# Municipal Solid Waste Sanitary Landfill Compressibility Study with Linear Regression Application

Luciana Paulo Gomes, Marcelo Oliveira Caetano

**Abstract.** This paper refers to a Municipal Solid Waste (MSW) compressibility study of waste disposed of in small scale sanitary landfills in the municipality of Presidente Lucena in the State of Rio Grande do Sul, Brazil. The research aims at the application and development of settlement prediction models based on settlement data collected on site. The studies were divided into the following stages: application of prediction models based on Soil Mechanics' classical concepts and the creation of a regression model, based on the physical and chemical landfill monitoring results, in order to estimate differential settlements. The results showed that the application of data collected at the monitored small scale landfills through classical settlement prediction models resulted in significant errors. However, the model created based upon the regression analysis, perhaps because it considered the specifics associated with disposal techniques in small landfills, was the most realistic in terms of settlement prediction, such that it is applicable to other similar systems, be it due to the characteristics of disposed waste, as well as to the employed operational details.

**Keywords:** urban solid waste, sanitary landfill, compressibility, settlement model, linear regression.

## 1. Introduction

Solid waste generation, as well as its impacts, is directly related to human cultural and technological evolution. Several authors (for instance, Zanta & Ferreira, 2003; Tillmann, 2003; Schneider *et al.*, 2004; Boff, 2005) report cultural, social and educational factors, number of inhabitants, activities carried forth by the population, technology and economic matters as influential factors that affect MSW production, as well as its physical, chemical and biological characteristics.

The Ministry of the Cities/Environmental Sanitation National Agency/Sanitary Sector Modernization Program (MCIDADES/SNSA/PMSS) (2008) has recently published a historical series that includes research on solid waste management in Brazil. Despite the fact that, for the year of 2006, the research has brought forth results from a sample of 48.8% of the Brazilian population corresponding to an urban population mainly from large cities, the final disposal result indicates that 16% of the units reported by managers are open dumps, 18% are controlled landfills, 5% are incineration units and 22% correspond to sanitary landfills.

Jucá (2003), describes a MSW landfill as an engineering workmanship intended for the disposal of such wastes, which undergo mass loss as a result of physical, chemical and biological processes. This phenomenon causes a reduction in the mass height of the disposed waste, known as settlement that is settlement.

Settlements and volume reduction of the deposited waste occur as a result of the transformation of its components through physical, chemical and biological processes resulting in gas emissions and leachate formation (Carvalho *et al.*, 2000). However, the quantification of these landfill geotechnical properties and settlement prediction in sanitary landfills is very complex due to factors such as: diversity, heterogeneity and waste decomposition processes, refuse type individual compressibility, as well as regional climate condition variations (Pereira, 2000; Carvalho *et al.*, 2000; Bowders *et al.*, 2000; Chen *et al.*, 2009).

Both the importance and need to understand landfill geotechnical characteristics may be justified by the imminent possibility to use these areas for waste relocation and/or environmental recovery, such as future reforestation projects, for instance. Park & Lee (2002) report that area usage, after sanitary landfill closure, is restricted mainly due to differential settlements as well as the generation of both leachate and gas emissions.

Among other advantages of settlement prediction is the simulation and/or establishment of applicable mathematical relations as they may be able to help project designers of these workmanships when it comes to the calculation of the space to be created by such phenomena, thus making it possible to discard more waste in the same area, maximizing landfill life cycle. Generally, in sanitary landfills, settlements reach nearly 25 to 30% of the theoretical landfill height (Gandolla *et al.*, 1994 and Santos, 1994).

Accordingly, Santos (1994) adds yet several advantages that point to the study of settlements in MSW landfills, such as: remediation of sanitary landfill or open dump areas with the establishment of parks, gardens, soccer fields, traffic routes and small buildings. These actions depend upon load capacity and settlements that such struc-

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Submitted on August 10, 2009; Final Acceptance on January 23, 2010; Discussion open until April 29, 2011.

tures may be able to withstand after their implementation. Additional advantages are: settlement evolution curves represent an auxiliary method in the monitoring of physical and chemical modifications and of MSW decomposition; in addition, they may be useful in the assessment and stability of landfill slopes.

Amorim & Bernardes (2007) report that settlement monitoring in MSW landfills is a phenomenon that determines landfill operational control and management procedures, besides the fact that it also affects future area occupation.

Following the same line of thought, Park *et al.* (2007), Liu *et al.* (2006) and Bowders *et al.* (2000) describe that understanding settlements throughout time is both important and critical to a an MSW landfill project, operation and management. Besides, it is essential to the project of landfill rehabilitation, and may be useful in the construction of parks, houses and roads. El-Fadel *et al.* (1999) supplements this statement by mentioning that this phenomenon is an integral part of landfill closure planning, as well as of area reuse.

Finally, an important aspect mentioned by Simões *et al.* (2005) refers to MSW landfill safety. Both horizontal and vertical landfill movement monitoring allow for the identification of movement pattern alterations in such a way that these variations may be indicative of instability problems, thus rendering a geotechnical assessment as important from both a legal and technical point of view.

Gandolla *et al.* (1994) also mentions this preoccupation with the safety element, such that settlement monitoring may be used in a way to improve landfill stability, as it mainly refers to cover layer inclination determination.

Taking all problems and needs pointed out to into consideration, the work to be presented refers to a compressibility study of MSW disposed of in small scale sanitary landfills in Presidente Lucena in the State of Rio Grande do Sul, Brazil, aimed at the application and development of a settlement prediction model.

## 2. Waste Compressibility

Conventional geotechnical engineering considers settlements as vertical soil deformations resulting from external load application or from its own weight. Both deformability and landfill deformation speed are influenced by waste gravimetric composition. According to Oliveira (1995), landfills with larger inert waste composition tend to be harder in comparison with landfills with a larger percentage of domestic solid waste (decomposing organic matter, plastic and paper). As for this statement, Park & Lee (2002) describe that settlement characteristics in MSW sanitary landfills are particular due to the considerable occurrence of such phenomenon as a result of organic waste decomposition, which lasts for a long time throughout the landfill's life cycle.

The compressibility mechanisms of MSW disposed of in sanitary landfills are described and conceptualized by several authors. According to Sowers (1973), Pereira (2000) and Carvalho *et al.* (2000), MSW compression mechanisms are: 1. Mechanical – particle structural collapse (distortion, bending, crushing and component reorientation); 2. Fine particle migration to empty spaces created by larger particles; 3. Physical and chemical changes – due to corrosion, oxidation and combustion; 4. Biochemical degradation – aerobic and anaerobic fermentation and decomposition processes and 5. Interaction – interaction of physical, chemical and biochemical processes.

