Assessment of Long-Term Settlement Prediction Models for Municipal Solid Wastes Disposed in an Experimental Landfill

Gustavo Ferreira Simões, Cícero Antonio Antunes Catapreta

Abstract. Settlement evaluation in sanitary landfills is a complex process, due to the waste heterogeneity, time-varying properties and influencing factors and mechanisms, such as mechanical compression due to the load application and creep, and physical-chemical and biological processes caused by the wastes decomposition. Many empirical models of analysis and long-term settlement prediction are reported in the literature, which require the application to real case studies in order to be validated. In this paper, four models of long-term settlement prediction (Rheological, Hyperbolic, Composite and Meruelo models) reported in the literature were applied to assess the mechanical behavior of an experimental landfill, composed of 6 different cells of municipal solid waste. Concerning the long-term settlement prediction, the results enabled a critical evaluation of the models, pointing out some advantages and limitations. During the monitoring period of 3 years, significant vertical strains were observed (of up to 22%) in relation to the initial height of the experimental landfill, which can be considered high and is due to fresh wastes with high organic content disposed. The results also suggest that the operational procedures influenced the settlements in the experimental landfill. The long-term settlement prediction indicated a final strain range from 22% to 42%, with respect to initial waste height and the composite model presented better comparisons between field measurements and predictions.
Keywords: sanitary landfill, solid wastes, monitoring, settlement, experimental landfill, settlement prediction models.

1. Introduction

As pointed out by many authors (*e.g.* El-Fadel *et al.*, 1999), landfills remains an essential part of waste management system and in many countries the only economic form of municipal solid waste (MSW) disposal. The need to reuse landfills sites after closure associated with the large long-term vertical strains observed in these structures are enhancing waste settlements studies, mainly concerning the validation of long-term settlement prediction models.

MSW deposited in landfills suffer large long-term settlements, associated with volume reduction caused by the decomposition of organic solids, and also by physical creep of MSW skeleton (Sowers, 1973; Park *et al.*, 2002), leading to an increase in storage capacity.

Mechanisms governing the settlement occurrence in MSW landfills are many and complex and less known than in soils, due to waste particles deformability, heterogeneity of the material, particles of varied sizes, and to the loss of solids due to biodegradation (Sowers, 1973; Gabr *et al.*, 2000). Liu *et al.* (2006) mention that landfill settlement can be attributed to both mechanical compression and biological decomposition of solids. According to Hossain *et al.* (2003), with the enhancement of the waste decomposition, compressibility properties and, subsequently, the rate and magnitude of waste settlement change.

According to Edil *et al.* (1990) and Simões & Campos (2002), the identification of the mechanisms of settlement development in MSW landfills is important for the interpretation of geomechanical behavior, proposition of long-term settlement models and carrying out long-term simulations. The main factors affecting the MWS settlements include:

- Waste composition and biodegradable material content;
- Initial unit weight and void ratio;
- Landfill dimensions;
- Compaction methods;
- Stress history, involving all the filling stages;
- Wastes pre-treatment (incineration, composting and others);
- Leachate level and fluctuations;
- Existence of gases collection and extraction systems;
- Environmental factors, such as moisture content, temperature and gases present or generated by the biologic decomposition of waste.

As cited by Singh (2005), the total amount of settlement is dependent on the amount of mechanical compaction applied when placing the waste, the percentage of organics in the waste stream and the waste-to-soil ratio within the landfill. Mechanical compaction will reduce voids in the waste pile and allow placement of a larger vol-

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ume of waste within a geometry profile defined in the design, but there are other processes that affect settlement after placement. These processes, including particle migration, biodegradation and collapse of matter, may increase the long-term settlement rate.

According to Park & Lee (2002) the most important cause of long-term settlements is generally the volume reduction caused by organic solids decomposition, which may continue for a very long period and is dependent of biodegradable organic solids content. Liu *et al.* (2006) mention that the decomposition of organic material in landfills causes a considerable amount of settlement as the organic material is converted into decomposition products, such as liquids and gases, mainly methane and carbon dioxide. Wall & Zeiss (1995) describes that the biodegradation components of long-term compression, or bioconsolidation, is due to a four stage process (hydrolysis, acidogenesis, acetogenesis, methanogenesis) by which solid organic particles present in the waste are solubilized and converted to methane and carbon dioxide. Long-term settlements due to waste decomposition can theoretically reach 40% of the original thickness and can last for several years after closure in a continuous decreasing rate, depending on stabilization processes within the landfill (El-Fadel *et al.*, 1999).

Estimation of total settlement of sanitary landfills range from 25% to 50% of the landfill initial height (Edgers *et al.*, 1992; Wall & Zeiss, 1995; Ling *et al.*, 1998). This volume reduction caused by settlements can increase the landfill capacity and its life time. Besides, waste compression makes the landfill slopes less steep, contributing to the landfill stability and allowing future vertical expansions.

However, the settlement occurrence is undesirable in landfill maintenance, since it may lead to surface ponding and accumulation of water in the top of the landfill, development of cracks and failures of the cover system, deterioration of the leachate and gases drainage systems and safety issues (Bjarngard & Edgers, 1990; Edgers *et al.*, 1992; Ling *et al.*, 1998; Singh, 2005). Settlement occurrence can also be indicative of slope failures or, in more common situations, it changes the landfill surface configuration, causing irregular alterations in the surface drainage systems.

Several approaches and models for estimating landfill settlement have been proposed. These models, summarized in Liu *et al.* (2006), can be divided into the following categories: (i) consolidation models, based on Terzaghi's consolidation theory; (ii) rheological models; (iii) biodegradation models, which account for organic matter decomposition processes; (iv) regression models, which use common functions, such as logarithmic, hyperbolic and bi-linear, to simulate the landfill settlement.

As pointed out by Marques *et al.* (2003), each of these approaches addresses at least one of the three important mechanisms of MSW compression: (i) immediate response to applied loading; (ii) time-dependent mechanical creep, and (iii) biological decomposition of the waste. The models proposed by Simões & Campos (2002) and Marques *et al.* (2003) incorporate three separate expressions to explicitly account for all three mechanisms of MSW compression.

In this work, four long-term settlement prediction models presented in the literature, and described below, were investigated to evaluate the Belo Horizonte Experimental Sanitary Landfill behavior and the long-term settlement prediction. In this analysis a critical evaluation of the models performance was made, verifying their advantages and limitations. The models were selected in order to represent three of the categories cited previously, empirical (hyperbolic), rheological (composite and rheological) and biodegradation (Meruelo).

This study aims to contribute to the understanding of sanitary landfills mechanical behavior, concerning the long-term settlements. Usually, as a result of operational procedures in sanitary landfills, the initial settlements monitoring time occurs after the landfill closure or after some deformation has been observed. Landfills operating in real scale with the monitoring beginning immediately after closure are not common. In this study, the settlement monitoring started immediately after the experimental landfill filling.

Some considerations regarding the applicability of four long-term settlement prediction models mentioned in the literature are discussed in this study, trying to assess their advantages and limitations, as well as analyzing the parameters obtained by fitting field data to the models and trying to compare them to the results given in the literature.

The study is completed with the simulation using the four long-term settlement models, whose results are compared with the experimental landfill monitoring field data, allowing the identification of which model is more suitable to represent the observed data.

