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A composite compressibility model to investigate the settlement of an existing MSW landfill

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ABSTRACT

In this work, a composite compressibility model has been developed to investigate the settlement of Municipal Solid Waste (MSW) in an existing landfill in Belgium. Instantaneous response to load, time-dependent mechanical creep, and time-dependent biological decomposition of the waste are three essential concepts for developing the model. The model parameters are based on laboratory one-dimensional compression tests, topographical measurements using a drone data acquisition system, and note that the data available at the Pollux Consulting Database from published literature and experience. Parameter values for the MSW at the landfill were obtained by nonlinear regression analysis. Furthermore, due to biological waste decomposition, landfill gas is produced as a result of a sequence of physical, chemical, and biological processes occurring within an anaerobic landfill. Based on the specific composition of the waste and the individual biological landfill gas potential values of the different waste streams, one can calculate the specific biological landfill gas potential value of a landfill. Our investigations showed that the application of the composite model requires five parameter values and knowledge of the history of waste placement. Depending on the amount of information available for a particular landfill under consideration, the parameter values can be adjusted to provide the best fit with the available data. Moreover, the biogas potential depends on the number of organics and the amount of carbon in the organic material. External factors play a crucial role in biodegradation kinetics, such as temperature, rainfall, compaction of the waste, and filling technique.

Keywords: Compressibility, Municipal Solid Waste (MSW), landfill, composite model, nonlinear regression analysis

1 INTRODUCTION

Municipal solid wastes (MSW), including trash, are a highly non-homogeneous mixture of residential, commercial, and industrial sectors. Regular residential and commercial MSW contain clothing, disposable tableware, yard adornments, cans, office staff, paper, and boxes. In contrast, institutional and industrial MSW involves restaurant trash, paper, classroom wastes, wood pallets, plastics, corrugated boxes, and office papers. Although the composition of MSW could be highly variable, there is a broad consensus that organic materials are the most significant component of MSW.

The fast increase of MSW leads to an impressive challenge to sustainable global development. If this waste is not treated correctly, it will yield pollution in rivers, lakes, oceans, and air, entertain extensive zones including farming land, destroy the urban landscape, sweep illnesses through vectors, and exposes a threat to human health and survival (Srivastava et al., 2016).

World Bank statistics reveal that the world generated about 2.01 billion tons of MSW in 2016. It is predicted to get 3.4 billion tons per year by 2050, with MSW generation seriously outpacing population growth by more than twice as much (Kaza et al., 2018). Around the world, almost 37% of global MSW has been managed in the form of landfills (out of which 8% in sanitary landfills), followed by 33% to dump sites, 19% through recycling and composting openly, and the remaining 11% treated by thermal and WtE facilities.

At present, landfill is still the most common and cost-effective treatment method for MSW worldwide (Machado et al., 2009; Chen et al., 2012; Wong et al., 2013; Reddy et al., 2017; Feng et al., 2019; Kumar and Reddy, 2019) which lined landfills provide for economical and environmentally safe disposal. However, it can be challenging to discover new landfill sites due to regulatory constraints, contending demands for land use, and/or public resistance. Thus, it is necessary to maximize the storage capacity of current landfills by intense compression, leachate recirculation to improve biodegradation, and other compromises. In this work we consider the capability to indicate waste compression during the active life of a landfill that is an essential mechanism for landfill administrators. Furthermore, post-closure use of landfilled areas often requires prediction of primary settlements in reaction to surcharge loads and resuming settlements due to mechanical creep and biological decomposition procedures.

Several approaches and efforts were applied to study and calculate the processes and factors that effects on the compression of municipal solid waste. Several studies (Sowers, 1973; Yen and Scanlon,1975; Zimmerman et al.,1977; Bjarngard and Edgers,1990; Edil et al., 1990; Edgers et al., 1992; Gandolla et al.,1992; Diaz et al.,1995; Van Meerten et al., 1995; Coumolous and Koryalos, 1997; Park and Lee, 1997; Ling et al., 1998; Gabr et al., 2000; and Leonard et al., 2000) showed that three important mechanisms of MSW compression can be introduced: (1) immediate response to applied loading, (2) time-dependent mechanical creep, and (3) biological decomposition of the waste.

While investigations of these approaches address at least one of three mentioned important mechanisms of MSW compression, none of them incorporates three separate expressions to explicitly account for all three mechanisms of MSW compression.

In this work, we implement three mechanisms of MSW compression for one of the Belgium landfills. Similar to (Marques et al, 2016) measurements of compression of a test fill at the landfill and of the underlying MSW were made over a 12-year period. Note that, in the time of model calculation the data form the year 2008 until 2019 were in access. These data provided a good opportunity to assess the performance of existing models for landfill compression, and to develop a composite model for one-dimensional compression of MSW that explicitly comprises all three mechanisms of landfill compression. This paper also displays a description of the potential biogas generations that depends on the number of organics and the amount of carbon in the organic material.

As the global waste characterization has been mentioned above, it is also worthwhile to have the waste composition data of the study place in Belgium. Here below in **Figure 1**, the data has been drawn. As you can see, the data belongs to the year 2009 to 2021. As it can be seen, organic waste mostly contributes to the waste composition.