On the other hand, Oliveira (1995) defines that sanitary landfill vertical deformations are associated to two periods: 1. Landfill construction period due to the increased load of its own weight, such that larger vertical deformations tend to occur during this period; 2. Landfill post-construction secondary deformations resulting from waste layer consolidation caused by pore expelled water due to landfill material components' deformation.

Finally, another sanitary landfill settlement description and classification is made by Jucá (2003) and Liu *et al.* (2004). For them, there are three types of MSW landfill settlements: immediate or initial, primary and secondary. According to the authors, initial compression occurs due to external pressure caused by compacting machines in the beginning of the waste disposal process. Primary settlements result from liquid and gases being expelled from the interior of the waste mass and occur in the first 30 days according to Wall & Zeiss (1995) *apud* Jucá (2003). Finally, secondary settlements refer exclusively to biodegradation, which can be influenced by humidity level and flow, as well as by buried waste composition.

According to Pereira (2000) and Carvalho *et al.* (2000), several factors affect settlement mechanisms such as: specific weight or void ratio, nutrient availability for microbiological growth, waste composition and moisture content, landfill height, overload, leachate level and fluctuation; operational and project details, in addition to environmental and climatic factors such as moisture content, rainfall, evaporation and temperature.

As a complement to what has been said, Melo *et al.* (2006) describes that MSW landfill settlement magnitude and speed are influenced by various physical, chemical and biological processes, being that the last one is responsible for the majority of this influence.

Pereira & Mañas (2001) monitored superficial settlements in order to evaluate immediate and primary settlements (installation of referential marks) and deep ones to evaluate secondary settlements (installation of a sliding micrometer) at the Valdemingómes sanitary landfill in Madrid, Spain. From the results it may be observed that for a waste disposal height equal to 18 m monitored for approximately 600 days, immediate settlement was measured at 0.067 m; primary at 0.314 m and secondary at 0.860 m, totalizing 1.241 m of measured settlement at the reference positions, which means a deformation of 6.89%. The authors also found that primary and secondary compression transition occurred within 100 monitoring days.

In another research, settlement monitoring of the first installed 2.0 m layer at the Columbia, Missouri sanitary landfill in the United States, which is operated without leachate recirculation, settlement was recorded at 0.3 m during 180 days of monitoring activities; in other words, 15% of total height (Bowders *et al.*, 2000).

The same author shows a study in the Victoria sanitary landfill in Australia, where settlements of 0.7 m were measured in a section where there was leachate recirculation at the portion where plates were placed on top of the landfill (approximate thickness height of 18 m). In the section without recirculation, settlement was approximately 0.5 m.

## 3. Msw Landfill Settlement Prediction Models

Due to the lack of specific models to determine MSW landfill compressibility, classical concepts of Soil Mechanics have been used with some adaptations, as is the case in the models presented by Sowers (1973), Bjarngard & Edgers (1990), Yen & Scanlon (1975), Gibson & Lo (1961) and Edil *et al.* (1990) *apud* Carvalho *et al.* (2000).

Equation (1) indicates the model presented by Sowers (1973), while Eq. (2) presents the proposals set forth by Bjarngard & Edgers (1990), both of which are used to predict sanitary landfill settlements.

$$S_{(t)} = \frac{H}{1+e_0}\left[C_c \log\frac{\sigma_0' + \Delta\sigma}{\sigma_0'} + C_\alpha \log\frac{t}{t_{(1)}}\right] \quad (1)$$

$$\frac{S_{(t)}}{H} = C_C' \log\frac{\sigma_0' + \Delta\sigma}{\sigma_0'} + C_{\alpha 1}' \log\frac{t_{(2)}}{t_{(1)}} + C_{\alpha 2}' \log\frac{t_{(3)}}{t_{(2)}} \quad (2)$$

where $S_{(t)}$ = settlement in time $t$; $H$ = initial layer thickness; $e_0$ = initial void ratio ; $C_c$ = primary compression index; $C'_c = Cc/(1 + e_0)$ = primary compression index coefficient ; $C_\alpha$ = secondary compression index; $\sigma_0$ = initial vertical stress; $\Delta\sigma$ = increase in vertical stress; $t_{(t)}$ = time to complete initial compression; $t_{(2)}$ = time to complete intermediary compression; $t_{(3)}$ = ideal length of time to predict a settlement; $C'_{\alpha 1}/(1 + e_0)$ = intermediary secondary compression index; $C'_{\alpha 2} = C_{\alpha 2}/(1 + e_0)$ = intermediary secondary compression index, in the long run.

Several studies have been conducted in order to estimate essential coefficients, which aid in the application of settlement prediction models mentioned in the literature. Unfortunately, it is emphasized that they are reasonably complex to obtain; void ratio, as well as primary and secondary compression indexes are examples of this complexity.

Sowers (1973) determined the primary and secondary compression index according to waste characteristics. The values defined for primary compression were $0.15e_0$ (wastes containing little organic matter) and $0.55e_0$ (wastes with high levels of organic matter). The author obtained the following numbers for secondary compression index: $0.03e_0$ (unfavorable degradation conditions) and $0.09e_0$ (favorable degradation conditions).

It is so that Marques (2001) and Simões & Campos (1998) describe a series of research projects that estimate such indexes, which are presented in Tables 1 and 2.

In the Bandeirantes Sanitary Landfill study, Carvalho *et al.* (2000) determined, in the laboratory, these parameters described in Tables 1 and 2. The results indicated a variation in the primary compression index *Cc* from 0.56 to 0.92;

**Table 1** - Settlement prediction parameters – Obtained in the laboratory.

| Authors | Place | Primary compression | | Secondary compression | |
|---|---|---|---|---|---|
| | | Index (*Cc*) | Coefficient (*C'c*) | Index ($C\alpha$) | Coefficient ($C'\alpha$) |
| Sowers (1973) | - | $0.15e_0$ to $0.55e_0$ | - | $0.03e_0$ to $0.09e_0$ | - |
| Rao *et al.* (1977) | - | - | 0.160 to 0.235 | - | 0.015 to 0.045 |
| Sargunan *et al.* (1986) | - | 0.44 | | 0.0036 to 0.005 | - |
| Gabr & Valero (1995) | - | 0.4 to 0.9 | 0.15 to 0.22 | 0.03 to 0.09 | - |
| Landva & Clark (1984, 1986, 1990) - Sanitary landfills: | Kingston | - | 0.17 | - | 0.0210 |
| | Edmonton | - | 0.35 | - | 0.0180 |
| | Hantsport | - | 0.22 | - | 0.0280 |
| | Ottawa | - | 0.21 | - | 0.0070 |
| | Edmundston | - | 0.36 | - | 0.0020 |
| | Stolport | - | - | - | 0.0150 |

**Table 2** - Settlement prediction parameters – Obtained in experimental cells.

| Authors | Primary compression | | Secondary compression | |
|---|---|---|---|---|
| | Index ($Cc$) | Coefficient ($C'c$) | Index ($C\alpha$) | Coefficient ($C'\alpha$) |
| Espinace *et al.* (1991) | 0.13 to 0.40 | - | 0.14 to 0.59 | - |
| Cartier & Baldit (1983) | 0.54 to 0.90 | - | 0.30 to 0.55 | - |
| Wall & Zeiss (1995) | - | 0.21 to 0.25 | - | 0.033 to 0.056 |

$C'c$ from 0.175 to 0.229; secondary compression $C\alpha$ from 0.0213 to 0.0442; and $C'\alpha$ from 0.0105 to 0.016.