2. Long-Term Settlement Prediction Models Evaluated

2.1. Rheological model

The Rheological Model (Edil *et al.*, 1990) is composed of two elements: a Hookean element (of constant a) in series to a Kelvin element (a Hookean element, of constant b, associated in parallel to a Newtonian element, of viscosity $\lambda/\mathbf{b}$), as presented in Fig. 1.

After a stress increment, that can be originated by the weight of the waste or by applied loads in the surface, the Hookean element of constant a is compressed immediately, similar to the primary compression in soils. The compression of the Kelvin element is delayed by the dashpot, in a similar way to the secondary compression under constant effective stress in soils. The load is, then, progressively transferred for the second Hookean element. After a certain time, the whole effective stress will be supported by the two

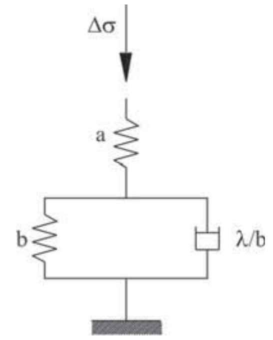

Figure 1 - Rheological model.

Hookean elements. This physical model can be represented by the mathematical expression (Eq. (1)):

$$\Delta H(t) = H \times \Delta\sigma\left[a + b\left(1 - e^{-\frac{\lambda}{b}t}\right)\right] \quad (1)$$

where: ΔH = settlement (m); a = primary compressibility parameter (kPa^{-1}); b = secondary compressibility parameter (kPa^{-1}); λ/b = rate of secondary compression (day^{-1}); $\Delta\sigma$ = compressive stress (kPa); H = initial height of MSW landfill (m); and t = time (day).

2.2. Hyperbolic function

The Hyperbolic Model was proposed by Ling *et al.* (1998), and is represented by the following expression (Eq. (2)).

$$S = \frac{t}{\frac{1}{\rho_0} + \frac{t}{S_{ult}}} \quad (2)$$

where t = difference between the time of interest and initial time ($t = t_i - t_o$) (day); S = difference between settlement at time ti and initial settlement ($S = Si - So$) (m); ρ_o = initial rate of settlement; S_{ult} = final settlement (m). The parameters ρ_o and S_{ult} may be determined through t/S *vs.* t relationship by conducting a linear regression analysis (Eq. (3)).

$$\frac{t}{S} = \frac{1}{\rho_0} + \frac{t}{S_{ult}} \quad (3)$$

2.3. Composite compressibility model

The composite biological model (Marques *et al.*, 2003) incorporates three mechanisms for one-dimensional compression of MSW: instantaneous response to loading from overlying layers, mechanical creep associated with the stresses from self-weight and the weight of overlying layers and biological decomposition.

The mechanisms of this model can be represented by three rheological components, as presented in Fig. 2. A Hookean element (primary mechanical compression), associated with a Kelvin element (secondary mechanical compression), represented by the association of a Hookean element and a Newton element (dashpot), and a third body (secondary biological compression) represented by the association in parallel of a finite compression element and dashpot.

Analytically, the model can be expressed as (Eq. (4)):

$$\varepsilon = \frac{\Delta H}{H} = C'_c \log\left(\frac{\sigma_0 + \Delta\sigma}{\sigma_0}\right) + \Delta\sigma \times b(1 - e^{-ct'}) + E_{DG}(1 - e^{-dt''}) \quad (4)$$

where ε = deformation (%); H = height (m); ΔH = settlement (m); C'_C = compression ratio (primary mechanical compression); σ_0 = initial vertical stress (kPa); $\Delta\sigma$ = change in vertical stress (kPa); b = coefficient of mechanical creep (secondary compression) (kPa^{-1}); c = rate constant for mechanical creep (secondary compression) (day^{-1}); E_{DG} = total amount of strain that can occur due to biological decomposition; d = rate constant for biological decomposition (day^{-1}); t'' = time since placement of the waste in the landfill; t' = time since application of the stress increment.

2.4. Meruelo model

Described in Diaz *et al.* (1995) and Espinace *et al.* (1999), this model is based on the loss of mass of the degraded materials that occurs during the anaerobic phase, which is conditioned by the organic matter hydrolysis rate. The loss of mass and consequent volume reduction is associated to the expected settlement (ΔH). The model is valid only for the long-term settlement prediction under the action of the decomposition processes (secondary compression due to waste biodegradation) (Eq. (5)).

$$\Delta H = \alpha \times H \times \mathrm{COD}\left[1 - \left(\frac{1}{K_h \times t_c}\right) \times (e^{-K_h(t - t_c)} - e^{-K_h t})\right] \quad (5)$$

where α = coefficient of mass loss; H = height of MSW landfill (m); COD = biodegradable organic matter present

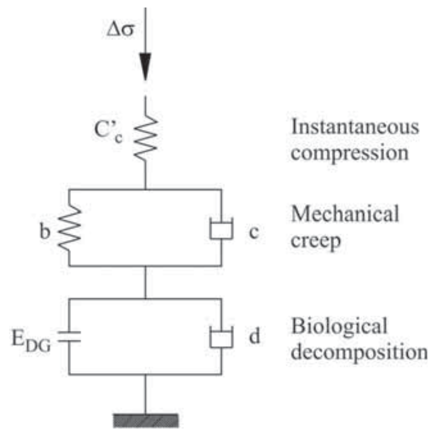

Figure 2 - Composite compressibility model.

in the wastes; t_c = time of landfill construction (day); K_h = hydrolysis coefficient (day^{-1}); t = time (day).

3. Material and Methods

3.1. Experimental landfill

The construction of the experimental landfill aimed to investigate the influence of operational aspects, mainly those concerning waste compaction, in the behavior of sanitary landfills. The study was carried out with the construction and monitoring of an experimental landfill for municipal solid wastes disposal, operating in real scale. The study also aimed at evaluating the mechanical behavior of the landfill and the evolution of the physical and chemical parameters of the leachate and gases generated, as well as evaluating the water balance and the performance of the landfill final cover (Catapreta, 2008). The focus of this paper is on long-term settlement analysis and modeling.

The experimental landfill is located at BR 040 Solid Waste Treatment Facility, in Belo Horizonte City, Minas Gerais State, Brazil, and it covers an area of about 5.26 x 10^3 m^2, with a total initial height of 3.8 m (3.2 m of waste and 0.60 m of final cover). About 8.6 x 10^3 mg of MSW, corresponding to 11.55 x 10^3 m^3, were disposed in the experimental landfill.

The construction of the experimental landfill was carried out between June of 2004 and May of 2005. The initial earthworks involved the removal of the existent vegetation layer and regularization of the area, to enable the liner and leachate collection system installation. The liner was composed of a support layer, constituted of 0.40 m compacted silty-clay soil, a synthetic flexible asphaltic membrane, 4.0 mm thick, and a protection layer, constituted of 0.30 m compacted silty-clay soil. Over the liner, the leachate collection system, composed of gravel-filled trenches, was constructed. All these construction stages were subjected to quality control, involving topographical measurements and field and laboratory tests carried out in earthen materials used.

The MSW disposal in the experimental landfill took one month, from May to June of 2005, and involved a series of controlled operational procedures. The filling procedures consisted of spreading the wastes in thin layers on the working face of the landfill and compaction with Track-Type Tractors, with weight of 17 mg. The daily waste densities were obtained using topographical measurements carried out at the end of each day and the weight of wastes disposed, obtained in Belo Horizonte Sanitary Landfill weighting facility.