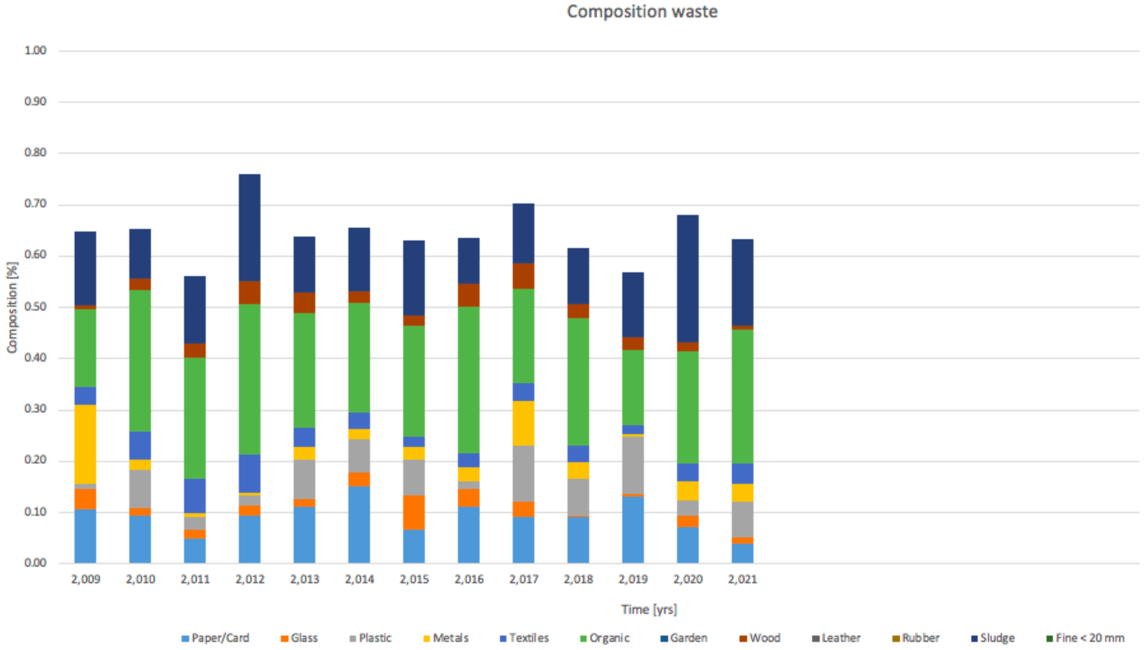

Figure 1 Here it has been showing the MSW composition in Belgium. The data has been acquired from Pollux Consulting Database.

The composite compressibility model is a mathematical framework that characterizes the consolidation response of landfill waste, considering the influence of both the waste compressibility and the biological degradation on settlement.

To apply the model, one must collect the subsequent input parameters:

1. Landfill Parameters, including a time history of landfill filling represented by lift heights (ΔHi) over time (ti), reflecting the gradual waste accumulation. Additionally, you should measure the waste unit weight (ɣi), which is the product of the waste density and acceleration due to gravity. As the composition of the waste changes, the waste unit weight may also vary over time.
2. Waste Parameters, comprising the compressibility coefficient (C'c), a measure of the waste material's compressibility obtained from laboratory testing. Furthermore, the biological degradation settling (E_{DG}) accounts for the impact of biological activity on waste settlement, and you can estimate it based on the landfill environment and waste composition.
3. Fitting parameters, namely b, c, and d, are empirical fitting parameters used to adjust the model to the experimental data. You can determine these parameters by curve fitting.

Those parameters are all together five, in summery compressibility coefficient (C'c), biological degradation settling (E_{DG}) and fitting parameters, namely b, c, and d. After collecting these input parameters, those can be applied in an appropriate equation that is drawn in the following text to calculate the landfill's settlement over time using the composite compressibility model. The model's outcome will be a prediction of the landfill's settlement, which is valuable for planning future waste disposal activities and assessing the landfill's long-term stability.

2 MODEL SETUP

2.1 Composite Compressibility Model for MSW

Instantaneous response to load, mechanical creep, and biological decomposition are the main mechanisms of the one-dimensional compression of MSW proposed by (Marques et al, 2016). Consequently, we follow this approach and the strain of the MSW is expressed as

$$\in = \in_P + \in_C + \in_B \tag{1}$$

where the strain is due to all three mechanisms, $\in_P$ is the strain resulting from instantaneous response to the applied load, $\in_C$ is the time-dependent strain due to mechanical creep, and $\in_B$ is the time-dependent strain due to biological decomposition. The Results of strain from an immediate reaction to surcharge loading is suggested as

$$\in_P = C_C' \log \frac{\sigma_0 + \Delta\sigma}{\sigma_0} \tag{2}$$

where C_C' is the compression ratio, σ_0 is the initial vertical stress and $\Delta\sigma$ is the change in vertical stress. The mechanical creep leads to a time-dependent strain which can express as

$$\in_C = b(\Delta\sigma)\left(1 - e^{-ct'}\right) \tag{3}$$

where b is the coefficient of mechanical creep, c is the rate constant for mechanical creep, and t' is the time since application of the stress increment, $\Delta\sigma$. Since biological decomposition varies concerning time, thus it leads to a time-dependent strain as follows.

$$\in_B = E_{DG}\left(1 - e^{-dt''}\right) \tag{4}$$

where E_{DG} is the total amount of strain that can occur due to biological decomposition, d is the rate constant for biological decomposition, and t'' is the time placement of the waste in the landfill.

