targeted samples of raw / shredded waste materials using a laboratory reactor cell of 1 m^3 [Olivier et al. (2003b), Olivier and Gourc (submitted)].

Although it is advisable to remain cautious regarding the selection of compression ratios, significant progress has been made and the experience gained makes it possible today to propose reasonable ranges of variation for C_R^* and $C_{\alpha\varepsilon}^*$.

3. EVALUATION OF THE STORAGE CAPACITY OF FERQUES LANDFILL

3.1 Presentation of the landfill project

The former quarry site of Ferques represents a deep cavity developing from a bottom elevation of + 11 m NGF (French Height Datum) to a top elevation of between + 96 and + 106 m, with typical slope gradients of 1/1 (45°). It extends over a surface area of between 1.9 and 10.6 ha, representing an overall volume of 5.97 Mm^3 (Figure 3).

The storage of waste itself would be implemented over 76 m of height from a bottom elevation of + 17 m (min./max.: + 16 - 18 m) to a top elevation of + 93 m (min./max.: + 88 - 100 m), representing an available air space of 4.16 Mm^3.

The waste will be elevated as a sequence of nine intermediate lifts (of initial height approximately 10 m, except the two upper lifts) which operation will be divided into between 4 and 22 periods corresponding to the filling of cells of surface area ≤ 5,000 m^2 (Figure 4 and Table 1). Approximately 800 tons of waste will be spread each day and heavily compacted over the complete surface of the operated cell in layers of 30 to 40 cm. In this way, the filling of one cell should roughly take 2 to 2.5 months.

$$\bar{\rho}(t) = \frac{\sum_{i=1}^{n} \rho_i(t).V_i}{\sum_{i=1}^{n} V_i} \tag{8}$$

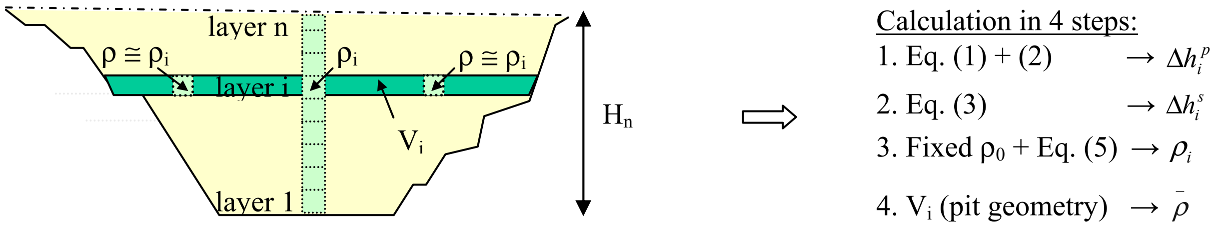

Figure 2. Principle of calculation of the overall operational density $\bar{\rho}$.

Figure 3. Aerial view of Ferques pit before rehabilitation (a) Western view (b) Northern view.

3rd lift: 9 cells

7th lift: 22 cells

Figure 4. Expected operational phasing of the landfill cavity (a) lift 3: cells 11 to 19 (b) lift 7: cells 67 to 88.

Table 1 – Characteristics of the 9 intermediate operation lifts.

Lift	Final height (m)	Surface area (m^2)	Net volume V_i (m^3)	Duration of the operation period as initially expected (year)	Number of cells
1	10	19,324	125,516	0.5	4
2	20	28,923	217,593	0 .9	6
3	30	42,699	326,454	1.4	9
4	40	60,787	469,247	1.9	13
5	50	75,244	609,973	2.6	16
6	60	89,655	739,485	3.1	18
7	70	106,219	864,172	3.6	22
8	Variable	102,516	652,609	2.7	21
9	Variable	54,073	153,058	0.6	11
Total	-	-	4,158,107	17.3	120

With regard to the collection of biogas, two large diameter vertical wells will be installed progressively during the filling operation. The waste will be placed horizontally to avoid disrupting the wells (as a result of lateral thrust). Also, corrugated pipes will be installed around the concrete wells to limit off lateral frictions induced by the settlement of the waste. At every lift, the drainage of biogas and the recirculation of leachate will be guarantied by a network of radial sub-horizontal pipes connected to the two central wells. The non-active cells (at surface) will be overlain by synthetic temporary covers made of woven polyethylene hardly permeable to water and gas, while being actively wet up to stimulate biodegradation. Water will be pumped into in-pit storages to prevent the waste from being saturated by natural inflow and moisture addition. Eventually, a 2.20 m thick cap cover will be installed at the very end of the landfill operation (whose weight is not accounted for in the modelling: conservative approach).