Marques (2001) reports that sanitary landfill settlements are normally estimated by considering a mechanism of one-dimensional consolidation. The application of settlement estimate models applied to wastes is complex. It is considered that the primary and secondary compression indexes are a function of the void ratio, whose value is variable and difficult to obtain from waste. There occur significant variations in both the primary and secondary compression indexes due to stresses produced in sanitary landfills, and primary settlements are a function of the effective stresses, which depend upon waste specific weight and leachate levels, both of which are parameters equally as hard to assess.

Due to variability, heterogeneity, individual compressibility and MSW degradation, Marques (2001) describes that the determination of the adequate settlement prediction model, just like the calculation of its parameters, presents itself as a limiting factor in sanitary landfill deformability analysis.

According to Liu *et al.* (2006), sanitary landfill estimate models can be divided into the following categories: 1. Consolidated Models: Terzaghi's theory applied to soil settlements is adapted to both primary and secondary settlement calculation; 2. Rheologic Model: waste compression behavior is modeled by using a rheologic model; for instance, in the viscoelastic model by Gibson & Lo (1961), primary and secondary compressibility is simulated by springs and suspension; 3. Biodegradation Model: organic matter gradual biodegradation is considered in model formulation; 4. Regression Model: several common functions (for instance, logarithmic, hyperbolic, *Creep* exponential model, bi-linear, multi-linear) are used to simulate settlements in sanitary landfills. The parameters of these functions are obtained through landfill settlement data.

Of these categories, the most utilized is the consolidated theory; however, there are many fundamental discrepancies between sanitary landfill settlement mechanisms and soil settlements. In the consolidated theory, the condition that soil is saturated is assumed. Thus, settlement is attributed to excess water dissipation in the pores, while secondary compression is responsible for a small portion of the total settlement. Nevertheless, sanitary landfill wastes are not saturated and organic matter degradation produces a significant amount of gas emissions, causing a high consolidation level (Liu *et al.*, 2006).

As for linear regression models, Liu *et al.* (2006) additionally report that this method is also very much used to predict settlements. Regression analysis aims at finding an appropriate coefficient to reach the best possible result; however, according to the authors, this method does not take settlement physical mechanisms into consideration. In addition, the authors describe that although biodegradation models consider the decomposition process associated to secondary compression, they fail to consider mechanical compression.

When applying the Bjarngard & Edgers Model (1990) to monitored settlement data at the Bandeirantes sanitary landfill in São Paulo, Brazil (7 year monitoring period and disposal variation height ranging from 26.3 m to 58.6 m), Carvalho *et al.* (2000) found secondary compression results with a variation of 12% when compared to the initial landfill height, which means settlements varying from 3 m to 7 m. Similar values were found, using the same data, by applying the model proposed by Gibson & Lo (1961). Thus, for the data studied by the authors, secondary settlements may be satisfactorily modeled by any one of the used models. The authors concluded that, although soil mechanics concepts are not entirely appropriate to estimate settlements, they have been the starting point. In addition, the model that was conceived primarily to measure secondary compressibility in peat (Gibson & Lo, 1961) seemed to closely reproduce the results obtained on site.

Armed with settlement monitoring data from the Bandeirantes sanitary landfill, Marques (2001) applied a series of prediction models described in the literature. The results showed that the Yen & Scalon Models (1975) and the logarithmic functions proposed – Models by Yen & Scalon (1975) and Ling *et al.* (1998) - are not recommended for use to predict settlements with the studied data. On the other hand, models based on the hyperbolic proposals by Ling *et al.* (1998) and Gibson & Lo (1961) reproduced settlement curves versus time quite well and, with a few adjustments, can be recommended for use. Proposals with models based on potency functions – Edil *et al.* (1990), Model by Edgers *et al.* (1992), Bjarngard & Edgers (1990) and Sowers (1973) did not prove to be as precise, although they are recommended for use after a few model adjustments. The author concluded that, despite the satisfactory performance of some models (based on simple mathematical formulas, with parameters and coefficients without physical meaning that simply aim at adjusting points on a curve), they must be avoided or used with reservation. Another aspect is the consideration that the sanitary landfill is a solid piece, such that models disregard the entire disposal sequence and the compression processes that act differently on each buried layer.

Park & Lee (2002) applied the biological model in order to predict long run settlements to data obtained from settlement monitoring in seven lysimeters and sanitary landfills of several ages. The authors divided the landfills in three groups: new (few years of operation), middle-aged (approximately 10 years) and old (up to 25 years). Results showed that the biological deformation estimate for new landfills was estimated to be between 11% and 25%, such that the entire settlement shall occur between 10 to 20 years. For landfills that are between 2 and 10 years old, biological deformation total quantity is higher depending on the age of the landfill, such that a full long run settlement rarely occurs prior to reaching 20 years of age.

Jucá (2003) applied the settlement models developed by Sowers (1973) and Gandolla *et al.* (1992) in Muribeca landfill (Recife, Brazil). Analyzing the results, the author concluded that: 1) due to cell age (*C*1 and *C*2 - approximately 18 years old) and consequential low organic matter level, settlements occurred exclusively due to secondary settlements; 2) both settlement measurements varying from 122 mm to 778 mm (for a monitoring period of 17 months) and their speed determination, which varied from 286 mm/day to 2381 mm/day, were considered small by the author due to the low microbiologic activity and final methane generation stage; 3) observed that the overload (placement of 30 cm of soil), as well as liquid and gas drainage (opening of an access channel) increase settlement speed; and 4) the models by Sowers (1973) and Gandolla *et al.* (1994) yielded results with similar values to those measured on site.