The experimental landfill was divided in 6 cells (strips), which were filled with the same type of waste, but subjected to different compaction conditions. The field compaction energy (number of compactor equipment passes) and slope of working face were varied in order to obtain different initial densities for each cell, and consequently, to enable the evaluation of the influence of these aspects in the settlements.

The final cover of the cells was installed just after the filling phase. In 50% of the landfill, an evaporative final cover, constituted of 0.60 m thick compacted clay (permeability of 10^{-8} m.s^{-1}), was constructed. On the other half of the landfill, a capillary barrier, constituted of 0.30 m thick recycled demolition and construction waste layer under 0.30 m thick compacted clay (permeability of 10^{-8} m.s^{-1}), was constructed.

Immediately after the final cover construction, 18 settlement plates were installed, 3 on each cell. Figure 3 shows the experimental landfill, indicating the 6 cells and the installed settlement plates (SP 01 to SP 18).

The design and construction of this experimental landfill were carried out aiming the uniformity of waste composition. The average gravimetric composition of MSW disposed in all experimental landfill cells was: organic matter: 62%; paper and cardboard: 10%; plastics: 11%; metals: 2%; glasses: 3%; construction and demolition wastes: 3%; rubber, foam and ceramics: 1%; wood, textiles and leather: 4%; others: 5%. Based on Tchobanoglous *et al.* (1993), the methodology to obtain gravimetric composition consisted in quartering, sampling, segregation in categories

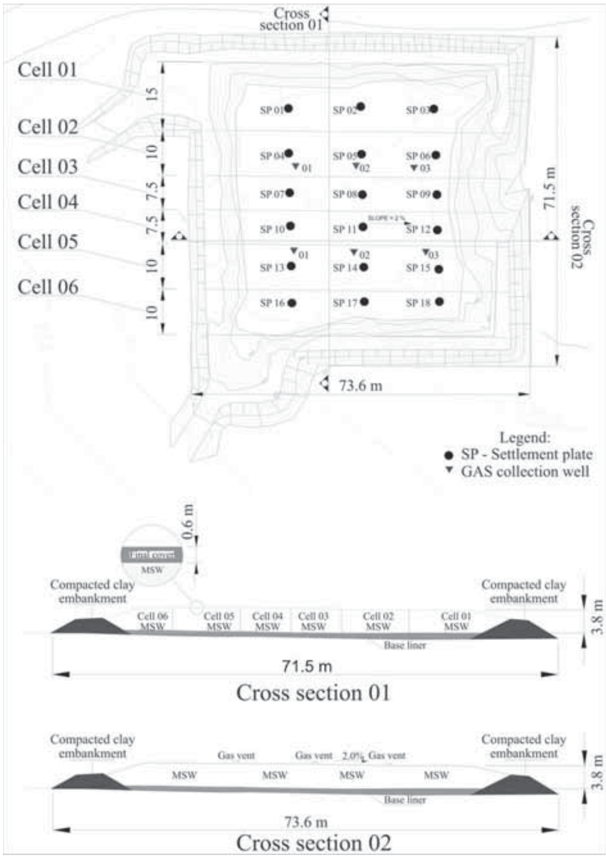

Figure 3 - Experimental landfill.

and weighting. The initial average moisture content was 60% in wet basis.

3.2. Settlement measurements

The settlement monitoring was carried out using the installed settlement plates, as showed in Fig. 3. These settlement plates were constituted of a concrete block with a steel rod, to allow the measurements, and were installed between the wastes surface and the final cover. The distribution of the settlement plates aimed at establishing the relationship between observed settlements, operation methods and initial waste densities in each cell. The settlements were measured using conventional topographical equipments.

The settlement analysis was performed using the average settlements observed for each group of plates, for each cell. To obtain and validate this average, the non-parametric Tukey Test (Larsen & Marx, 1986) was carried out. This test allows establishing the minimum significant difference, or in other words, the smallest average difference of samples that should be taken as statistically significant.

The settlement monitoring started immediately after the end of the experimental landfill construction and spanned over a period of approximately 3 years, from June 2005 to September 2008. Considering the geotechnical properties and the homogeneity of the soil underneath the experimental landfill associated with the low stresses induced by the experimental landfill, the long-term foundation settlements were not considered.

3.3. Settlement models calibration and simulation

The settlements analysis was accomplished considering the field data observed during the period of 3 years and were divided in two stages. In first stage, denominated Phase I, the first year monitoring data were used to calibrate the models. With the parameters obtained, a simulation of the second year was carried out to verify if the models adjusts to the field data observed.

In the second stage, described as Phase II, the 3 years monitoring data were used to calibrate the models and to simulate the long-term settlement for a period of 30 years.

The calibration of the models and long term simulation were obtained using a spreadsheet. For each cell settlement data, the best parameters of each model were achieved using an interactive approximation procedure, where the deviations (D), defined as the average of the square differences between the fitted and field data (Eq. (6)), were minimized.

$$D = \frac{\sum\left(Y - \overline{Y}\right)^2}{n} \qquad (6)$$

where: Y = fitted values; $\overline{Y}$ = field values; n = number of data.

4. Results and Discussion

The Tukey test indicated that the settlements observed in the set of three plates installed on each cell, could be represented by the average value. Therefore the influence of the small differences observed between the end of filling of each cell and the beginning of settlement monitoring were eliminated.

Table 1 shows the average settlement observed for the first and third years, as well as the cells initial densities. Figure 4 presents the curves of average measured settlement for each cell *vs.* time. As it can be observed the settlement plates presented a similar movement, however with different strain rates for each cell.

Considering that the MSW moisture content in all cells was similar, about 60% as described previously, the wet waste density was considered in the analysis.

The results suggest that the total vertical strains observed during the monitoring period are influenced by the initial wastes densities, with the larger settlements associated with the larger initial wastes densities. This observation is clear when Cells 2 and 4 are compared, where the settlement presented the smallest and highest values, respectively.

This result seems, in fact, contrary to the expected since wastes with same composition and smaller initial

Table 1 - Settlements observed in the experimental landfill.

Cell	Settlement plates	Settlement (m)		Average Settlement (m)		Waste density ($kN.m^{-3}$)
		Year 1	Year 3	Year 1	Year 3	
1	1	0.372	0.615	0.341	0.593	7.3
	2	0.319	0.583			
	3	0.331	0.581			
2	4	0.358	0.625	0.352	0.623	5.8
	5	0.313	0.626			
	6	0.386	0.617			
3	7	0.396	0.655	0.387	0.646	8.1
	8	0.351	0.584			
	9	0.414	0.698			
4	10	0.461	0.712	0.425	0.717	8.2
	11	0.385	0.655			
	12	0.430	0.782			
5	13	0.402	0.644	0.402	0.684	8.1
	14	0.356	0.612			
	15	0.449	0.796			
6	16	0.345	0.594	0.376	0.642	8.0
	17	0.334	0.560			
	18	0.449	0.771			

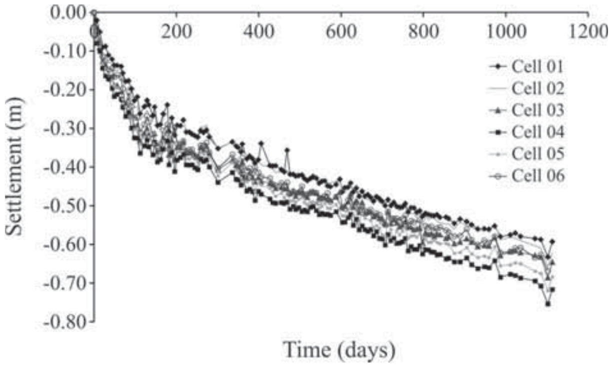

Figure 4 - Settlements observed in the experimental landfill.

densities tend to present higher settlements, mainly when subjected to stress increments. However this influence may not have affected the results, since the only stress increment was imposed by the final cover, which was similar for all cells. Considering the long-term behavior, although more compressible, the wastes with smaller densities are subject to smaller stresses due to self weight and the wastes with larger initial densities and, despite the lower compressibility, would be subject to larger stresses due to self weight. That could be contributing to the occurrence of larger settlements in the cells with larger initial densities.