At the present time, the future landfill is expected to receive 245,000 tons of waste (basic estimate), of which 56.4 % of household waste (including 4.1 % of bulky waste), 36.6 % of commercial waste, 3.4 % of sorting residues, 2.1 % of cinders and 1.5 % of composting residues (Source: internal report from Cadet International). In order to increase the surface of contact between solid and liquid phases (to accelerate the biodegradation and the production of biogas), ≅ 50 % of commercial waste and bulky waste shall be shredded by passing through a twin-shaft static reducer. Also, the waste shall be intensively wetted until coming close to its field capacity (expected water content at equilibrium close to 40 % of the global volume).

3.2 Calibration of the model

Based on the authors' experience of waste compressibility in relation with its composition, placement procedures, height and treatment, the following parameter values were assumed:

- Initial as-placed waste density: based on the waste composition, the shredding of voluminous waste and the heavy compaction (> 40 tons), two values were considered for ρ_0 (0.85 and 0.90 T/m^3).
- Primary compression ratio: based on the waste composition et and the experience gained from Chatuzange and Lapouyade landfills (Olivier, 2003), 3 values of C_R^* were tested (0.14, 0.17 and 0.20) assumed as minimum, mean and maximum estimates.
- Secondary compression ratio: based on different observations from conventional landfills of height > 15 m (Table 2), three $C_{\alpha\varepsilon}^*$ values were tested (0.10, 0.14 and 0.18) again corresponding to minimum, mean and maximum expected values.

Table 2 – Values of the secondary compression ratio derived from field settlement surveys conducted on conventional landfills of height > 15 m.

Landfill site	Number of cells	Average waste composition[1]	Initial height[2] (m)	Operation duration (months)	Survey duration (months)	$C_{\alpha\varepsilon}^*$
Torcy	1	CW: 100%	15	60	42	0.11 - 0 .13
Lapouyade	1	CW: 34% ; HW: 28% ; BW: 18% ; VR: 18%	16	26	34 in progress	0.10
Montech	8	HW: 62% ; VF: 22%; CW: 5%	20 - 22	4 - 23	26 - 74	0.08 - 0.11
Chatuzange	3	HW: 59% ; CW: 18% ; VR: 11%	30 - 38	23 - 89	46 - 61 in progress	0.10 - 0.18
Hong-Kong (NENT)	1	HW: 72% ; CD: 16% ; CW: 7%	20 - 40[3]	18 - 32	11 - 41	0.08 - 0.18
Montreal (CESM)	5	majority of HW but % uncertain	58 - 75	36 - 84	35 - 239	0.15 - 0.20

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[1] HW: Household Waste ; CW: Commercial Waste ; BW: Bulky Waste ; VR: Various Residues ; VF: Vegetables and Fruits ; CD: Construction Debris.

[2] Initial waste height at the end of the landfill operation (except Montreal: height at start of the settlement survey).

[3] 3D displacements: the application of the ISPM model is questionable.

If the effect of leachate recirculation on biodegradation (and consequently settlements) is manifest at the scale of laboratory cells (Olivier et Gourc, submitted) or small pilot cells representative of a few thousands tons of waste [e.g. Sonoma County (USA) and Yolo County (USA) as reported by Olivier (2003)], conditions of application at a larger scale are not yet completely finalised. Considering the few bioreactors including a follow-up of settlements worldwide [e.g. Lyndhurst (Australia), Sandtown (USA), Lons-le-Saunier (France) as reported by Olivier (2003)], recurring weaknesses were observed such as absence of control cells, recurrent uncertainties on reinjected / infiltrated water flows and short periods of observation (< 5 years). Also, leachate flow rates are generally not significant and their distribution remains non-homogeneous. For these reasons, the $C_{\alpha\varepsilon}^{*}$ values derived from traditional landfills (without leachate recirculation) were not raised (conservative approach).