In another study, Park *et al.* (2007) classified fifteen MSW sanitary landfills in three different categories according to settlement magnitude and the age at which landfill closure occurs. Later, the authors applied several models used in settlement prediction (Gibson & Lo Model (1961), Hyperbolic function Model by Ling *et al.* (1998), Bjarngard & Edgers (1990) Model, Park & Lee Biological Model (1997; 2002), among others) to settlement data collected on site at these landfills. In the results, the authors verified that for sanitary landfills Type I (young landfills – below 3 years old), settlement estimate was significant for all models, except for the *Creep* exponential model. For Type II (young landfills like the ones in Type I, only that component substantial decomposition and biodegradation was observed), the tested models are appropriate to estimate long run settlements, except for the *Creep* Exponential Model and the Bjarngard & Edgers Model. Finally, for Type III (landfills that range from 8 to 25 years old), all models, except for the *Creep* Exponential Model, adequately estimate long run settlements. Thus, there was a similarity when comparing the application of settlement prediction models studied and the models based on the settlement data collected in the different types of landfills.

Recently, a model based on organic matter degradation was developed by Amorim & Bernardes (2007). In order to test the mathematical formulas, a model adjustment was made with monitoring data collected for forty months in settlements that occurred in an experimental cell built in the sanitary landfill in Brasilia, Brazil. A numeric simulation proved to be satisfactory in comparison to data collected on site.

## 4. Methodology

This work's methodology followed the stages described in Fig. 1.

### 4.1. Stage 1: Study area – data collection

Monitoring of the Superficial Settlements was conducted by using six stakes and one reference point through the Simple Geometric Leveling Method with one level and a centimeter rule (precision of 0.015 m), for a period of two years, in small scale sanitary landfills in the municipality of Presidente Lucena in the State of Rio Grande do Sul, Brazil. The municipality has 2100 inhabitants and its economy is basically based on agriculture, although is also has some small shoe making manufacturing companies, fruit processing, wood and textiles.

Data were collected in three different cells (T1 and T2), whose dimensions were approximately 4.0 x 5.3 x 2.5 m. The disposed buried MSW composition corresponds to 50% food scrap, 2% paper, 14% plastic and 34% other materials, mainly biological contaminants (toilet paper, disposable diapers and other sanitary and personal hygiene refuse).

The final landfill cover consisted of local soil (20 cm), being that intermediary coverings were not applied during solid waste disposition. Only T1 received a cover with a PVC membrane prior to the mineral superior layer with the proposal to reduce the entry of rain. High Density Polyethylene (HDPE) 0.8 mm thick geomembranes were used to minimize percolation on the sides and at the bottom.

The following parameters were weekly measured in the generated leachate in the three cells: pH, total solids (TS), total suspended solids (TSS), volatile suspended solids (VSS), chemical oxygen demand (COD), total nitrogen (TN), ammonia nitrogen (AN), phosphorus ($PO_4$), chrome (Cr), iron (Fe), lead (Pb), cadmium (Cd) and zinc (Zn). All analyses were made according to APHA (1995).

Similarly, differential settlement measurements were taken every week, in addition to counting of total anaerobic micro-organisms. Regional climate conditions data such as rainfall, relative air humidity and temperature were also

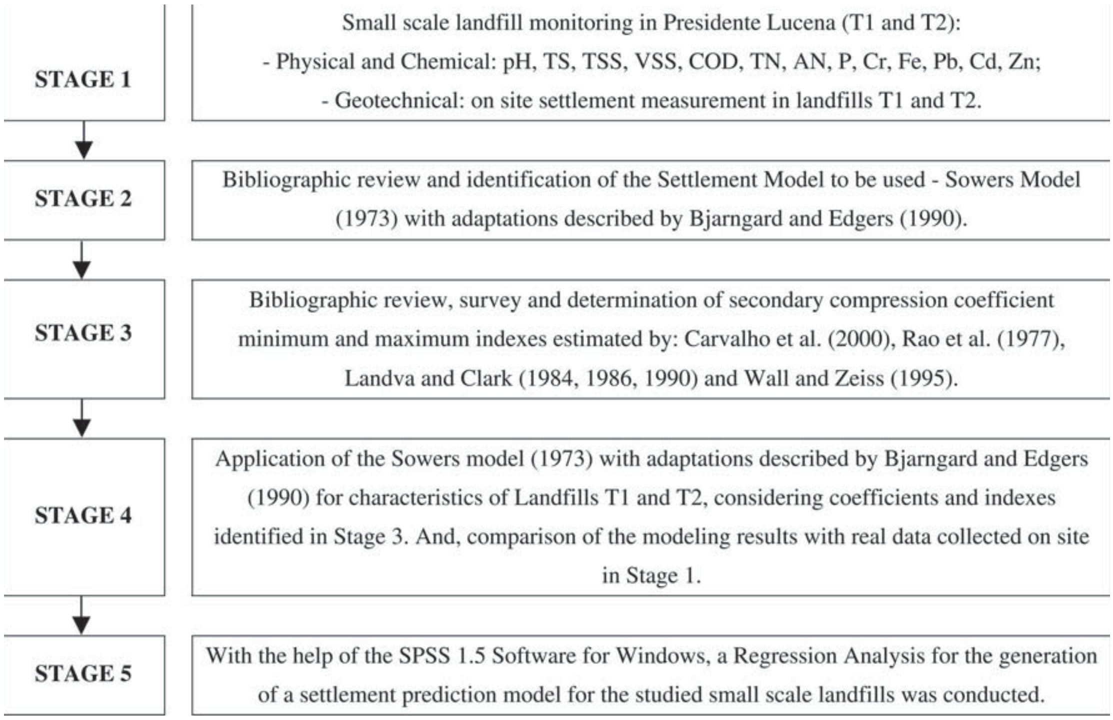



**Figure 1** - Research methodological stages.

collected and tabulated. The moment at which the trench was closed was considered as the initial time to monitor settlements ($t = 0$).

### 4.2. Stages 2, 3 and 4: Application of settlement prediction model in MSW landfills

In order to test sanitary landfill settlement prediction existing models mentioned in the consulted bibliography and, aiming at comparing the generated/estimated curve with the actual data collected on site, data measured *in situ* at the small scale sanitary landfills T1 and T2 were applied to the Sowers Model (1973) with adaptations described by Bjarngard & Edgers (1990) - Eq. (2). This model was chosen because, according to Liu *et al.* (2006), it is the one that is mostly used in settlement prediction.