4.1. Phase I calibration

The initial calibration, called Phase I, used the first year field data. The parameters and deviations obtained are shown in Table 2. The four models presented small and similar deviations, showing a good agreement between the fitted and observed data. As can be observed in Fig. 5, all the models presented a similar pattern, which can be attributed to the small number of records used in the calibration.

The parameters obtained in Phase I calibration were used to predict the settlements of the complete monitoring period (3 years). The comparison of the models results and the field data is shown in Table 3 and Fig. 6. As it can be seen in Fig. 6 and despite the small deviations observed in the calibration (Table 2), the models were not able to predict correctly the 3-year field data. All the models underestimate the settlements. Relations between predicted and measured settlements of up to 84% were observed. This confirms the need of larger set of data to predict more accurately landfill settlements.

4.2. Phase II calibration

The second calibration, called Phase II, used the three-year field data. The parameters and deviations obtained are shown in Table 4. The deviations observed are higher than those obtained for Phase I calibration. As can be observed in Fig. 7, all the models presented a similar pattern, excepting the Composite model, which presented better results, with lower deviations.

Table 2 - Obtained parameters for the Phase I calibration.

Cell	Rheological model			Hyperbolic model			Composite model					Meruelo model		
	D (x 10^4)	λ/b (x 10^3)	b (x 10^3)	D (x 10^4)	ρ_o (x 10^3)	S_{ult}	D (x 10^4)	b (x 10^3)	c (x 10^3)	Edg (x 10^3)	d	D (x 10^4)	α	K_h (x 10^3)
	m	day^{-1}	kPa^{-1}	m		m	m	kPa^{-1}	day^{-1}	-	day^{-1}	m	-	day^{-1}
1	2.4	9.17	9.44	2.3	3.90	0.466	2.2	8.24	8.02	6.96	0.102	2.6	0.19	7.06
2	3.3	11.54	11.34	2.9	4.95	0.426	2.9	9.30	9.50	10.79	0.151	3.0	0.18	8.85
3	3.4	13.41	9.22	3.1	6.81	0.470	2.8	7.75	11.28	12.24	0.303	3.0	0.20	10.27
4	4.2	14.12	9.83	3.4	7.91	0.502	3.1	8.16	11.18	17.37	0.357	3.1	0.22	10.77
5	3.9	12.94	9.57	3.5	6.78	0.490	3.2	8.14	10.72	13.28	0.408	3.3	0.21	9.94
6	4.1	11.41	9.31	3.9	5.54	0.483	3.6	8.07	9.63	10.83	0.222	3.8	0.20	8.80

D: deviation.

Table 3 - Settlement prediction for 3 years using parameters of Phase I.

Cell	Field data	Rheological model		Hyperbolic model		Composite model		Meruelo model	
	(m)	(m)	R (%)	(m)	R (%)	(m)	R (%)	(m)	R (%)
1	0.593	0.353	68.01	0.421	40.94	0.375	58.31	0.363	63.36
2	0.622	0.337	84.62	0.395	57.35	0.352	76.33	0.348	78.82
3	0.646	0.382	68.80	0.443	45.76	0.397	62.64	0.391	64.98
4	0.717	0.413	73.60	0.475	50.81	0.428	67.52	0.425	68.47
5	0.684	0.397	72.34	0.460	48.52	0.412	65.84	0.407	67.86
6	0.669	0.381	75.37	0.448	49.49	0.399	67.72	0.392	70.58

R: ratio between modeled and field data.

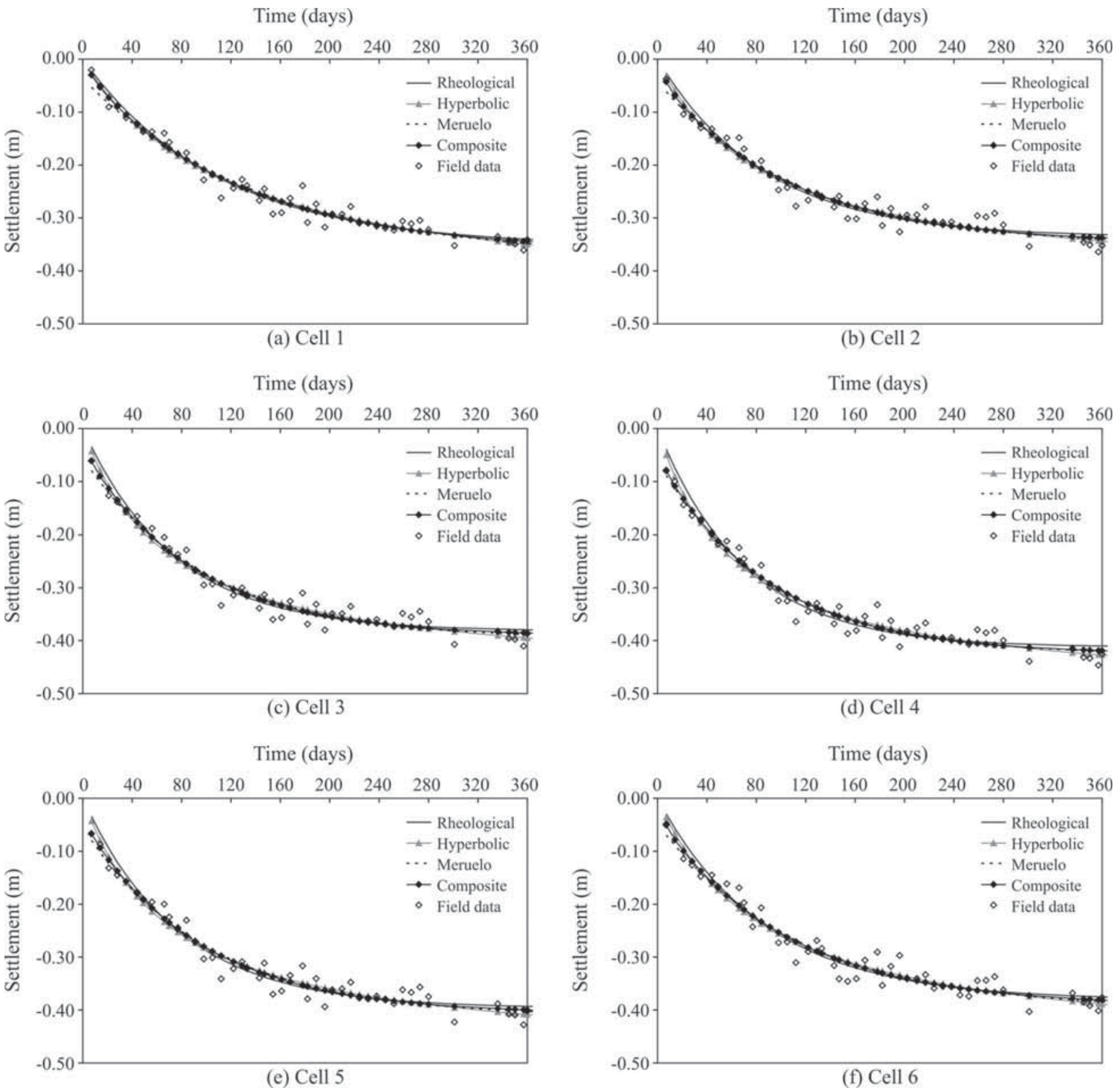

Figure 5 - Calibration of settlement models with the observed field data for Phase I (1 year).