2.2 Implementation of the Composite Model

In landfills, MSW layers usually overlay vertically year by year. In executing the composite model represented by Eqs. (1)– (4), waste displacement is idealized as going in a series of lifts as displayed in **Figure 2**.

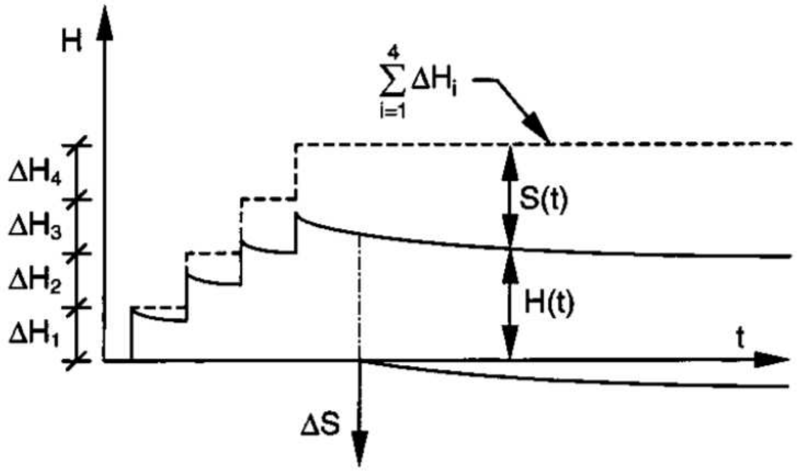

Figure 2 The schematic of the composite model response. The plot is reproduced from the paper (Marques et al, 2016)

The lifts' thickness may be identical to the compressed thickness of the day-to-day cells. After all, lifts have been overlied, the settlement, S, of the landfill surface at time, t, is provided by.

$$S(t) = \sum_{i=1}^{N} \Delta H_i\left[\in_{P,i} + \in_{C,i}(t) + \in_{B,i}(t)\right] \tag{5}$$

where N is the number of the lift in the landfill, ΔH_i is the initial thickness of compacted lift i. $\in_{P,i}$ is the strain in lift i resulting from immediate response to loading from overlying lifts that is defined as

$$\in_{P,i} = C'_C \log\left(\frac{\frac{1}{2}\gamma_i \Delta H_i + \sum_{j=i+1}^{N}\Delta\sigma_{i,j}}{\frac{1}{2}\gamma_i \Delta H_i}\right) \tag{6a}$$

where γ_i is the unit weight of lift i, $\Delta\sigma_{i,j}$ is the increment of vertical stresses imposed by lift j on lift i for $j > i$. In Eq. (5) the $\in_{C,i}$ can be calculated through

$$\in_{C,i}(t) = b\left[\frac{1}{2}\gamma_i \Delta H_i\left(1 - e^{-c(t-t_i)}\right) + \sum_{j=i+1}^{N}\Delta\sigma_{i,j}\left(1 - e^{-c(t-t_j)}\right)\right] \tag{6b}$$

and $\in_{B,i}$ is the strain at time t in lift i which is led by biological decomposition of lift i expressing through the following form.

$$\in_{B,i}(t) = E_{DG}\left(1 - e^{-d(t-t_i)}\right). \tag{6c}$$

A time history of filling and constant parameter values of the model in Eqs. (5) and (6) are the main part of the implementation of the composite compressibility model, which are obtained in the next section.

2.3 Biogas generations

The biogas emission forms by the anaerobic digestion procedure of high organics samples that is predominantly influenced by its organic loadings, temperatures, retention time in the reactors, pH, and the degree of contact between the incoming substrate (feed slurry) and a feasible bacterial population. The explicit anticipation of the producible biogas quantity and its methane content is one of the essential characteristics of an anaerobic digester. The chemical compositions of a feedstock determine the potential biogas products and the gas composition as well.

The production of biogas in a landfill is influenced by several factors, including the composition of waste, conditions in the waste body, temperature, moisture content, leachate quality, fractioned waste, and drainage facilities. Waste with higher organic content will produce more biogas, and the conditions in the landfill affect the kinetics of the biodegradation process that produces biogas. Temperature, moisture content, and leachate quality also impact biogas production. Proper drainage facilities and sorting of waste into different fractions can help increase biogas production. Collecting biogas from landfills requires the use of vertical wells or shafts to capture the gas. The efficiency of biogas production varies depending on the aforementioned factors, and the collection system must be isolated from the landfill environment to prevent gas release. The number and placement of collection wells must be sufficient to capture the biogas produced, and a piping network must be in place to carry the gas to a treatment or utilization system. The piping network must allow for free flow of biogas without obstruction or pressure buildup.

Biogas production models are utilized to assess the potential quantity of biogas that a landfill can generate. The models employ two key parameters: the biological landfill gas potential (BLP) value and the K-value. The BLP value is connected to the waste type and is a fixed value that is not affected during landfilling. It is established on the waste's chemical composition, particularly the amount of organic matter it contains. Waste with higher organic content generates more biogas due to its higher BLP value. The K-value, on the other hand, depends on the waste type and landfill conditions and is influenced by factors such as moisture content, compaction, and temperature. It is a kinetic aspect of biogas production that can be affected during landfilling. The K-value is employed to predict the rate of biogas production over time. Biogas production models are useful in determining the amount of biogas that a landfill will generate over its lifespan. This information aids in the design and management of biogas collection systems.