In this stage of the research, the operation method of landfills T1 and T2, waste characteristics and local geotechnical conditions were taken into consideration, as follows:

• Initial waste layer thickness (trenches' depth) = 2.5 m;

• Waste density in the landfill = 12 tons of MSW were disposed of in the landfill whose volume was measured at 53 $m^3$. Waste density was determined to be 2.21 $kN/m^3$;

• Because there was no compression due to the use of machines, initial stress ($\sigma'_0$) was considered at 5.55 $kN/m^2$; in other words, the actual landfill weight alone;

• Increased stress ($\Delta\sigma'_0$) is the actual landfill weight calculated at 5.55 $kN/m^2$;

• Because waste compaction did not occur either during disposal or in the preparation of the final landfill cover layer, it was assumed that there was no primary compression. Thus, for this paper, the primary compression index coefficient ($C'c$) was considered to be equal to zero;

• Time of 133 days was considered as the period to complete intermediary compression in landfill T1, being that the very same period was used for landfill T2. This parameter was obtained by observing a sudden change in the line angle in the settlement graphs, suggesting a modification in settlement speed. The total settlement monitoring time at each landfill was as follows: T1 = 441 days and T2 = days;

In addition to these characteristics, both primary[*] and secondary compression coefficients identified in Table 3 were tested, in order to apply the model expressed in Eq. (2), as follows:

### 4.3. Stage 5: Data processing and linear regression analysis

From the actual landfill monitored settlement data, corrections were applied, such that values were estimated according to the evolution trend of each parameter. A correlation matrix was created to cross-analyze the several monitored parameters, identifying those with more significant correlations to be used in the creation of the prediction model.

From the data collected on site in T1, a Regression Analysis was made, making it possible to generate three

**Table 3** - Primary and secondary compression coefficients used.

| Author | Primary compression Coefficient ($C'c$)* | | Secondary compression coefficient ($C'\alpha$) | |
|---|---|---|---|---|
| | Minimum | Maximum | Minimum | Maximum |
| Rao *et al.* (1977) | 0.160 | 0.235 | 0.015 | 0.045 |
| Landva & Clark (1984, 1986, 1990) | 0.170 | 0.360 | 0.002 | 0.028 |
| Wall & Zeiss (1995) | 0.210 | 0.250 | 0.033 | 0.056 |
| Carvalho *et al.* (2000) | 0.175 | 0.229 | 0.0105 | 0.0116 |

(*) In the case of small scale landfills, as is the case in this paper, the primary compression coefficient is equal to zero.

Models. The Software SPSS 1.5 for Windows was used in the study, which generated model coefficients, as well as the significance of each one of them.

Armed with calculated coefficients, there was an attempt to apply the model to data collected on site in Landfills T2 and T3, in addition to verifying the applicability of the model to other landfills with similar characteristics.

## 5. Results and Discussion

### 5.1. Stage 1: Small scale landfill monitoring (T1 and T2)

Leachate monitoring results from the sanitary landfills in Presidente Lucena are presented in Table 4. Daily rainfall measured on site during the experiments varied from 0 to 59.7 mm and environmental temperature ranged between 5.1 and 34.7 °C.

Through monitoring activities, it was proven that solid waste has recently been disposed of as illustrated by organic matter yet to be degraded, as well as leachate high nutrient concentration. Heavy metals were identified according to ranges presented in Table 4.

Through the monitoring of both physical and chemical parameters, as well as settlements measured in landfills T1 and T2, the relationship between organic matter decomposition and landfill consolidation as described by the authors was delineated, thus confirming biochemical degradation as one of the mechanisms responsible for the compressibility of MSW disposed in sanitary lanfills. Figure 2 depicts a graph illustrating the relationship between COD and settlements measured in the T1 landfill in Presidente Lucena throughout time.

### 5.2. Stages 2, 3 and 4: Sower Model Application (1973) with adaptations described by Bjarngard & Edgers (1990)

The Sowers Model (1973) with adaptations described by Bjarngard & Edgers (1990) was applied to landfills T1 and T2.

Figure 3 demonstrates the graph that was generated from the input of data collected in landfill T1 in Presidente Lucena to the Sowers Model (1973) with adaptations described by Bjarngard & Edgers (1990). Both primary (equal to zero) and secondary compressibility coefficients, as well as data previously mentioned in Table 3 of this article were used. In the same graph, it is possible to observe the curve containing the actual settlement measurements taken on site.

By applying Eqs. (1) and (2) to the maximum limits of secondary compression, a complete settlement in T1 was obtained, with 441 monitoring days, equal to 0.021 m (coefficients by Carvalho *et al.*, 2000); 0.059 m (coefficients by Rao *et al.*, 1977); 0.036 m (coefficients by Landva & Clark, 1984, 1986, 1990) and 0.073 m (coefficients by Wall & Zeiss, 1995). Considering that the actual settlement measured in T1 was 0.118 m (corresponding to approximately 5% of landfill depth), the identified differences between this actual settlement and those that were estimated vary between 0.045 m and 0.097 m, which means, 38% and 82% as related to the actual settlement measured on site.

For landfill T2, the numbers varied from 0.019 m to 0.057 m, thus presenting errors of 26% and 79%, respectively.

**Table 4** - Leachate physical and chemical analyses' results from landfills T1 and T2.

| Parameters | T1 | | T2 | |
|---|---|---|---|---|
| | Minimum value | Maximum value | Minimum value | Maximum value |
| pH | 6.1 | 7.4 | 6.4 | 7.5 |
| TS | 1165.0 | 7096.0 | 1625.5 | 5763.0 |
| TSS | 63.5 | 820.0 | 82.0 | 1000.0 |
| VSS | 25.5 | 440.0 | 36.0 | 880.0 |
| COD | 152.0 | 5700.4 | 310.8 | 1574.0 |
| P | 1.3 | 401.0 | 3.5 | 265.3 |
| TN | 26.4 | 195.7 | 41.3 | 373.4 |
| AN | 23.3 | 140.8 | 34.6 | 285.4 |
| Cr | 0.1 | 0.4 | 0.2 | 0.7 |
| Fe | 32.1 | 78.9 | 44.0 | 72.8 |
| Zn | 0.1 | 1.9 | 0.1 | 0.3 |
| Cd | 0.0 | 0.9 | 0.0 | 0.0 |
| Pb | 0.1 | 0.9 | 0.5 | 1.0 |

Unit: mg/L except for pH, which has no dimension.