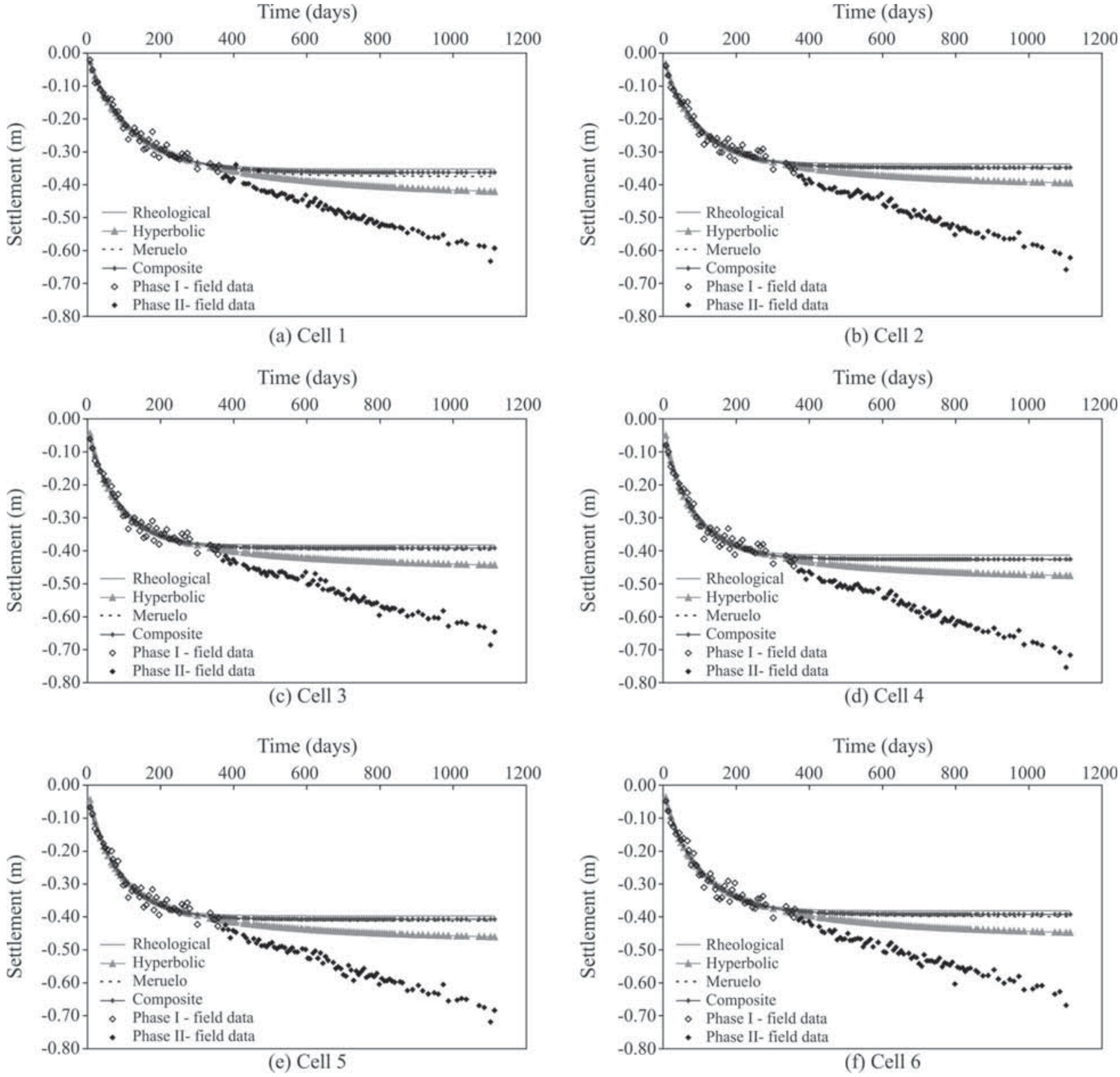

Figure 6 - Comparison of models results and field data using Phase I parameters.

Correlations between calculated and measured strains (settlement to initial height ratio) using Phase II calibrated parameters are shown in Fig. 8. The composite model was the only model to predict adequately the long term settlements.

Based on the results from the calibrations of Phase II, some remarks about the parameters obtained can be done.

Initial settlement rates observed for the Hyperbolic Model varied between 2.35×10^{-3} and 3.88×10^{-3} m.day^{-1} (Cells 1 and 4), similar to the rates observed by Ling *et al.* (1998): 1×10^{-3} and 3.0×10^{-3} m.day^{-1}. As Cell 1 presented a smaller density than Cell 4, the results suggest that the smaller the density, the smaller the settlement rates.

Despite the good fitting obtained for Phase I Calibration, for the total period of monitoring (Phase II) the Rheological Model presented a poor fitting. The compressibility parameters of the model were similar to the ones mentioned in the literature. The smallest secondary compression rate (λ/b) was observed for Cell 2, presenting values close to 3.31×10^{-3} day^{-1}, while the largest value was 4.46×10^{-3} day^{-1}, for Cell 4. Similar values were observed by Park *et al.* (2002).

The Meruelo Model has the advantage of representing the degradation process, which is important for the long-term settlement prediction. For this model, the observed values of mass loss coefficient (α), around 0.29 to

Table 4 - Obtained parameters for the Phase II calibration.

Cell	Rheological model			Hyperbolic model			Composite model					Meruelo model		
	D (x 10^4)	λ/b	b	D (x 10^4)	ρ_o	S_{ult}	D (x 10^4)	b	c	Edg	d	D (x 10^4)	α	K_h
		(x 10^3)	(x 10^3)		(x 10^3)			(x 10^3)	(x 10^3)	(x 10^3)				(x 10^3)
	m	day^{-1}	kPa^{-1}	m		m	m	kPa^{-1}	day^{-1}	-	day^{-1}	m	-	day^{-1}
1	10.2	3.32	14.80	5.7	2.35	0.70	1.3	18.89	0.64	64.20	0.0160	7.8	0.29	3.01
2	15.3	3.31	18.91	9.6	2.48	0.71	2.0	29.62	0.48	64.63	0.0209	12.0	0.29	3.00
3	21.0	4.46	13.63	11.6	3.55	0.68	2.1	26.84	0.34	85.45	0.0207	16.6	0.29	4.00
4	26.7	4.44	14.70	15.0	3.88	0.74	2.1	35.04	0.28	92.70	0.0223	21.1	0.32	3.98
5	22.1	4.24	14.37	12.5	3.51	0.72	2.3	27.35	0.36	86.63	0.0205	17.4	0.31	3.81
6	16.8	4.07	13.88	9.4	3.15	0.70	2.4	20.70	0.49	79.97	0.0182	13.2	0.29	3.67

D: deviation.