Also, it should be noted that localised side effects along the slopes of the cavity have not been considered in the model. Settlement monitoring campaigns conducted at Montreuil-sur-Barse landfill (Thomas, 2000) and Lapouyade landfill (Olivier, 2003) have indicated indeed increased deformations along lateral slopes of landfills established in excavation.

3.3 Results

For the exercise of simulation, the central waste column was schematically subdivided into 18 virtual elementary layers (2 virtual layers / lift).

- <u>*Design approach # 1:*</u> *the duration of the landfill operation being fixed (17.3 years), one tries to evaluate the waste storage rate (assumed constant with time).*

Based on the maximum authorised storage height of 76 m, predictions of settlement (Δh_i), deformation ($\Delta h_i / h_0$) and operational density (ρ_i) were carried out for every layer of waste. Figure 5 illustrates the increase of the deformation and the operational density with depth (from the 18th layer set at the top surface down to the bottom layer).

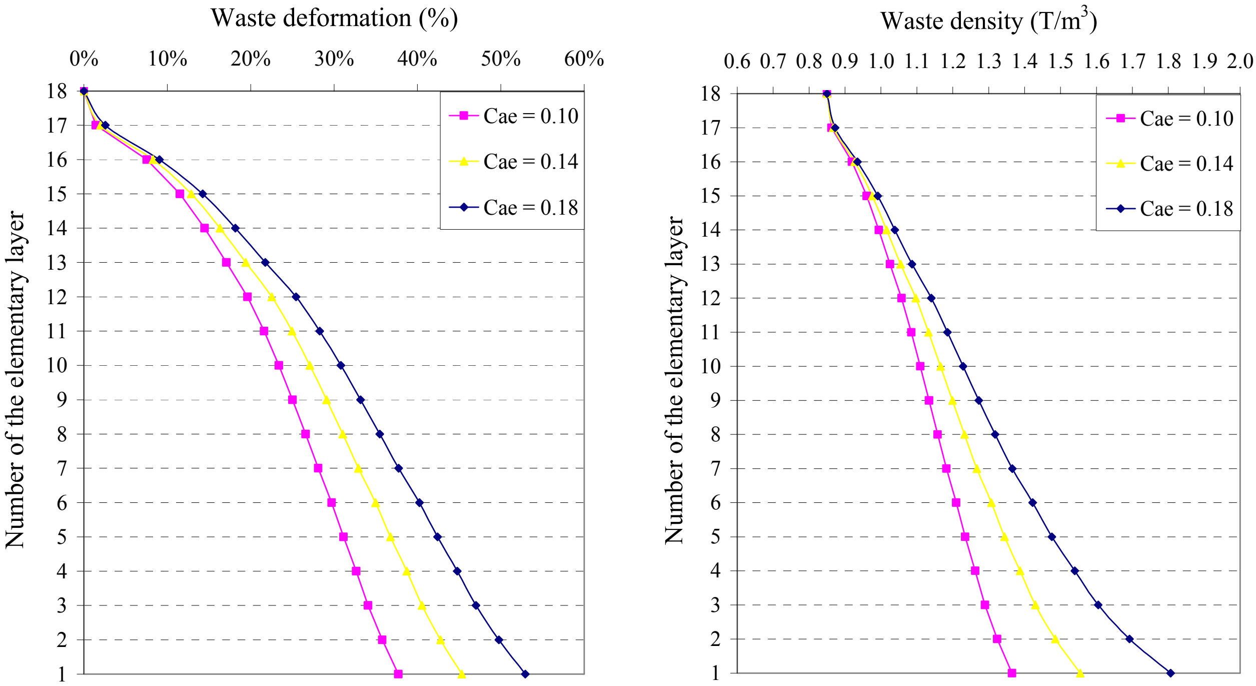

Figure 5. Deformation and operational density of elementary layers relating to the central waste column at the end of operation (17.3 years) ($\rho_0 = 0.85$ T/m^3 ; $C_R^* = 0.14$).

