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A new model for immediate settlement predictions in landfills

Un nouveau modèle pour des prévisions de règlement immédiats en remblais de résidus

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ABSTRACT
This paper presents a new model to predict the immediate settlements in sanitary landfills based on research conducted at the University of New Orleans (UNO). Compressibility tests in Municipal Solid Wastes (MSW) were performed at the UNO Geotechnical Laboratory using a large-dimension chamber specifically designed for wastes. The model is essentially hyperbolic and has only 2 parameters, which are easily determined. These parameters have physical meanings and are strongly dependent on the initial unit weight of the waste. The model can be easily used with the Hyperbolic Model for MSW long-term compression presented by Ling et al.(1998) for a complete rheological model capable of estimating the final settlements of landfills. A comprehensive discussion about the use of soil mechanics classical models to MSW is also presented.

RÉSUMÉ
Cet article présente un nouveau modèle pour prévoir les tassements immédiats en remblais sanitaires basés sur la recherche conduite à l'University of New Orleans (UNO). Des essais de compressibilité dans les déchets solides municipaux (MSW) ont été réalisés au laboratoire géotechnique d'UNO en utilisant une chambre de grand-dimension spécifiquement conçue pour des déchets solides. Le modèle est essentiellement hyperbolique et a seulement 2 paramètres, qui sont facilement déterminés. Ces paramètres ont des significations physiques et dépendent fortement du poids spécifique initial de déchets solides. Le modèle peut être facilement employé avec le modèle hyperbolique pour la compression à long terme de MSW présentée par Ling et al.(1998) pour un modèle rhéologique complet capable d'estimer les tassements finals des remblais. Une discussion complète au sujet de l'utilisation des modèles classiques de mécanique de sol à MSW est également présentée.

1 INTRODUCTION

Land disposal has been the most common method of disposal for solid wastes throughout the world, particularly for Municipal Solid Wastes (MSW). The scarcity of new potential disposal areas produces higher and higher landfills and in order to utilize the maximum capacity of those areas, it is necessary to understand the importance of the geotechnical characteristics of solid wastes. In this context, knowledge of the compressibility of waste landfills represents a powerful tool to evaluate alternatives for optimization of old, present, and future disposal areas, as well as for the development of new solid waste technologies.

Although the mechanisms that generate settlements in Municipal Solid Waste (MSW) landfills are well known, a complete model for settlement prediction is not current available for Landfill Engineers. In general, classical soil mechanics compressibility theories are commonly used for waste settlement prediction throughout the world; however, they have several deficiencies when used for MSW (de Abreu, 2000). Other formulations that take into consideration several of the waste settlement mechanisms (e.g., Zimmerman et al., 1977) are extremely complex and require as input an extensive number of uncommon parameters to be determined; therefore, they are very difficult to apply in practice.

The prediction and monitoring of waste landfill settlements, as well as the associated settlement rates, are important for the estimation of the lifetime of landfills, reuse after landfill closure, design and implementation of hydraulic structures and drainage systems, geotechnical monitoring, and final cover performance.

In non-active landfill cells, where immediate settlement has already occurred, the calculation of immediate settlements sometimes may be unnecessary (but not always) depending on the case analyzed. It must be noted that in several instances, as for example, in the vertical expansion of landfills, where the new waste is considered as a load to the existing waste, the immediate compression must be taken into consideration. Other examples of necessity for immediate compression calculations are the cases of stocking of soil for cover or construction of structures over existing landfill cells.

2 CRITICISM OF THE CLASSICAL MODEL AS APPLIED TO MSW

Even though logarithmic formulations similar to the primary and secondary consolidation expressions used in Classical Soil Mechanics are often used as models for MSW settlement estimates and prediction, they have several deficiencies when utilized for MSW (de Abreu, 2003). Some of these deficiencies are presented in the following paragraphs.

