Leachate production estimation for a landfill in south of Brazil using Hydrus-1D

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Abstract. The disposal of municipal solid waste (MSW) is currently a great challenge to society mainly due to the threat posed by leachate and gases released from the decomposition sites. Landfills have been widely used for this purpose because their waterproofing, drainage and treatment systems have reduced the risks of soil, water and air contamination. Estimating the amount of leachate and gases generated is extremely important for the control and operation of these systems. In this context, this study was developed in the landfill of Timbó, State of Santa Catarina, Brazil, in order to estimate the generation of leachate and to evaluate the effect of profile composition. HYDRUS-1D was used to simulate unsaturated fluid flow through layers. Data on soil matrix such as characteristic curve and unsaturated hydraulic permeability were obtained from previous studies and pedotransfer functions and the respective curves for MSW were obtained from literature. Thirteen layers were simulated by attributing an atmospheric variably boundary condition on top cover and free drainage on the bottom of the profile for two hydrologic years (2017-2019). HYDRUS-1D overestimated the leachate volume by 33.67% when compared with field data. Layers distribution showed an attenuation effect on leachate production which is consistent with design.

1 Introduction

The municipal solid waste (MSW) resulting from human activities pose a great challenge for the nowadays society. Due to the population growth its generation has also increased significantly. MSW need proper management, treatment and final disposal so that they do not cause environmental harm or became a threat to human health.

Although landfilling is been discontinued in the developed countries it is still the major final disposal alternative in developing countries [1].

The decomposition of solid waste leads to the generation of leachate and pollutant gases such methane, therefore, the control of these effluents generated in the final disposal area are of primary importance. To this end, the landfill design envisages the installation of drainage and collection systems for both gases and leachate, as well as waterproofing systems and a vegetative cover for avoiding potential contamination of the soil, air and groundwater.

Estimating the amount of leachate and gases generated is extremely important to assist in the design of the systems, ensure the proper operation of the landfill, evaluate the long-time behaviour of landfilling and, consequently, avoid environmental damage. In this sense, several methods arise for this purpose. The methods can be categorized as analytical, experimental and numerical. The last are most used since field and lab work generally are rather costly. Many models are now

reported in literature but HELP, MODUELO and LEACHM still are among the most utilized. HYDRUS 1D is a software package, capable of simulating water, heat and transport flows of solutes in variably saturated conditions [2] and thus represent a powerful tool for landfill performance assessment.

All those models have in common the fact that they perform a water balance in soil. For this purpose, many different data as required but rarely available.

Technical concerns on landfill and general solid waste disposition have gained attention over the last years with an increasing number of works focused on understanding the geotechnical behaviour of soils and MSW. Particular interest rests on coupling phenomena [3] with mechanical, hydraulic, chemical and thermal gradients being studied. Beyond that landfilling invariably implies unsaturated conditions [4].

This work was carried out in a landfill located in the municipality of Timbó, Santa Catarina, Brazil. Its main goal was to use HYDRUS 1D to estimate leachate rates and compare it with *in situ* measurements from the drainage/collection system.

2 Methodology

2.1 Study area

This study took place in a sanitary landfill located in the municipality of Timbó, Santa Catarina, Brazil (fig. 1).

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The landfill is currently managed by Consórcio Intermunicipal do Médio Vale do Itajaí (CIMVI) and its operation begun in 2003.

Fig. 1. Study area localization.

The cells were designed to receive non-hazardous wastes mostly non inert and based on the depression method due to the local topography. A total of thirteen municipalities send its wastes into this landfill and the waste composition is predominantly organic (up to 55%), however plastic and paper can surpass 20% each.

The projected area of the studied cells adds up to 52,300 m². The liner system, upwards, is composed of a compacted silt clay soil followed by a high-density polyethylene (HDPE) made up geomembrane (2 mm) and a non-woven geotextile. On the top goes a drainage layer (30 cm) made of gravel which also works as a protection. Each cell has six waste layers up to 3 m high switched between 40 cm silt sandy which is also used on the cover (1 m) (fig. 3). A further description of the soils can be found in [5].

Fig. 2. Scheme of the vertical landfill profile.

2.2 Conceptual model

Estimating flows and hydraulic heads in a landfill is one of the primary goals in design and can further be applied to evaluate to long term performance. Several models have been developed with this purpose, including analytical techniques, field measurements and numerical codes with highlights for HELP (Hydrologic Evaluation for Landfill Performance), MODULO [6], UNSAT-H and LEACHM. HYDRUS 1D is a free powerful software package with multiple applications for unsaturated soils yet a bit less employed for landfills. The possibility of coupling effects in future works made easy the choice by the authors.

HYDRUS 1D considers a one-dimensional uniform water movement through a porous media with different degrees of saturation which is described by Richards equation (eq. 1).

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left[k \left(\frac{\partial h}{\partial x} + \cos \alpha \right) \right] - S \quad (1)$$

In eq. 1, h is the water pressure head [L], θ is the volumetric water content [L³.L⁻³], t is time [T], x is the spatial coordinate [L], S is a sink term [L³.L⁻³.T⁻¹], α is the angle between flow direction and the vertical axis and k the is unsaturated hydraulic permeability [L.T⁻¹].