To determine the potential biogas production from a landfill, use the formula:

$BGP = (BLP \times W \times K \times V) / (M \times L)$

Here, BGP represents the potential biogas production in cubic meters per year. BLP is the biological landfill gas potential in cubic meters per kilogram. W denotes the waste input in kilograms per year. K represents the degradation constant in inverse years, which can be influenced by factors such as temperature, compaction, and moisture content. V is the landfill volume in cubic meters. M is the molecular weight of $CH4$ in grams per mole, and L is the landfill life in years. The BLP value is determined by the type of waste and remains constant during landfilling. In contrast, the K-value can be influenced by landfill circumstances and waste type. Accurate estimation of potential biogas production requires consideration of both parameters.

The Chian-De Walle-Hammerberg (CDW) model is a simplified empirical model that correlates the biological landfill gas potential (BLP) to the volatile solids content and chemical oxygen demand (COD) to volatile solids (VS) ratio of the waste (Chian et al., 1975). The model does not involve a specific chemical reaction.

However, the underlying biochemical reactions that occur during anaerobic digestion of organic waste in landfills involve a complex series of microbial processes that convert organic matter to biogas, primarily composed of methane ($CH4$) and carbon dioxide ($CO2$). These reactions are mediated by various groups of microorganisms, including hydrolytic bacteria, acidogenic bacteria, acetogenic bacteria, and methanogenic archaea, and are influenced by various factors such as pH, temperature, moisture content, and nutrient availability (Møller et al., 2002). The stoichiometry of these reactions can be described by a series of chemical equations, but the actual reactions and rates may vary depending on the specific conditions of the landfill.

The simplified reaction model, also known as the Chian-De Walle-Hammerberg (CDW) model, for predicting the biological landfill gas potential (BLP) is expressed as follows:
BLP = S/(1.42 x 10^-4 x (1 + 1.29 x R)) where BLP is the biological landfill gas potential in m^3/kg volatile solids, S is the volatile solids content of the waste in kg/m^3, and R is the ratio of the waste's chemical oxygen demand (COD) to its volatile solids (VS) (Chian et al., 1975). It should be noted that the CDW model assumes a specific composition of the waste, which may not be representative of all landfill wastes. Therefore, it is recommended to validate the model with actual landfill data before applying it to a specific case.

The results of elemental analyses showed the chemical composition of the feed used in this study to be $C_vH_wO_xN_y$ (Kreith & Tchobanoglous, 2002). An empirical equation, Eq. (7), was used to calculate the biogas production in anaerobic digestion.

$$C_{15}H_{21}O_6N + 7H_2O \rightarrow 8CH_4 + 7CO_2 + NH_3 \tag{7}$$

The rate at which biogas is created in an MSW landfill does not stay over time constant. The time-dependent evolution of the biogas generation rate in landfills can be determined from different mathematical approaches for instance by kinetic reaction formula as

$$\frac{dC}{dt} = kC^n \tag{8}$$

where the k is the kinetic reaction constant.

3 RESULTS AND DISCUSSIONS

In this work, the Weighted Nonlinear Least Square (WNLS) method was used in model calibration, as shown in Eq. (9)

$$\sum_{i=1}^{n} W_i \left(S_i(t) - S_i^{Obs}(t)\right)^2 \tag{9}$$

where W_i is the weight factor for experimental (observation) data. Calibration for each parameter mentioned in Eqs. (5) and (6) was obtained using observation data, as calibration targets, in the landfill's settlement. The optimized parameter values are listed in Table 1.

Table 1. Parameters used in Eqs. (5) and (6)

Constants	C'_C	E_{DG}	c	b	d
Values	3.23E-03	12.2882	0.001478	0.012352	2.55E-05

In this work the parameters such as initial thickness of compacted lift (ΔH_i) and the total amount of strain that can occur due to biological decomposition E_{DG}, are set as 3.5 and 0.00087 respectively for the studied landfill. In **Figure 3** a comparison is shown of the model with respect to observation data used in the calibration for landfill settlement. As shown in this figure the agreements between the observation data and calculated data are in good order and the error is less than 10%. Also, in this figure the settlement is about two meters for three years.

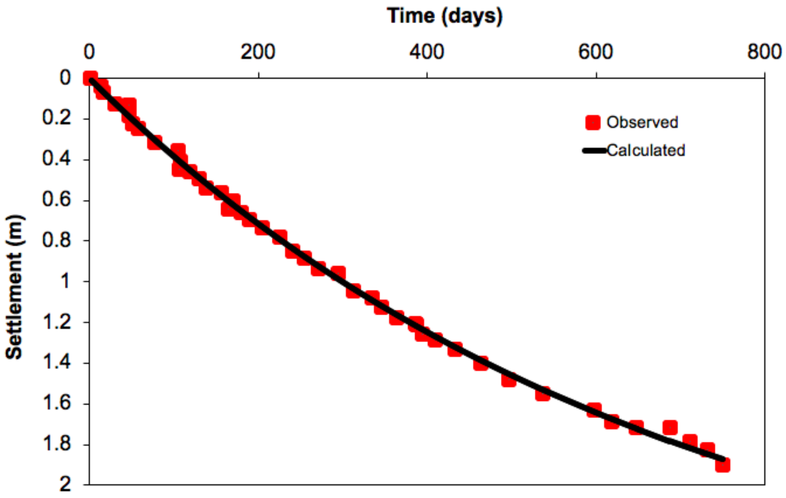

Figure 3 Comparison between results for the composite model for MSW compressibility and observation data (symbols).