The classical model hypotheses adopted for soils are not adequate for MSW. One may note that in the development of Terzaghi's classical theory, some simplified hypotheses are adopted that do not always satisfactorily model the MSW behavior. The hypotheses include complete saturation, homogeneous incompressible solid particles, independence of some of the properties from increasing or decreasing effective stress, one-dimensional compression, one-dimensional flow, and a linear relationship between stress and void ratio (Taylor, 1948). Therefore, the classical model applied to MSW must be understood as an empirical adjusted model, since it does not represent the phenomenon that occurs in reality. In representing the secondary compression, the coefficient of secondary compression parameter is not constant with even the logarithm of time. Also, there are difficulties in establishing what the MSW initial thickness is (especially in old landfills), necessary to the formulation.

The division of settlement phases into the classic initial, primary, and secondary settlements causes confusion, since it is not compatible with the MSW settlement mechanisms. This deficiency can be noted more when the initial and primary compressions are modeled together. The primary compression is determined by an expression in which there is no time variable, and must be used as a final value; however, it is considered to last 30 days (Sowers, 1973), and it is just a reference value. In practice, it is difficult to isolate the primary compression from secondary compression because, unlike most soils, MSW has no clear distinction in the settlement curve as a function of time for the two processes (de Abreu, 2000; Marques, 2001).

Furthermore, the definition of the time for the end of the primary compression stage is somewhat vague. Similarly, authors have utilized different approaches in the consideration of the initial waste thickness: the thickness at the beginning of instrumentation (Carvalho, 1999) or the thickness after the conclusion of primary compression (Morris and Woods, 1990). The great majority of authors do not explain which thickness should be used. Therefore, the same data can furnish different values for the coefficient of secondary compression, depending on the initial thickness adopted.

Regarding the immediate compression of MSW (sometimes referred as “initial compression”, and sometimes as “primary compression”), it is also shown that the coefficient of primary compression is not constant in a logarithmic scale, since the strain versus log-stress relationship becomes nonlinear at high stress levels (Rao et al., 1977). Therefore, the use of logarithmic functions to describe the immediate compression of MSW may not be adequate, as will be discussed in Section 3.2.

3 MSW COMPRESSIBILITY TESTS

Several MSW compressibility tests have been performed under different conditions at the UNO using a large-dimension chamber specifically designed for solid wastes. The main purpose of the tests was to evaluate the MSW compressibility in order to predict immediate settlements due to loading.

3.1 *Equipment description and test set-up*

The equipment fabrication and experimental set-up was done at the Geotechnical Engineering Laboratory of the Department of Civil and Environmental Engineering, UNO. The chamber is 61 cm in diameter and approximately 120 cm tall with a blind flange at the bottom and open at the top. The main body of the chamber is made of PVC pipe with 1.9 cm thick walls. The base of the chamber supports the overall test chamber. It is made of a PVC ring, closed at the bottom, 61 cm in diameter (external), 15 cm high, and 1.9 cm thick. The PVC ring was attached to the chamber by aluminum angles at two points. A steel loading frame was used to hold the test chamber and as a reaction for the hydraulic jack during the application of load. Two types of hydraulic jacks were used for applying load to the samples, depending on the load capacity needed. This included one jack system with a 200 kN capacity (100 kN in each ram) and a second with a 500 kN (250 kN in each ram) capacity. Figure 1 presents a schematic of the compressibility test set-up.

The chamber was prepared for each test by placing a 5-cm thick layer of coarse sand at the bottom of the chamber and putting a geotextile fabric immediately over it to isolate the sand from the waste. A layer of approximately 75 cm (divided in four sub-layers of 20 cm or less) of MSW was placed in the chamber. Compaction was applied by tamping with a wooden block, which made the surface of each sub-layer horizontal. Another piece of geotextile fabric was placed over the final layer of waste. After filling the chamber with the MSW, a pair of PVC and steel circular plates was placed on top of the geotextile.

The loading device (pair of hydraulic jacks) was positioned between the steel plate and the frame and the load was applied slowly. Successive increments of load were applied to the waste with measurements of the displacement of the plates. The vertical displacements of the plates were measured in three points from the top of the chamber with a ruler with a resolution of 1 mm. The load pattern (total stress applied to the MSW) for the compressibility tests was typically 5, 10, 20, 25, 50, 100, 150, and 350 kPa. Settlement measurements were taken immediately after each load level was reached.