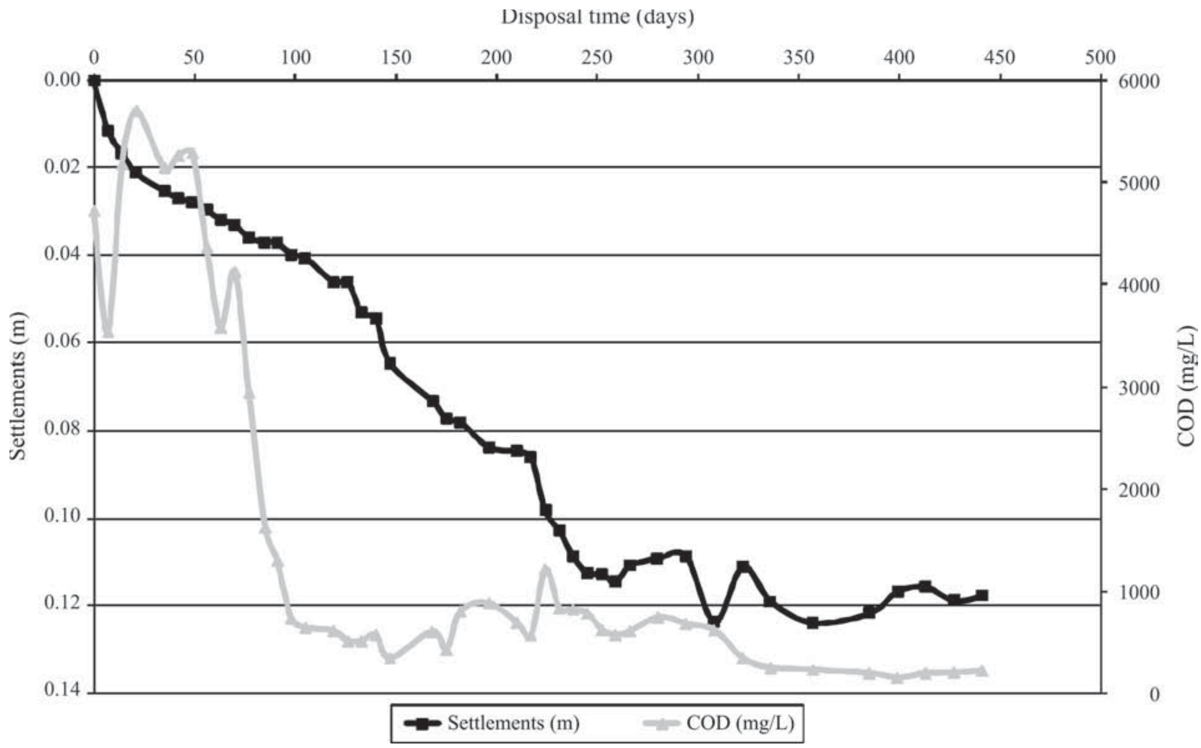
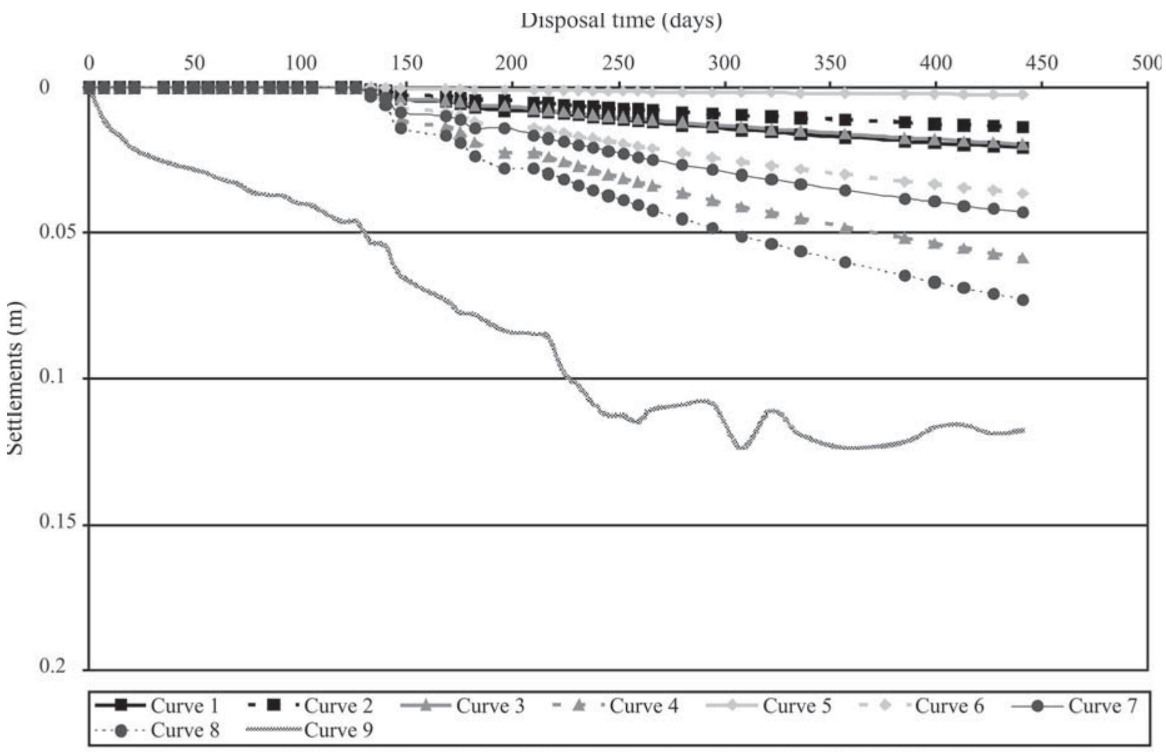



**Figure 2** - Actual Measured Settlements and COD x Disposal Time – T1 Landfill.




Curve 1: Carvalho *et al.* (2000)'s coefficient - C'α = 0.0105; Curve 2: Carvalho *et al.* (2000)'s coefficient - C'α = 0.0116; Curve 3: Rao *et al.* (1977)'s coefficient - C'α = 0.015; Curve 4: Rao *et al.* (1977)'s coefficient - C'α = 0.045; Curve 5: Landva & Clarck (1984, 1986, 1990)'s coefficient - C'α = 0.002; Curve 6: Landva & Clark (1984, 1986, 1990)'s coefficient - C'α = 0.028; Curve 7: Wall & Zeiss (1995)'s coefficient - C'α = 0.033; Curve 8: Wall & Zeiss (1995)'s coefficient - C'α = 0.056.

**Figure 3** - Settlement data collected on site in T1 and settlement prediction applying the Bjarngard & Edgers Model (1990).

On the other hand, by using secondary compression minimum coefficients, for 441 monitoring days, total T1 settlement was 0.014 m (coefficients by Carvalho *et al.*, 2000); 0.020 m (coefficients by Rao *et al.*, 1977); 0.003 m (coefficients by Landva & Clark, 1984, 1986, 1990) and 0.043 m (coefficients by Wall & Zeiss, 1995). When comparing the actual settlement to the estimate by applying the models found in the literature, it was found that errors varied from 0.075 m to 0.115 m, corresponding to approximately 64% and 98% of the total landfill settlement, respectively.

Similarly, for landfill T2, the errors varied from 0.041 m to 0.070 m, thus showing errors of 56% and 97%, respectively.

According to these analyses and the comparison with Fig. 3, with the model application, the error is higher than that which was measured on site. That may be explained due to the fact that the Presidente Lucena landfill has inferior dimensions than MSW sanitary landfills commonly found in the country (this is the case in Carvalho *et al.*, 2000 in the Bandeirantes Landfill), thus making it possible to present different primary and secondary compression coefficients from those mentioned in this research, which are then probably similar to the inferior limit of the coefficients presented in Fig. 3.