It is acknowledged that the parameter values acquired by regression analysis are not based on fundamental principles that separate the three components of MSW compression. Rather, they are merely the values that supply the best agreement between measured and calculated landfill heights.

It would be interesting to perform laboratory tests to determine the parameter values from direct measurements. However, it may be challenging to isolate the mechanical creep from the biological decomposition, even in carefully handled laboratory tests. One benefit of using regression analyses of data from instrumented landfills is that the heterogeneity and impact of larger particles in the waste are taken into consideration. This would not be easy to achieve with laboratory samples.

Parameter values for the composite model of MSW compressibility surely rely on several elements involving waste composition, initial water content, compaction, precipitation, ambient temperature, and landfill management approaches. It would be interesting to assess the impact of these factors on parameter values for the composite model by performing nonlinear regression analyses on instrumentation data from well-documented landfills in several different regions and environments.

The data sets used for these regression analyses include about three years of data. The significance of the back-calculated parameter values is expected to increase for data sets covering more extended periods. Data collection continues, and the parameter values can be reviewed after a few more years of data collection.

Biogas production in landfills is a complex process that occurs over an extended period after the settlement process. The rate and duration of biogas production depend on several factors, including the landfill's age, the type and composition of waste materials, and the landfill management practices.

In Belgium, the biogas production rate from landfills is typically measured using the LFG50 parameter, which represents the volume of landfill gas produced per hour, measured in normal cubic meters (Nm3) at 50% methane content. As the landfill waste undergoes biodegradation, organic matter in the waste decomposes, producing a mixture of gases, including methane and carbon dioxide. These gases are collectively referred to as landfill gas (LFG).

The rate of biogas production typically increases after the settlement process as the waste materials continue to biodegrade. However, the rate of gas production varies depending on the waste composition, landfill age, and management practices. In some cases, biogas production can continue for decades after landfill closure.

Effective landfill management practices, such as the installation of gas collection systems, can help capture the produced biogas and utilize it for energy production or other beneficial purposes. The LFG50 parameter can be used to estimate the potential biogas production rate and the appropriate size and capacity of the gas collection system.

Here below, you will see a graph that has been generated based on the data that has been accessed by the Pollux Consulting Database.

The relationship between the height of a landfill and the biogas production rate can be complex and can depend on a variety of factors. As the landfill height increases, the amount of waste in the landfill also increases, which can lead to an increase in the rate of biogas production. This is because the biodegradable organic material in the waste decomposes and generates biogas, which can then be collected and used as a fuel source.

However, as the landfill height increases, other factors can come into play that can affect biogas production. For example, the increased weight of the waste can cause compaction and reduce the amount of air that can circulate through the landfill, which can limit the activity of the microorganisms responsible for producing biogas. Additionally, the deeper layers of waste may be less accessible for gas collection, which can limit the overall amount of biogas that can be recovered.

Therefore, while there is a general trend of increasing biogas production with increasing landfill height, the relationship can be influenced by a variety of factors and may not always be straightforward. It is important to carefully monitor biogas production rates and adjust collection methods as necessary to optimize biogas recovery.

The 100% theory assumes that all of the organic matter in the landfill is eventually decomposed and results in the production of biogas. The 70% theory assumes that only 70% of the organic matter is decomposed and generates biogas. Both theories provide estimates of the total biogas production potential of a landfill, but they are less conservative than the 40% theory. The different theories, 40%, 70%, and 100%, are used to estimate the maximum potential amount of biogas that can be generated from a landfill based on the total volume of waste in the landfill. The 40% theory assumes that only 40% of the total biodegradable material in the landfill will produce biogas, while the 70% theory assumes that 70% will produce biogas, and the 100% theory assumes that all of the biodegradable material will produce biogas.