0.32, are similar to those described by Palma (1995), who observed variations between 0.15 and 0.50. The hydrolysis coefficient (K_h) presented values varying between 3.0 x 10^{-3} and 4.0 x 10^{-3} day^{-1}, smaller than the results obtained by Palma (1995). However, the values presented in the literature for such parameters are not common, and usually relations between them and landfill height are not obtained.

For the Composite Model were obtained values varying between 18.89 x 10^{-3} and 35.04 x 10^{-3} kPa^{-1} (Cells 1 and 4) for the secondary mechanical compression coefficient (b); 0.28 x 10^{-3} to 0.64 x 10^{-3} day^{-1} (Cells 4 and 1) for the secondary mechanical compression rate (c); 64.20 x 10^{-3} to 92.70 x 10^{-3} (Cells 1 and 4) for the secondary biological compression coefficient (E_{DG}); and 0.0160 to 0.0223 day^{-1} (Cells 1 and 4) for the secondary biological compression rate (d). Marques *et al.* (2003) observed average values of 5.27 x 10^{-4} kPa^{-1} for the secondary mechanical compression coefficient (b); 1.79 x 10^{-3} day^{-1} for the secondary mechanical compression rate (c); 0.159 for the coefficient of secondary biological compression (E_{DG}); and 1.14x10^{-3} day^{-1} for the secondary biological compression rate (d).

The composite model presented the lowest deviations (D) for Phase I and Phase II calibrations, showing a good fit of the model results to the field data. It should also be considered that this model has one more fitting parameter than the other used models, what probably makes it more accurate than the others. Besides, this model couples mechanical creep and biodegradation effects individually.

4.3. Settlement prediction

The parameters obtained in the calibration of Phase II were used to predict the long-term settlement, considering a period of 30 years. Table 5 and Fig. 9 show the results. As some of the models consider the occurrence of long-term settlement due to the biodegradation, it was chosen a longer period for settlement evaluation, in order to estimate the period of waste stabilization. Certainly, if a more extensive monitoring period were used in the calibration, it would be possible to accomplish a more accurate settlement prediction.

The composite and hyperbolic models results presented a tendency to stabilization at larger times, when compared to the rheological and Meruelo models, however with different settlement rates and final settlements. Considering the presence of slowly degradable organic wastes (such as fractions containing lignine), it is expected that complete stabilization of the landfill takes place only in the long-term.

It must be pointed out the difference between the final settlements predicted by composite and hyperbolic models. The final vertical strain predicted by the composite model has an average of 42% and the hyperbolic model 22%, with respect to the initial height of the cells. These results are similar to values suggested in the literature.

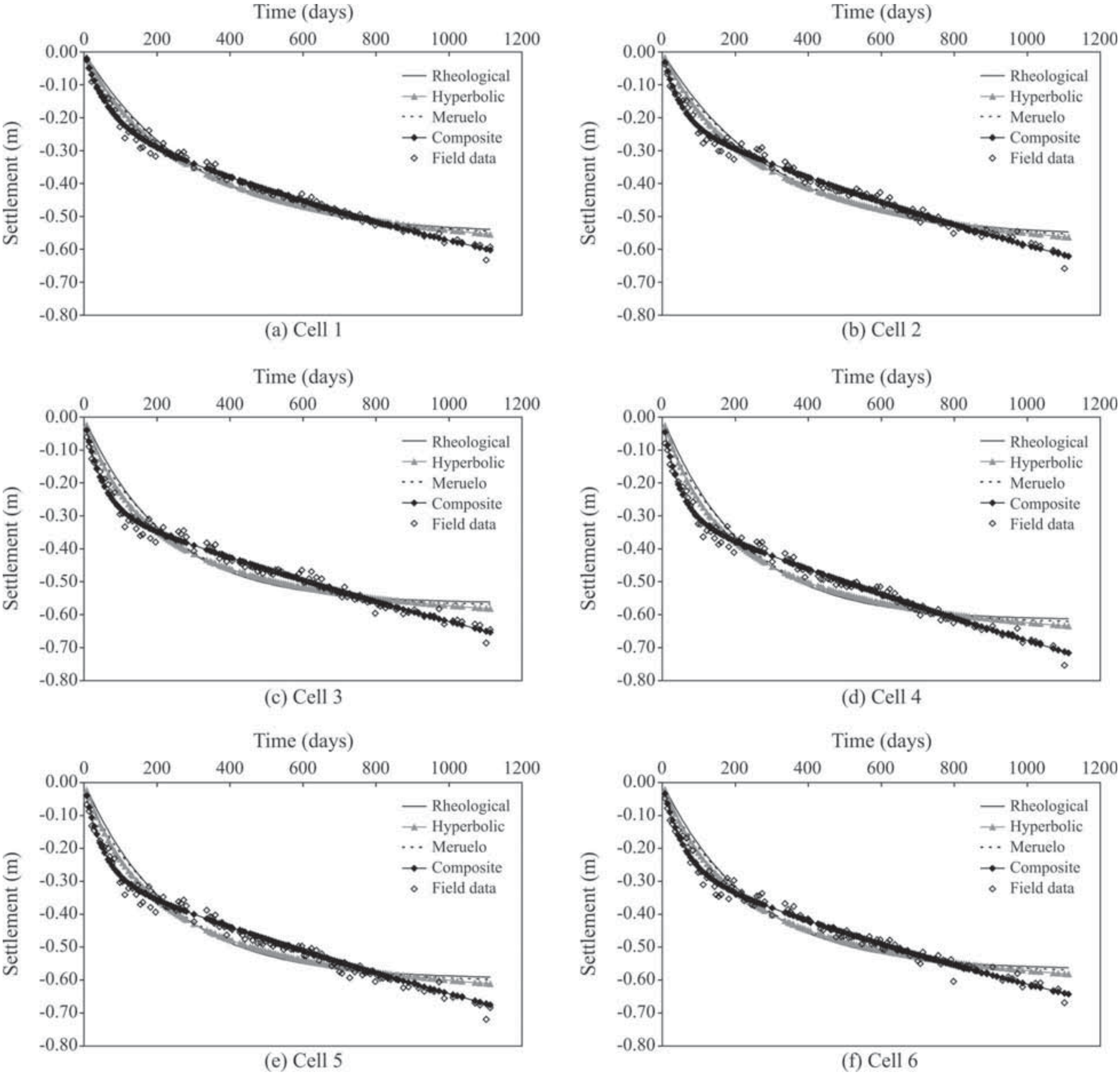

Figure 7 - Calibration of settlement models with the observed field data for Phase II (3 years).

The rheological and Meruelo models did not present satisfactory results, since the values observed in the long-term settlement prediction are indicating that the landfill would have reached the final phase of stabilization in approximately 3 years after wastes disposal, which, according to settlement field data that are still been collected is not happening (Catapreta, 2008).

5.Conclusions

The analysis of the vertical strains observed in the experimental landfill contributed to a better understanding of the waste settlement, allowing a critical assessment of the considered models, through the calibration of the field data and long-term settlement prediction.

The results demonstrate that settlement prediction in sanitary landfills is complex, what can be attributed to the wastes heterogeneity and the mechanisms involved in the process.