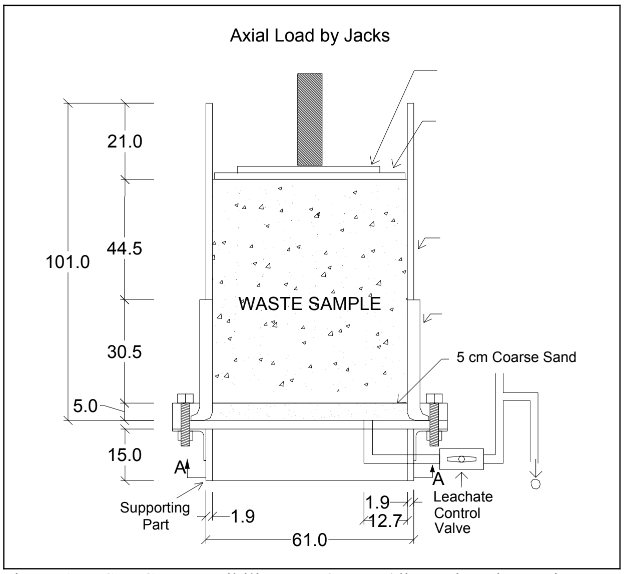

Figure 1. MSW Compressibility Test Set-up (dimensions in centimeters; not to scale)

Tests were performed utilizing old and new real MSW samples collected from the Tangipahoa Regional Solid Waste Facility in Louisiana as presented by Debnath (2000). Tests were also performed using artificial MSW prepared according to the United States average composition (U.S. EPA, 2000) under dry and wet conditions.

3.2 *Results*

Figure 2 presents the stress-strain pattern for the test utilizing artificial waste prepared under dry conditions. Similar patterns were observed for all other tests.

As presented by Rao et al. (1977), at high values of stress, the strain versus log-stress curve is non-linear. This was also noticed in these tests, and is quite logical since at some point the curve must become inflected, otherwise the strain could be greater than 100%, which is not physically possible. The same observation applies at very low values of stress, leading to a conclusion that the coefficient of primary compression is not constant and is dependent on the stress applied. The use of a coefficient that is not constant for modeling the compressibility of MSW at values greater than 200 kPa, a stress level reached in landfills with a depth greater than approximately 20 m appears not to be reasonable, or, at least, not practical.

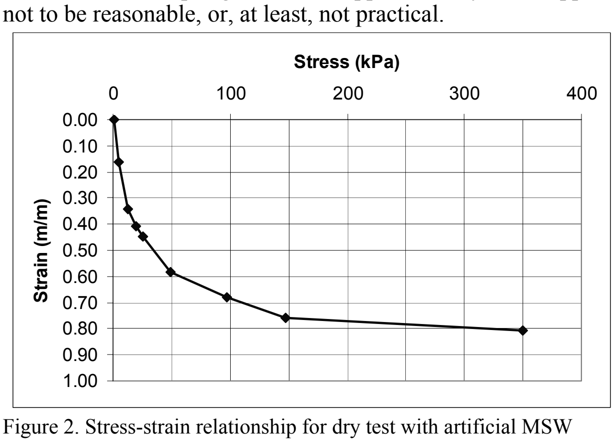

Figure 2. Stress-strain relationship for dry test with artificial MSW

3.3 *Hyperbolic Model for MSW immediate settlements*

In a first approach, the data were modeled using different mathematical functions. When the data were plotted as stress divided by strain versus the stress (or a hyperbolic-type curve), a strong linear relationship was observed. This was not a surprise since the two variables plotted (x and y axes) are not independent, but help in the study of the significance of the parameters of the curve, as will be shown further. Figure 3 presents the graph of stress-to-strain ratio as a function of stress for the dry test. The results for other tests follow similar patterns.