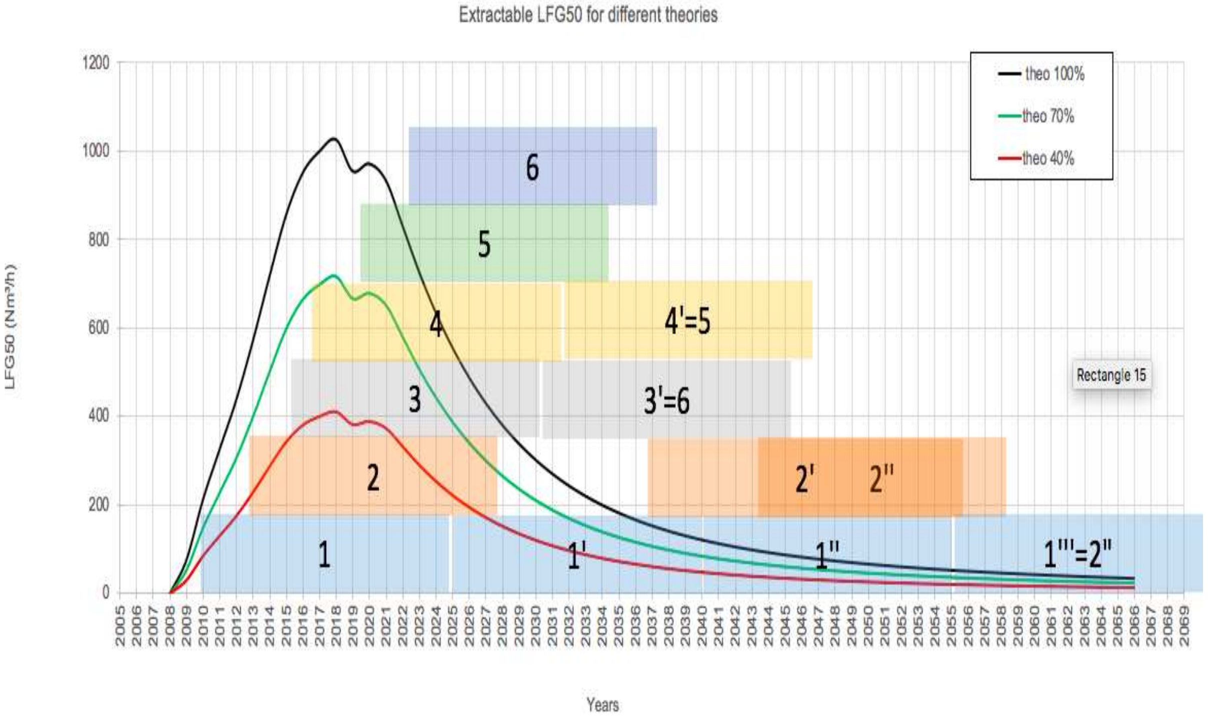

Figure 4 Biogas production in the landfill site that has been studied. The graph is representing the layer of the lifting in the course of the time. Based on different theories, the amount of gas production has been estimated and drawn on the graph.

The estimated extractable LFG50, which is the biogas generation rate in units of Nm3/h, is dependent on the theory used and the age of the landfill. In general, the biogas production rate is highest in the early stages of the landfill's life and decreases over time as the available organic material is consumed by microorganisms. The 40% theory is typically used for older landfills, while the 70% and 100% theories are used for newer landfills or landfills that are still active. As it can be seen, in **Figure 4** no matter what theory is considered, the biogas production has been raised in the course of the time after lifting. The landfill under study is started by 2008, after having passed around a decade, it reached to the highest amount of the gas production. As it can be seen, the lifting process was going on during this period of time, in a way six layer have been lifted on top of each other.

4 APPLICATION TO A REAL LANDFILL

Waste management in Belgium drops under the responsibility of three regions: Brussels Capital Region, Flanders, and Wallonia, where three separate commodities launch waste management planning and statistical reporting. All the relevant waste-related statistics are submitted individually to Eurostat. Eurostat compiles the information from the three regions to provide national data. This report presents an ex-post analysis for the whole country, but efforts are made to include the regional differences based on available information. In order to understand the context of the waste management situation in Belgium, it is essential to understand that the Brussels Capital Region represents 9 % of the MSW generated in Belgium, Flanders represents 60 % of the MSW generated, and Wallonia represents 31 % of the MSW generated (the total MSW generated in Belgium in 2010 is about 5 million tons). This MSW generation share among the three regions has remained constant between 2000 and 2010. However, overall, the MSW generated between 2001 and 2010 increased by about 5 %. This is probably due to an increase in the migrant population, as the MSW generated per capita decreased by about 1 % between 2001 and 2010. **Figure 5** displays a landfill investigated in this study in which the parameters listed in table 1 implemented the prediction of the settlements. The test fill shown in Fig. 5 was divided in a grid intersecting 15 points where the input heights of the waste were collected and where the settling and initial heights were calculated using the input tonnage, the input measured calibrating heights and the multilayer model implemented in this study.