Limitations of some of the models considered in this study were verified, showing that long-term settlement prediction in MSW Landfill may not be restricted to the use of a single model. The use and comparison of different models should be considered and used to define final settlements ranges.

For a monitoring period of 3 years, the observed results indicated significant vertical strains, of up to 22% in relation to the initial height of the experimental landfill, what can be considered high and may be due to the fresh-

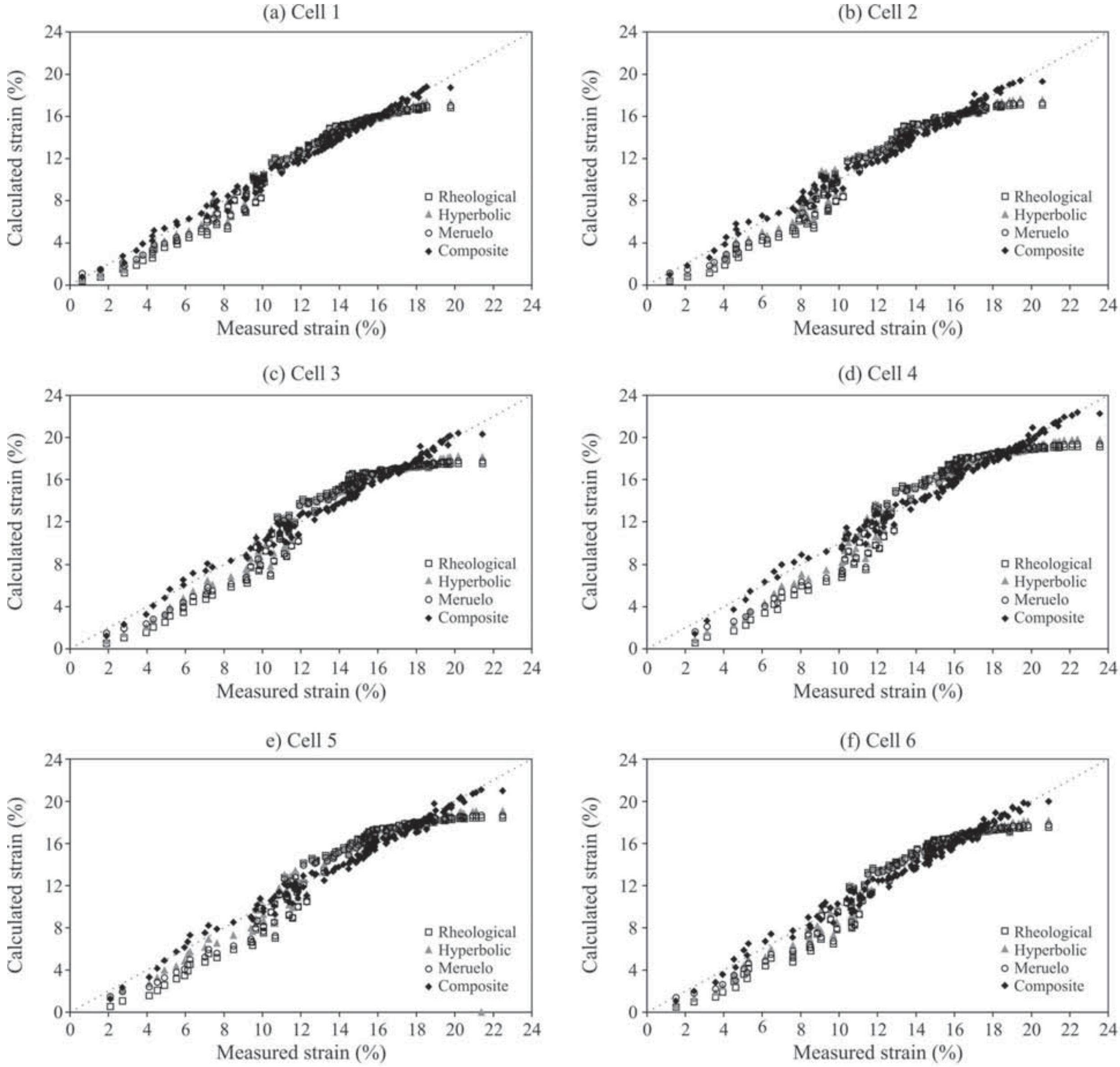

Figure 8 - Comparison of modeled and field strains using Phase II calibrated parameters.

Table 5 - 30-years Settlement prediction (m).

Cell	Rheological model	Hyperbolic model	Composite model	Meruelo model
1	0.553	0.686	0.986	0.564
2	0.561	0.690	1.199	0.576
3	0.565	0.671	1.462	0.575
4	0.617	0.731	1.808	0.627
5	0.596	0.711	1.480	0.606
6	0.568	0.685	1.169	0.578

ness and high organic content of the wastes being disposed.

The results obtained for the long-term settlement prediction with the rheological and Meruelo models indicate that the landfill would be reaching the final phase of stabilization in approximately 3 years after wastes landfilling. However, the settlement, leachate and gases monitoring that were carried out suggested that this stabilization has not occurred (Catapreta, 2008).

Others factors, related to mass loss, such as gas production and pressure, and position of gas vents, may also influence landfill settlements. However the monitoring program included only gas quality monitoring. Some tests