Table 3 – Overall operational density $\bar{\rho}$ of the landfill at the end of operation (t = 17.3 years) (a) $(\rho_0)_{\min}$ = 0.85 T/m^3 (b) $(\rho_0)_{\max}$ = 0.90 T/m^3

$(\rho_0)_{\min}$ (= 0.85 T/m^3)	$(C_R^*)_{\min}$ = 0.14	$(C_R^*)_{mean}$ = 0.17	$(C_R^*)_{\max}$ = 0.20
$(C_{\alpha\varepsilon}^*)_{\min}$ = 0.10	1.08	1.12	1.16
$(C_{\alpha\varepsilon}^*)_{mean}$ = 0.14	1.13	1.18	1.23
$(C_{\alpha\varepsilon}^*)_{\max}$ = 0.18	1.19	1.25	1.30

$(\rho_0)_{\max}$ (= 0.90 T/m^3)	$(C_R^*)_{\min}$ = 0.14	$(C_R^*)_{mean}$ = 0.17	$(C_R^*)_{\max}$ = 0.20
$(C_{\alpha\varepsilon}^*)_{\min}$ = 0.10	1.15	1.19	1.24
$(C_{\alpha\varepsilon}^*)_{mean}$ = 0.14	1.20	1.25	1.31
$(C_{\alpha\varepsilon}^*)_{\max}$ = 0.18	1.27	1.33	1.39

When integrated across the full depth of the waste body, operational densities (ρ_i) give access to the overall operational density $\bar{\rho}$ (Equation 8) relating to the complete waste mass (Figure 2). Based on the values selected for ρ_0, C_R^* and $C_{\alpha\varepsilon}^*$, most reasonable values of $\bar{\rho}$ derived at the end of the placement operation (after 17.3 years) are ranging from 1.18 to 1.25 T/m^3 (Table 3), corresponding to constant waste storage rates of between 285,000 and 305,000 tons/year. A pretty conservative estimate would assume a $\bar{\rho}$ value of 1.12 ton/year (271,000 tons/year).

➢ *Design approach # 2: the waste storage rate being fixed (245 000 tons/year), one tries to evaluate the landfill operation duration.*

Another design approach could be to fix, instead of the operation duration, tonnages of waste (assume 245 000 tons/year as initially expected) and to evaluate the actual waste placement operation period. Presently, a conservative estimate based on the following parameter values (ρ_0 = 0.85 T/m^3 ; C_R^* = 0.17 and $C_{\alpha\varepsilon}^*$ = 0.10) indicates an operation period of 19.2 years, representing a 2 years extension of the initial operation period.

4. PROSPECTS

Although the application of the ISPM model requires a relatively precise knowledge of the landfill operation phasing, this condition is not problematic in the case of modern landfills. Provided indeed that certain assumptions relating to the landfill geometry (available air-space and height), the waste storage rate / composition and the management procedures can be made, the model offers the possibility to evaluate the storage capacity of new landfills.

As indicated earlier, the evaluation of compression parameters remains however very sensitive. In this context, laboratory experiments have been conducted in a large-scale compression reactor (Olivier et al., 2003b) with the objective to represent the complete landfilling process (from the initial loading until stable methanogenic biodegradation) of selected waste samples (raw or shredded). After 4 years of laboratory testing, derived values of primary and secondary compression ratios (C_R^* and $C_{\alpha\varepsilon}^*$) indicate that the compressibility of laboratory waste samples is pretty well correlated to the compressibility of landfilled waste. Most importantly, the flexibility of laboratory reactors makes possible a parametric study that is not practicable on site. In this respect, interesting correlations were made between the mechanical behaviour of the waste and its hydro-physical characteristics, especially in the case of pretreated waste (Olivier and Gourc, 2005) or waste subject to conditions of intensive leachate recirculation (Olivier and Gourc, submitted).

Some characteristics...

1. Vertical compression up to 800 kPa
   ↳ Simulation of deep landfill conditions
2. Air-tight cells
   ↳ Continuous assessment of biogas production rates
3. Performing instrumentation
   ↳ Monitoring of various hydro-physical parameters

Figure 6. Compression cells in service as of 2005 (Creed – Lirigm).

A new program of laboratory testing, supported by four new fully-equipped reactor cells, is being developed jointly by Creed and Lirigm (Figure 6). Without any doubt, this will constitute a tool capable to support the design and the operational management of future landfills. With regard to Ferques bioreactor project, laboratory tests will make it possible to refine the values of compression parameters, further improving the assessment of the landfill storage capacity.

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