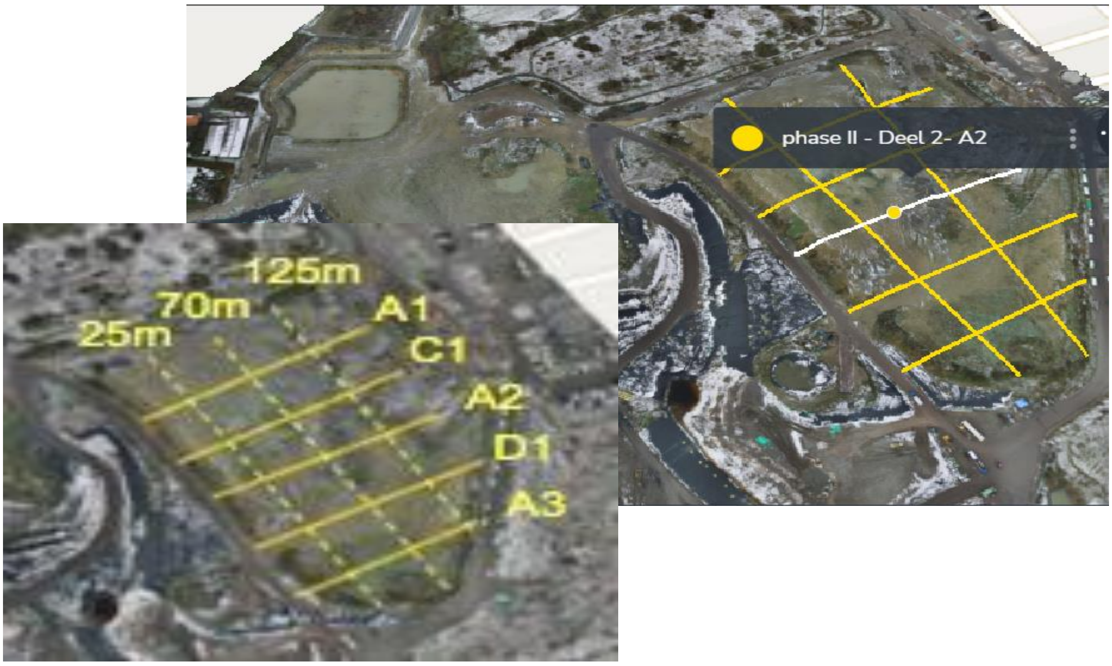

Figure 5 Aerial view of the Landfill with test fill location shown

For an individual waste layer, one timeline is started (t =0) for each sequential load. This timeline is continued for the period of interest. Each timeline's waste layer strain can be transformed into a dimensional compression value.

Due to a sequential load increment, this strain is assigned with respect to the layer's dimensions immediately prior to the load increment. Therefore, the assumption is that settlement is estimated by treating the waste column as a series of waste layers. As each layer is added, it acts as an additional incremental load on the underlying refuse layers. By combining the strains of each waste layer, the settlement of the waste column's surface can be determined. The advantage of this method is the ability to evaluate the strain regarding depth. The strain-at-depth is required to calculate densities and changes in hydraulic conductivity concerning depth. **Figure 6** shows the settlements of the landfill at the location A1-25m as indicated in Fig. 5, and a cumulative overall result.

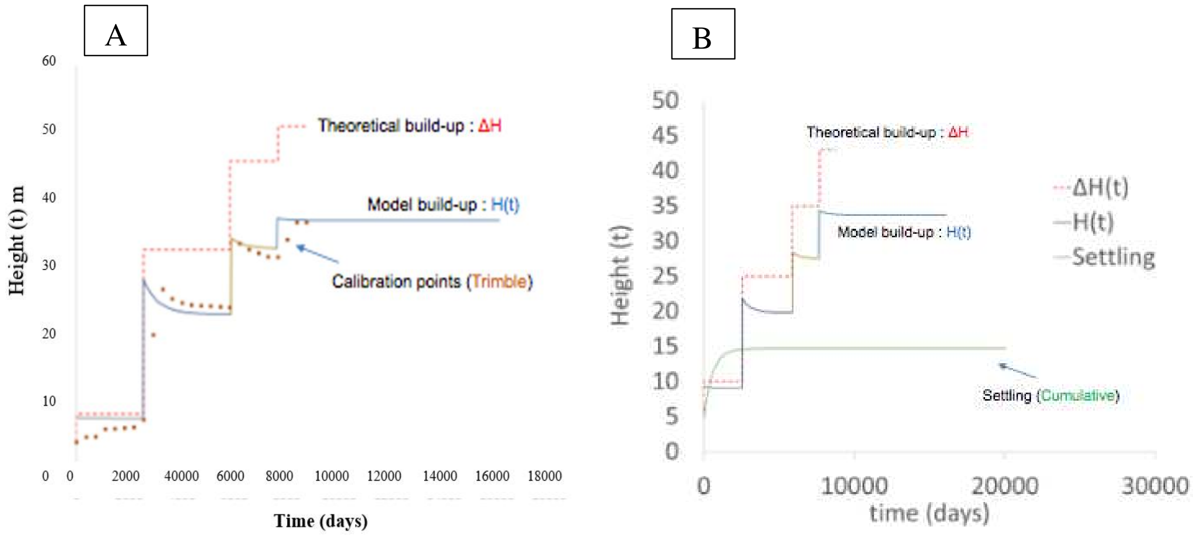

Figure 6 Settlements in the investigated landfill: (a) at the location A1-25m (see Fig. 4) and (b) showing cumulative results.

5 CONCLUSIONS

In this work, a composite compressibility model that takes into consideration rapid reaction to load, temporal mechanical creep, and biological decomposition of the MSW has been used to investigate the settlement of Municipal Solid Waste (MSW) in an existing landfill in Belgium.

Application of the composite model needs five parameter input values and an understanding of the record of waste placement. The composite model was executed in a computer program by the least square method to conduct one-dimensional analyses of the settlement of MSW landfills. The model and a computer program were used to predict the settlement of an existing landfill in Belgium, and it was found that the model can track the observed patterns of landfill settlement.

It is noteworthy to mention that the input parameters depend on the composition and mechanical behavior of the MSW, thus the correct parameters should be adopted.

Therefore, it is recommended to employ these values only as a starting point for settlement forecast at other landfills where limited information is available, applying the input to the calculated settlements that fit observed settlements as data evolution is available. Furthermore, we have shown that the landfill's biogas generation strongly depends on the landfill conditions and MSW composition.

REFERENCES

Bjarngard, A., and Edgers, L. (1990). Settlement of municipal solid waste landfills. Proc., 13th Annual Madison Waste Conf., University of Wisconsin, Madison, Wis., 192–205.

Chen KS., Chen RH, Liu CN. (2012). Modeling municipal solid waste landfill settlement. Environ Earth Sci, 66, 2301–2309.

Coumolous, D. G., and Koryalos, T. P. (1997). Prediction of attenuation of landfill settlement rates with time. Proc., 14th Int. Conf. on Soil Mechanics and Foundation Engineering, ISSMFE, Hamburg, Germany, Vol. 3, 1807–1811.