In addition, the majority of the coefficients used from the literature were determined from data from sanitary landfills in developed countries. Therefore, there is a great difference in the gravimetric composition of the disposed wastes, mainly related to the quantity of organic matter, which, in these cases, is known to be lower.

Another reason for the errors found in the model may be explained by using the work developed by Liu *et al.* (2006), which asserts that this model considers that MSW is saturated (the mean moisture content level of the wastes disposed of in sanitary landfills is approximately 60%) and that organic matter degradation produces a significant amount of gas, thus causing an increase in the consolidation degree.

Hence, this research diverges from the studies conducted by Carvalho *et al.* (2000), Park *et al.* (2007), Jucá (2003) and Bowders *et al.* (2000) in what relates to the application of such models. On the other hand, Marques (2001) demonstrated that by utilizing the model by both Bjarngard & Edgers (1990) and Sowers (1973), although presenting not exactly accurate prediction results, they were actually recommended for use in settlement prediction, after some model adjustments.

### 5.3. Stage 5: Statistical model – T1 landfill

Various data associated to on site T1 monitoring in Presidente Lucena were inputted to Software SPSS 1.5 for Windows, thus generating several models. According to the bibliography, MSW landfills are characterized by a mass of heterogeneous materials with diverse physical, chemical and biological behavior. Therefore, a data variation coefficient of 30% was considered to generate the Presidente Lucena Sustainable Landfill Settlement Model.

One of the considered variables, in addition to the usual environmental monitoring parameters (COD, total solids, nutrients (N and P)) was the landfill leachate recirculation. This is an operational alternative used in Brazil, which is considered to be a leachate treatment method. It must be emphasized that this method must be employed carefully when used in regions or seasons with high rainfall in order to avoid slope stability problems.

Five models were generated, such that models 1, 2 and 3 are linear and find themselves presented in Tables 5, 6 and 7. Two other exponential models were also tested and the obtained results expressed little adherence to the actual data. These adjustments were not considered in this analysis.

Monitoring data from landfill T1 were applied to models 1, 2 and 3 and compared to actual settlements. The errors found in each model as related to actual settlement are presented in Table 8 and were calculated by using the Minimum Square Method. Figure 4 presents the models in comparison with the actual measured settlement.

In analyzing data from Table 8 and Fig. 4, Model 2 obtained the best results, such that it was used in this re-

**Table 5** - Statistical Model 1 - based on the dependent variable "Settlement".

| Variables | Coefficients | Significance |
|---|---|---|
| Constant | -0.0149576 | 0.3328650 |
| Time | 0.0002990 | 0.0000000 |
| P | 0.0000415 | 0.0287630 |
| Av. env. temp. | 0.0005500 | 0.0850700 |
| Leachate recirculation | 0.0182998 | 0.0000059 |
| COD/TN | -0.0001339 | 0.3436450 |
| TN/P | 0.0005772 | 0.1784760 |
| TS | 0.0000035 | 0.2235130 |

$R^2$ = 0.958. Av. env. temp.: Average environmental temperature.

**Table 6** - Statistical Model 2 - based on the dependent variable "Settlement".

| Variables | Coefficients | Significance |
|---|---|---|
| Constant | -0.1359486 | 0.0035150 |
| Time | 0.0002756 | 0.0000000 |
| P | 0.0000310 | 0.0754610 |
| Leachate recirculation | 0.0173660 | 0.0000024 |
| TN/P | 0.0005716 | 0.1458620 |
| pH | 0.0220027 | 0.0016710 |

$R^2$ = 0.961.

**Table 7** - Statistical Model 3 - based on the dependent variable "Settlement".

| Variables | Coefficients | Significance |
|---|---|---|
| Constant | -0.1327638 | 0.0182800 |
| Time | 0.0002948 | 0.0000000 |
| P | 0.0000198 | 0.2224990 |
| Leachate recirculation | 0.0159054 | 0.0000122 |
| pH | 0.0202842 | 0.0163770 |
| COD | 0.0000011 | 0.3989860 |
| Av. env. temp. | 0.0003281 | 0.2974790 |

$R^2$ = 0.961. Av. env. temp.: Average environmental temperature.

**Table 8** - Theoretical Models' Estimated Error as compared to site data from landfill T1.

| Models | Sum of model errors |
|---|---|
| Model 1 | 0.002771 m |
| Model 2 | 0.002588 m |
| Model 3 | 0.002607 m |

search project to estimate settlement prediction in Presidente Lucena's sanitary landfills. The mean error obtained with the application of the statistical model was 2% (0.002588 m). This error corresponds to the difference during the entire monitoring period and not just to the last point (time = 441 days), indicating that leachate quality monitoring data applied to the proposed prediction model are the ones that must be used. It may be observed that if only the last point were evaluated, the difference between settlement measured in 441 days in landfill T1 was 0.118 m and the estimated value was 0.131 m, presenting an error of 11%. The obtained Model 2 is indicated in Eq. (3):

$$S = -0.1359486 + 0.0002756A + 0.0000310B + 0.0173660C + 0.0005716D + 0.0220027E \quad (3)$$

where $S$ = Settlement; $A$ = time (days); $B$ = Phosphorus (mg/L); $C$ = Leachate recirculation; $D$ = Total Nitrogen (mg/L) / Phosphorus (mg/L); $E$ = pH.

When comparing the obtained results to the model application presented in Eqs. (1) and (2) (errors from 38% to 82% and from 64% to 98% for the minimum and maximum compression coefficient, respectively), it may be observed that the prediction error in the statistical model was smaller. Even the best model results using secondary compression indexes by Wall & Zeiss (1995) resulted in a 38% error.

Another point that may be mentioned is that the obtained results confirm Liu *et al.* (2006), who report that larger errors may exist when the linear regression method is applied to landfills, since these authors did not consider settlement physical mechanisms, which is not the case here (small scale landfills, because of their simplified operation without intense compaction, do not need to consider such mechanisms).