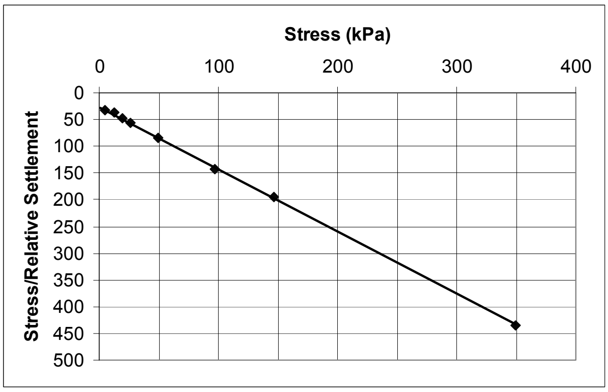

Figure 3. Stress to strain ratio as function of stress for the dry test

The same procedure was applied to other data published in the general literature. The studies of Debnath (2000) and Carvalho (1999) were added to the present study to understand the immediate settlement mechanism of MSW. Both studies utilized compression chambers to study the MSW compressibility. In all cases, the stress-to-strain ratios as functions of stress were straight lines. Therefore, it is reasonable to conclude that the MSW immediate settlement can be expressed as:

$$\frac{\sigma_v}{\varepsilon} = a \cdot \sigma_v + b \qquad (1)$$

where σ_v is the total vertical stress at the middle of the layer , ε is the strain and a and b are the constants of the linear curve. Since the strain can be written as the ratio between the settlement and the initial thickness of the layer, Equation 1 can be expressed as:

$$\Delta H_i = \frac{\sigma_v \cdot H_0}{a \cdot \sigma_v + b} \qquad (2)$$

where ΔH_i is the immediate settlement and Ho is the initial thickness layer (assuming the stress at the middle of waste layer equal to zero).

If the initial thickness under compression and initial stress are taken into account, Equation 2 can be represented by a more specific expression, as shown in Equation 3.

$$\Delta H_i = \frac{H_e \cdot \sigma_v \cdot (a \cdot \sigma_{ve} + b)}{[(a-1) \cdot \sigma_{ve} + b)] \cdot (a \cdot \sigma_v + b)} - \frac{\sigma_{ve} \cdot H_e}{(a-1) \cdot \sigma_{ve} + b} \qquad (3)$$

where σ_{ve} is the initial stress at the middle of the waste layer before compression and H_e is the respective initial thickness of the waste layer before compression.

Figures 4 and 5 present the compressibility parameters "a" and "b" as a function of the MSW initial weight utilizing the studies selected.

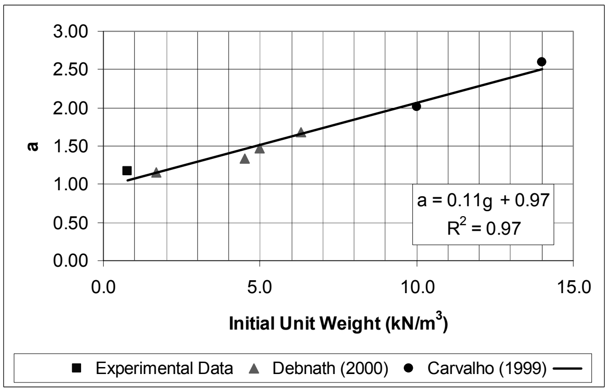

Figure 4. Graph of variation of parameter "a" with the initial unit weight

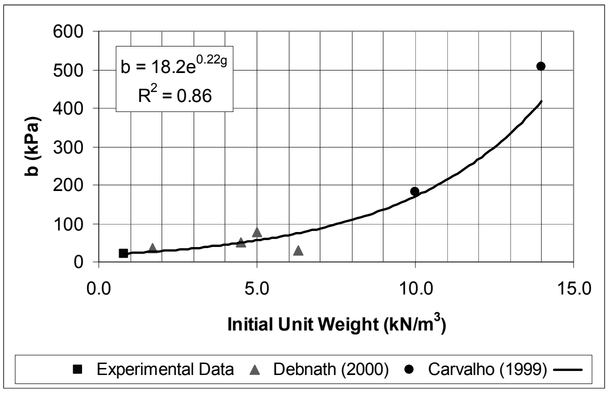

Figure 5. Graph of variation of parameter "b" with the initial unit weight

The parameter "a" can be physically understood as a "nonlinear spring coefficient" and the lower its value, the softer the material. Parameter "b" controls the initial stress-strain ratio (at stress = 0), and the lower the initial unit weight, the lower its value.