Diaz, J. G. L., Narea, M. S., Sanchez-Alciturri, J. M., Ibarra, A. A., Monzon, I. T., Gonzalez, J. P., and Lamia, M. F. (1995). Estimating material losses in sanitary landfills through biological degradation. Proc., 5th Int. Landfill Symp. Sardinia 95, CISA, S. Margherita di Pula, Cagliari, Italy, 203–208.

Edgers, L., Noble, J. J., and Williams, E. (1992). A biologic model for long-term settlement in landfills.'' Environmental geotechnology. Usmen and. Acar, eds., A. A. Balkema, Rotterdam, 177–184.

Edil, T. B., Ranguette, V. J., and Wuellner, W. W. (1990). Settlement of municipal refuse. Geotechnics of waste fills—Theory and practice, A. Landva and D. Knowles, eds., ASTM STP 1070, American Society for Testing and Materials, Philadelphia, 225–239.

Feng SJ., Chang JY, Shi H., Zheng QT., Guo XY., Zhang XL. (2019). Failure of an unfilled landfill cell due to an adjacent steep slope and a high groundwater level: A case study. Engineering Geology, 262(28), 105320.

Gabr, M. A., Hossain, M. S., and Barlaz, M. A. (2000). Solid waste settlement with leachate recirculation. Geotech. News, Newsletter of the North American Geotechnical Community, 18(2), 50–55.

Gandolla, M., Dugnani, L., Bressi, G., and Acaia, C. (1992). The determination of subsidence effects at municipal solid waste disposal sites.'' Proc., 6th Int. Solid Wastes Congress—ISWA 92, Madrid, 1–17.

Kaza, S., Yao, L., Stowell, A. (2016). Sustainable Financing and Policy Models for Municipal Composting. Urban Development Series Knowledge Papers; World Bank, Washington, DC. © World Bank.

Kreith, F.; Tchobanoglous, G. (2002). Handbook of Solid Waste Management; McGraw-Hill: New York, NY, USA.

Kumar G., Reddy KR. (2019). Constitutive Models for Municipal Solid Waste in Landfills. Geotechnical Engineering in the XXI Century: Lessons learned and future challenges.

Leonard, M. L., Floom, K. J., and Brown, S. (2000). Estimating method and use of landfill settlement. Proc., GeoDenver 2000 on Environ- mental Geotechnics, Denver, Colo., Geotechnical Special Publication 105, ASCE, 1–15.

Ling, H. I., Leshchinsky, D., Mohri, Y., and Kawabata, T. (1998). Estimation of municipal solid waste landfill settlement. J. Geotech. Geoenviron. Eng., 124(1), 21–28.

Machado S., Carvalho M.F., Gourcc J.P., Vilard OM., C.F.do Nascimentod J. (2009). Methane generation in tropical landfills: Simplified methods and field results. Waste Management, 29 (1), 153-161.

Marques ACM, Filz GM., Vilar OM. (2003). Composite Compressibility Model for Municipal Solid Waste, Journal of Geotechnical and Geoenvironmental Engineering, 129(4).

Park, H. I., and Lee, S. R. (1997). Long-term settlement behavior of landfills with refuse decomposition. J. Solid Waste Tech. Manage, 24(4), 159–165.

Reddy KR., Kumar G., Giri RK. (2017). Modeling Coupled Processes in Municipal Solid Waste Landfills: An Overview with Key Engineering Challenges. Int. J. of Geosynth. and Ground Eng, 3:6.

Sowers, G. F. (1973). Settlement of waste disposal fills. Proc., 8th Int. Conf. on Soil Mechanics and Foundation Engineering, Moscow, Russia, 22, 207–210.

Srivastava V., Ferreira de Araujo A.S., Vaish B., Bartelt-Hunt S., Singh P., Singh R.P. (2016). Biological response of using municipal solid waste compost in agriculture as fertilizer supplement. Rev Environ Sci Biotechnol, 15, 677–696.

Van Meerten, J. J., Sellmejer, J. B., and Pereboom, D. (1995). Prediction of landfill settlements. Proc., 5th Int. Landfill Symposium—Sardinia 95, CISA, S. Margherita di Pula, Cagliari, Italy, 823–831.

Wong C.T., Leung M.K., Wong M.K., Tang W.C. (2013). Afteruse development of former landfill sites in Hong Kong. Journal of Rock Mechanics and Geotechnical Engineering, 5(6), 443-451.

Yen, B. C., and Scanlon, B. S. (1975). 'Sanitary landfill settlement rates. J. Geotech. Eng., 101(5), 475–487.

Zimmerman, R. E., Chen, W. W. H., and Franklin, A. G. (1977). Mathematical model for solid waste settlement.'' Proc., Conf. on Geotechnical Practice for Disposal of Solid Waste Materials, Ann Arbor, Mich., 210–226.

Trivedi, Soham, Omprakash Chahar, and Krishna Mehta. "Solid waste management using biogas technology." International Journal of Current Engineering and Technology 5.4 (2015): 2742-2750.

Chian, E. S. K., De Walle, F. B., & Hammerberg, O. (1975). A simplified reaction model for predicting gas production from refuse. Journal of the Environmental Engineering Division, 101(6), 1001-1015.

Møller, H. B., Sommer, S. G., & Ahring, B. K. (2002). Methane productivity of manure, straw and solid fractions of manure. Biomass and Bioenergy, 22(5), 415-421.

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