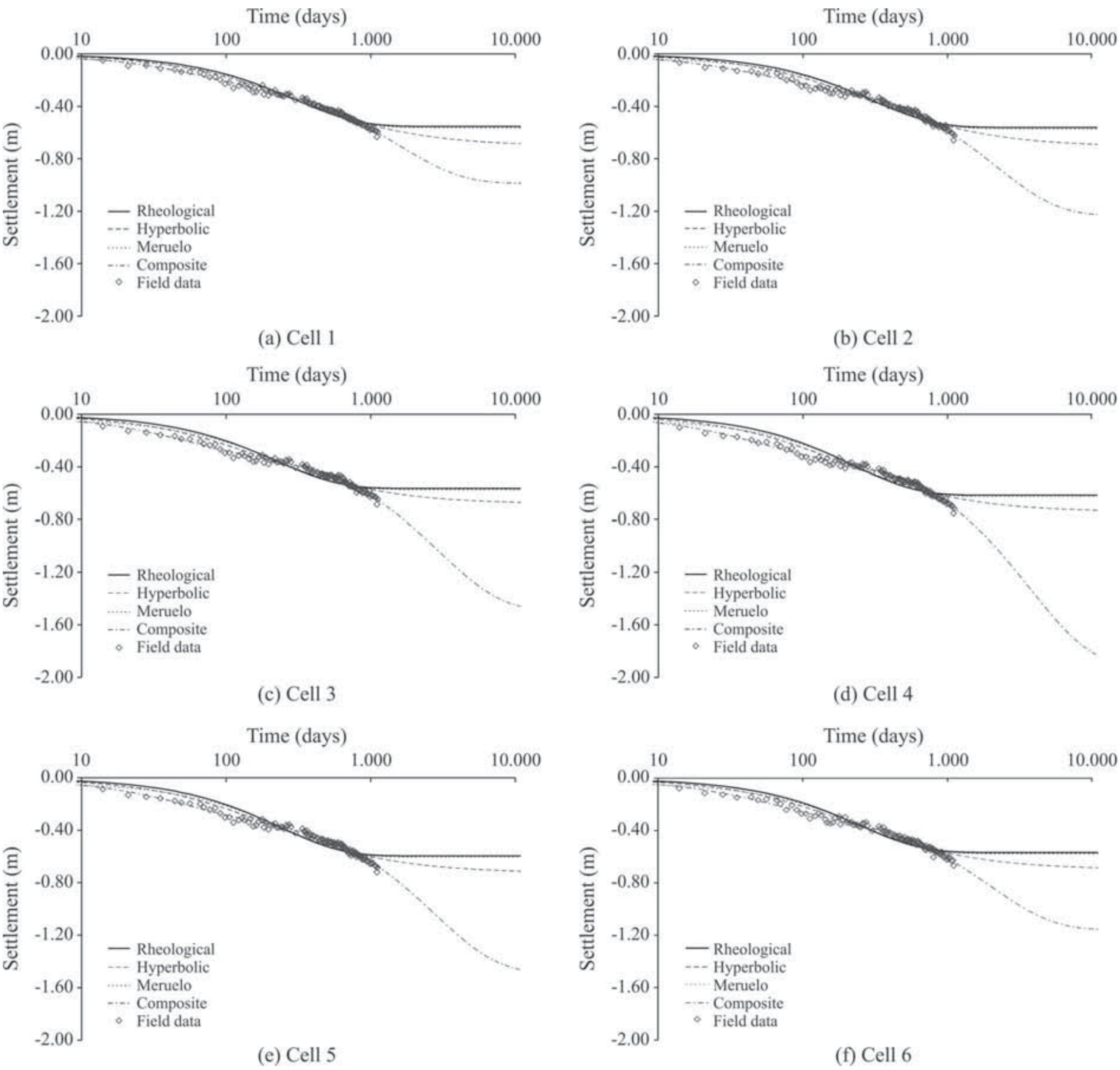

Figure 9 - Long-term settlement prediction.

were carried out to measure flow rates at gas vents, but the results indicated very small values, suggesting that the location of the vents did not influence the settlements in the experimental landfill.

The composite and hyperbolic models suggest settlements stabilization at larger times when compared to the rheological and Meruelo models, however with different settlement rates and final settlements. Considering these two models, a range of 22% to 42% of final strains could be suggested for long-term settlement prediction.

It should also be considered that the main reason for some models fit better than others may be due to the fact that they have more fitting parameters, enabling curve shapes that more closely resembles the field data.

Considering the mechanical component of the long-term settlement, the results also suggest that the operational procedures interfered directly in long-term settlements in sanitary landfills, indicating that the higher the initial densities, the higher are the stresses within the waste mass and, consequently, the larger are the long-term settlements.

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References

Bjarngard, A. & Edgers, L. (1990) Settlements of municipal solid waste landfills. Proceedings 13th Annual Madison Waste Conference, Madison, Wisconsin, v. 1, pp. 192-205.

Catapreta, C.A.A. (2008) Behavior of an Experimental Landfill: Assessment of Design, Construction and Operation Influence. PhD Thesis, Escola de Engenharia, Universidade Federal de Minas Gerais, 337 pp.

Diaz, J.G.L.; Narea, M.S.; Sanchez-Alciturri, J.M.; Ibarra, A.A., Monzon, I.T.; Gonzalez, J.P. & Lamia, M.F. (1995) Estimating material losses in sanitary landfills through biological degradation. Proceedings, 5th International Landfill Symposium – Sardinia 95, Cagliari, Italy, pp. 203-208.

Edgers, L.; Noble, J.J. & Williams, E. (1992) A biologic model for long term settlement in landfills. Proceedings of Mediterranean Conference on Environmental Geotechnology, Environmental Geotechnology, Cesme, Turkey, pp. 177-184.

Edil, T.B.; Ranguete, V.J. & Wuellner, W.W. (1990) Settlement of municipal refuse. Landva, A. & Knowles, G. D. (eds) Geotechnics of Waste Fills – Theory and Practice. American Society for Testing and Materials, Philadelphia, pp. 225-239.

El-Fadel, M.; Shazbak, S.; Saliby, E. & Lechie, J. (1999) Comparative assessment of settlement models for municipal solid waste landfill applications. Waste Management & Research, v. 17:5, p. 347-368.

Espinace, R.; Palma, G. & Sanchez-Alciturri, J.M. (1999) Experiencias de aplicacion de modelos para la determinacion de los assentamientos de rellenos sanitarios. Proceedings XI Panamerican Conference on Soil Mechanics and Foundation Engineering, Foz do Iguaçu, Brazil.

Gabr, M.A.; Hossain, M.S. & Barlaz, M.A. (2000) Solid waste settlement with leachate recirculation. Geotech. News, v. 18:2, p. 50-55.

Hossain, M.S.; Gabr, M.A. & Barlaz, M.A. (2003) Relationship of compressibility parameters to municipal solid waste decomposition. Journal of Geotechnical and Geoenvironmental Engineering, v. 129:12, p. 1251-1158.

Larsen, R.J. & M.L. Marx. (1986) An Introduction to Mathematical Statistics and its Applications, 2nd ed. Prentice-Hall International, Englewood Cliffs, 630 pp.

Ling, H.I.; Leshchinsky, D.; Mohri, Y. & Kawabata, T. (1998) Estimation of municipal solid waste landfill settlement. Journal of Geotechnical and Geoenvironmental Engineering, v. 124:1, p. 21-28.

Liu, C.N.; Chen, R.H. & Chen, K.S. (2006) Unsaturated consolidation theory for the prediction of long-term municipal solid waste landfill settlement. Waste Management & Research, v. 24:1, p. 80-91.

Marques, A.C.M.; Filz, G.M. & Vilar, O.M. (2003) Composite compressibility model for municipal solid waste. Journal of Geotechnical And Geoenvironmental Engineering, v. 129:4, p. 372-378.

Palma, J.H. (1995) Comportamiento Geotécnico de Vertederos Controlados de Residuos Sólidos Urbanos. Tesis Doctoral, Universidad de Cantabria, Santander, 294 pp.

Park, H.I. & Lee, S.R. (2002) Long-term settlement behavior of MSW landfills with various fill ages. Waste Management & Research, v. 20:3, p. 259-268.

Park II, H.; Lee, S.R. & Do, N.Y. (2002) Evaluation of decomposition effect on long-term settlement prediction for fresh municipal solid waste. Journal of Geotechnical and Geoenvironmental Engineering, v. 128:2, p. 107-118.

Simões, G.F. & Campos, T.M.P. (2002) A coupled mechanical and biological model to estimate settlements in solid waste landfills. Proceedings 4th International Symposium on Environmental Geotechnics, Rio de Janeiro, v. 1, pp. 283-288.

Singh, P. (2005) Landfill settlement effects. Proceedings 70th Annual Conference, Workshop And Expo, Rotorua, New Zeland.

Sowers, G.F. (1973) Settlement of waste disposal fills. Proceedings 8th International Conference on Soil Mechanics Foundation Engineering, Moscow, v. 2, pp. 207-210.

Tchobanoglous, G.; Theisen, H. & Vigil, S. (1993) Integrated Solid Waste Management: Engineering Principles and Management Issues, 1st ed. McGraw-Hill Book Company, New York, 978 pp.

Wall, D.K. & Zeiss, C. (1995) Municipal landfill biodegradation and settlement. Journal of Environmental Engineering, v. 121:3, p. 214-224.