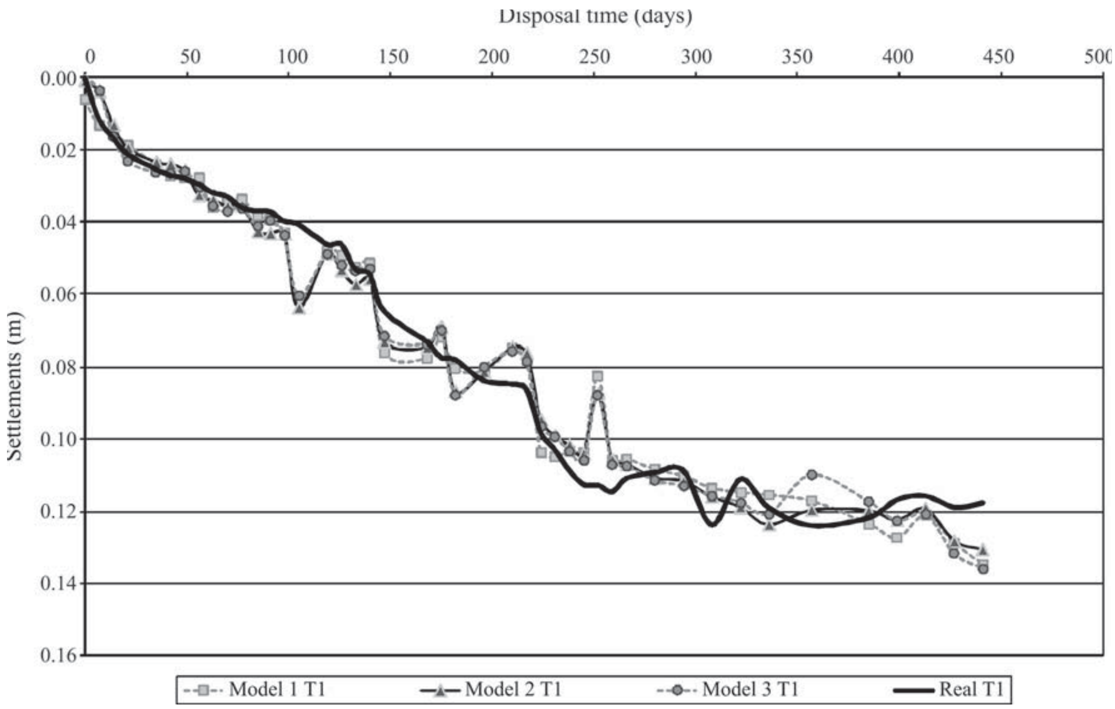



**Figure 4** - Estimated Models' Comparison with actual settlement measured in T1.

### 5.4. Stage 5: Statistical Model 2 - Application generated with data from T1 for small scale landfill T2

The application of model 2 to the on site monitored data from landfill T2 showed the possibility to use the same generated model. After 322 monitoring days at T2 (on site data collection), the mean settlement reached 0.072 m, such that the model calculated result reached a settlement of 0.103 m (difference between actual and estimate equal to 0.031 m or an error of 43% as related to the last measured point). By applying the Minimum Square Method, the error was 16% during the entire period.

### 5.5. Stage 5: Statistical Model 2 - Application generated with data from T1 for Catas Altas, Minas Gerais, Brazil – landfill

In order to verify the applicability of the generated Linear Regression Model, data from research developed simultaneously to this one in PROSAB (Basic Sanitation Research Program) research network were used. Data (reduced in number – monitoring time of 260 days, with eighteen settlement measurements, which employed a simplified on site determination method) were handed over by UFMG (State of Minas Gerais Federal University) Institutional Coordinator (Lange, 2001).

Statistical model 2 was applied to data collected on site at the small scale sanitary landfill operated by UFMG in the municipality of Catas Altas in the State of Minas Gerais. This landfill was operated in a similar fashion to Presidente Lucena landfill in the State of Rio Grande do Sul and the Catas Altas population generates waste with similar characteristics to the waste generated in the southern city.

Results showed a very significant error. For 260 monitoring days, settlement measured on site was 0.030 m, such that the model generated results presented a settlement of 0.137 m; therefore, a difference of 10.7 cm (356%).

## Conclusions

Settlement prediction models seen in the literature proved to be adequate for landfills, according to previous confirmation found in some studies. However, it is noted that such models are generic, based in Soil Mechanics studies, which fail to take some MSW specifics into consideration.

The application of these models to settlement data measured on site at small scale landfills in Presidente Lucena in the State of Rio Grande do Sul reveals significant errors, when comparing real data measured on site to predicted results, ranging from 38% to 98%.

For the case of settlement prediction in small scale landfills that operate without mechanical waste compaction both during disposal and in the preparation of the final cover layer, it is suggested that the primary compression index coefficient ($C'c$) be equal to zero.

The model generated from the statistical analysis (linear regression) proved to be more adequate in terms of prediction, showing an error of 2%.

Some conclusions can be perceived in the use of the generated statistical model:

- The generated model is also useful in estimating parameters that cannot be analyzed in the laboratory due to: malfunctioning equipment, lack of equipment, days without on site data collection, difficulties or operation costs;
- T1 model use in the other Presidente Lucena landfill (T2) showed that it is applicable to the same MSW disposal conditions;
- As for Catas Altas, it may be noted that, even though this landfill has similar characteristics to the one in Presidente Lucena, climatic differences, physical and chemical leachate parameters used in the model and equipment used in settlement monitoring may have influenced the found error; thus, in these cases, the employment of consolidated models is suggested.

The elaboration of a specific model to estimate sanitary landfill settlements, taking MSW specifics into consideration, is not an easy task to be accomplished. The use of the presented Regression Model considered such specifics and presented less significant errors in comparison to the application of on site data to the Sowers Model (1973) with adaptations described by Bjarngard & Edgers (1990).

In addition, the generated regression model is more realistic in terms of settlement prediction, although presenting monitoring time interval limits between 0 and 441 days and application only for small scale landfills such as the ones in Presidente Lucena.

## Acknowledgments

The authors thank CNPq (National Counsel for Scientific and Technological Development), PROSAB (Basic Sanitation Research Program), FINEP (Financial Aid for Studies and Projects – Ministry of Science and Technology) and Caixa Econômica Federal (governmental bank) for financing and setting the conditions for research development. The authors also thank Presidente Lucena City Hall for the possibility to obtain on site data.

In particular, we thank Professor Liséte Celina Lange from UFMG (Universidade Federal de Minas Gerais) for making Catas Altas data used in the comparative analyses of this research available.

We equally thank Professor Orêncio Monje Vilar, Ph.D. from EESC/USP (Universidade de São Paulo) for the final review and comments to this paper.

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## Symbol List

$S_{(t)}$ = settlement in time $t$
$H$ = initial layer thickness
$e_0$ = initial void ratio
$C_c$ = primary compression index
$C'c = Cc/(1 + e\, e_0)$ = primary compression index coefficient
$C\alpha$ = secondary compression index
$\sigma_0$ = initial vertical stress
$\Delta\sigma$ = increase in vertical stress
$t_{(1)}$ = time to complete initial compression
$t_{(2)}$ = time to complete intermediary compression
$t_{(3)}$ = ideal length of time to predict a settlement
$C'\alpha_{(1)}/(1 + e_0)$ = intermediary secondary compression index
$C'\alpha_{(2)} = C\alpha_{(2)}/(1 + e_0)$ = intermediary secondary compression index, in the long run
COD = Chemical Oxygen Demand
TN = Total Nitrogen
P = Phosphorus
TS = Total Solids