It is clear that the initial unit weight plays an important role in the immediate compressibility of MSW. From the tests with wastes under dry and wet conditions, no significant differences could be noticed.

It must also be noted that the model can be used for immediate settlements representing the immediate waste deformation due to load application, and therefore, for computation of total landfill settlement it must be utilized in conjunction with a long-term settlement (time-dependent) model as, for example, the Hyperbolic Model of Ling et al. (1998) based on the method of Tan et al. (1991) for soils.

3.4 *Verification of the Hyperbolic Model for immediate settlements*

An example is presented herein to verify the applicability of the new model. Utilizing the data from the Bandeirantes Landfill, located in Sao Paulo, Brazil, the compressibility of one test cell was evaluated. The sequence of construction of the cell was monitored by topographic survey and is described herein as presented by de Abreu (2000). After placement of 4.5 m of compacted MSW, a 0.5-m soil cover was placed at the top of the cell as schematically presented in Figure 6. Immediately (within a one-minute time frame) after the surcharge application (represented by the soil cover), the settlement of the cell was measured and was equal to 20 cm. The soil cover has a unit weight of approximately 15 kN/m^3 (according to the landfill operation procedures), and the initial unit weight of the compacted waste was assumed to be approximately 7 kN/m^3 (according to studies performed by Marques (2001), who conducted MSW field compaction tests in the same landfill). For this unit weight, the resulting MSW compressibility parameters are approximately a=1.74 and b=84.9 kPa when the equations presented on Figures 4 and 5 are applied. Calculations of the vertical effective stresses at the middle of waste layer for initial and final (after immediate compression) situations are shown on Figure 6.

The calculated settlement utilizing the model equation (Equation 3) for the weight parameters assumed and compressibility parameters determined above is approximately 24 cm, indicating that the predicted settlement was reasonably close to the observed settlement. The foundation settlement was considered negligible, since the landfill foundation is composed of a strong residual soil. The waste self-weight settlement can also be considered negligible, since waste compaction was performed before surcharge placement and because very short periods of time elapsed between the end of waste compaction and cover placement, and between cover placement and settlement measurement.

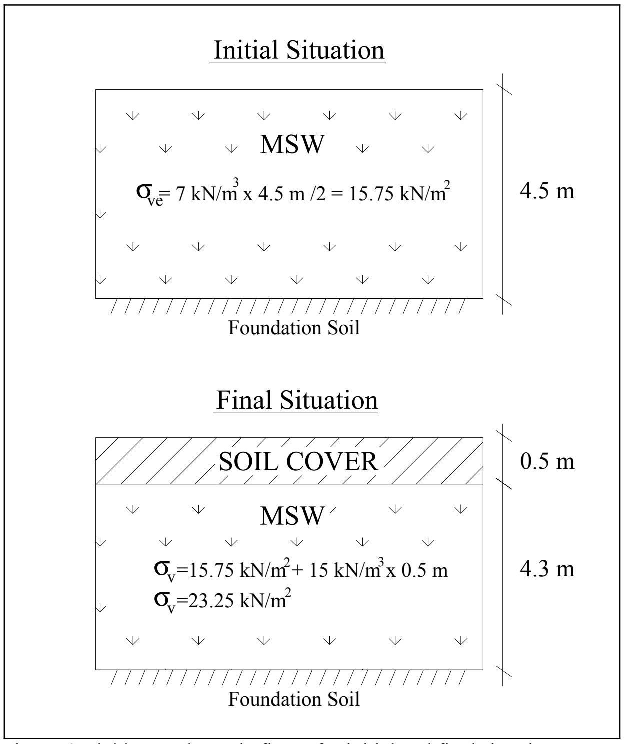

Figure 6. Field test schematic figure for initial and final situations

4 CONCLUSIONS

Based on the results obtained and analysis effectuated for the study of MSW compressibility, some conclusions can be drawn:

- The use of classical Soil Mechanics formulation to describe the compressibility of MSW is not adequate, primarily due to the fact that the settlement mechanisms of soils and MSW are different. In addition, even when the model is understood as an empirically adjusted model, it still presents several deficiencies.
- A division of MSW settlements into two categories, immediate and time-dependent, is more understandable than the traditional division of primary and secondary compressions.
- Using compressibility tests performed in this and other studies, it was determined that the immediate settlement can be modeled as a hyperbolic function of stress.
- Although it was shown that the model can adequately calculate immediate settlement in landfills, additional research is necessary, since the model considers only the case of a uniform, infinite load applied to the top of the waste. This consideration is valid for the center parts of a landfill, but not for the edges. However, when computing the solution for a finite load, it must be noted that the application of the Boussinesq theory to MSW is questionable since it is based on the theory of elasticity.

REFERENCES

Carvalho M. F. (1999), Municipal Solid Waste Mechanical Behavior, Thesis submitted to the Universidade de Sao Paulo in partial fulfillment of the requirements for the degree of Doctor in Geotechnics, Sao Carlos, Brazil (in Portuguese).

de Abreu R. C. (2000), Compressibility of Waste Landfills, Dissertation submitted to the Universidade de Sao Paulo in partial fulfillment of the requirements for the degree of Master in Engineering, Sao Paulo, Brazil (in Portuguese).

de Abreu, R. C. (2003), Facultative Bioreactor Landfill: An Environmental and Geotechnical Study, Dissertation submitted to the Graduate Faculty of the University of New Orleans in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Engineering and Applied Sciences Program, New Orleans, Louisiana.

Debnath D. K. (2000), Vertical Expansion of Landfills, Thesis submitted to the Faculty of the University of New Orleans in partial fulfillment of the requirements for the degree of Master of Science in Engineering, New Orleans, Louisiana.

Ling H. I., Leshchinsky D., Mohri Y. and Kawabata T. (1998), Estimation of Municipal Solid Waste Landfill Settlement, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol. 124, No. 1, pp. 21-28.

Marques A. C. M. (2001), Compaction and Compressibility of Municipal Solid Wastes, Thesis submitted to the Universidade de Sao Paulo in partial fulfillment of the requirements for the degree of Doctor in Geotechnics, Sao Carlos, Brazil (in Portuguese).

Morris D. V. and Woods C. E. (1990), Settlement and Engineering Considerations in Landfill and Final Cover Design, Geotechnics of Waste Fills - Theory and Practice, STP 1070, Landva and Knowles (eds), ASTM, West Conshohocken, Pa., pp. 9-21.

Rao S. K., Moulton L. K. and Seals R. K. (1977), Settlement of Refuse Landfills, Geotechnical Practice for Disposal of Solid Waste Materials, ASCE, Reston, Va., pp. 574-598.

Sowers G. F. (1973), Settlement of Waste Disposal Fills, Proceedings Eighth International Conference on Soil Mechanics and Foundation Engineering, Moscow, pp. 207-210.

Tan T., Inoue T. and Lee S. (1991), Hyperbolic Method for Consolidation Analysis, *Journal of Geotechnical Engineering*, ASCE, Vol. 117, n° 11, 1991, pp. 1723-1737.

Taylor D. W. (1948), *Fundamentals of Soil Mechanics*, John Wiley and Sons, 1948, pp. 225-226.

U.S.EPA (2000), Municipal Solid Waste Generation, Recycling and Disposal in the United States: Facts and Figures for 1998, EPA Publication EPA530-F-00-024.

Zimmerman R. E., Chen W. W. H. and Franklin A. G. (1977), Mathematical Model for Solid Waste Settlement, Geotechnical Practice for Disposal of Solid Waste Materials, ASCE, Reston, Va, pp. 210-226.