To represent the relationship between hydraulic head and water content as well as unsaturated hydraulic permeability it was used the van Genuchten model [7] as shown in equations 2 and 3.

$$\begin{cases} \theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + |\alpha h|^n \right]^m} & h < 0 \\ \theta(h) = \theta_s & h \geq 0 \end{cases} \quad (2)$$

$$k(h) = k_s S_e^l \left[1 - \left(1 - S_e^{1/m} \right)^m \right]^2 \quad (3)$$

In the above equations, θ_s is the saturated water content [L³.L⁻³], θ_r is the residual water content [L³.L⁻³], α is the inverse of air-entry value [L⁻¹], k_s is the saturated hydraulic permeability [L.T⁻¹], l is a pore-connectivity parameter assumed equal 0.5 for all soils, n is a pore-size distribution index and $m = 1 - 1/n$. A more detailed theoretical description of the HYDRUS 1D can be found in [2]. S_e is the effective saturation [-] and is given by equation 4.

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (4)$$

The foundation of the landfill lies beneath the liner system. This study focused on simulating the pumped leachate and so foundation was neglected during simulations.

2.3 Data acquisition

Leachate flux is commonly measured and recorded with the aid of and ultrasonomic meter (Nivelco Echo TREK

STP – 390-2) coupled with a Parshall flume. The engineering team from CIMVI made the data available.

Potential evapotranspiration (E_{tp}) was calculated with the empirical method of Jensen and Haise [8] (eq. 5). This formula was chosen because solar radiation data were obtained with Centro de Informações de Recursos Ambientais e de Hidrometeorologia de Santa Catarina (CIRAM/EPAGRI).

$$E_{tp} = (0,025T + 0,08) \frac{G}{59} \quad (5)$$

In eq. 5, T is average daily temperature ($^{\circ}\text{C}$), G is solar radiation ($\text{cal}/\text{cm}^2.\text{d}$) and E_{tp} is evapotranspiration (mm/d). Precipitation data was obtained in the webpage of Instituto Nacional de Meteorologia (INMET).

The retention curve for soils were obtained from pedotransfer functions promptly available in module Rosetta Lite inside HYDRUS 1D. The entry data is based on soils characterization developed by [5]. To account for the MSW it was used the retention curve published by [9] due to the similarity in composition between the solid wastes. The authors used shredded solid waste samples (maximum particle size = 25 mm) and measured the water retention curve and unsaturated permeability respectively using the hanging column method and the multistep outflow method both using de-aired water. Table 1 summarizes the coefficients values obtained for each soil plus the MSW.

Table 1. Summary of unsaturated hydraulic parameters.

Material*	θ_r	θ_s	$\alpha \text{ (cm}^{-1}\text{)}$	n	$k_s \text{ (cm/d)}$
01	0.0718	0.4060	0.0079	1.5389	8.21
02	0.0803	0.4148	0.0127	1.3912	5.75
03	0.0530	0.3747	0.0353	3.1798	642.98
04**	0.2200	0.5300	0.2860	1.6000	259.20

*01 - sandy silt (cover), 02 - silty clay (liner), 03 - drainage layer, 04 - MSW.

**the pore-connectivity parameter for waste equals -1.23 [9].

Fig. 3. Retention curves of soils and MSW.

As expected, fine-grained soils, in this case the silty clay, are capable of bearing higher levels of suction; meanwhile coarser soils (drainage layer) support much less tension. As one may notice from figures 3 and 4 the MSW tend to behave resembling a coarse-grained soil.

Fig. 4. Unsaturated hydraulic permeability for soils and MSW.

No aging effects upon solid waste were investigated by [9] during their study.

2.4 Numerical simulations

The infiltration of water into soil was simulated using a one-dimensional approach in the vertical direction, so that α from eq. 1 equals zero.

The first simulations covered scenario 1 in which a total of thirteen layers, ranging from cover to drainage system were simulated. The scenario 2 was intended to better understand the hydraulic behaviour of the layers individually and as an increasing assemblage. Initially only the cover layer was simulated as if it would exist alone. After that the cover was simulated together with the first (from top to bottom) waste layer. Those steps took place successively until the entire profile was simulated once again exactly as the scenario 1. The liner was not considered during simulations.

All simulations were carried out for the same period, the 2017-2019 hydrologic years. One hydrologic year corresponds to a 12-month period that begins at the start of the wet season and is concluded at the end of the dry season. Traditionally, it is defined from October-1 of one calendar year to September-30 of the next calendar year. The use of the hydrologic year is suitable especially because fluid flow through soil is rather slow when compared to run-off and may take even a few months for effective precipitation contribute at the bottom of a layered profile. The calendar year was also simulated to assess any possible incoherence, but the results showed no more than 1% of difference.

The initial condition of the model as hydraulic heads posed a major challenge since no information was available. Then several simulations were executed to investigate the best fit among data which only occurred when initial condition was set up as field capacity. That is also a default feature from HYDRUS 1D [2].

The software was built based on finite element method (FEM) and discretization of the model can include as many nodes as necessary for a fully description. The authors executed simulations for the following number of nodes 101, 300, 400, 500, 600, 700, 800 and 1000. After 600 nodes the difference in results practically ceased to exist, and thus this discretization was adopted.

In all simulations it was employed the van Genuchten – Mualem model with no hysteresis [2]. On the top of the profile was used an atmospheric boundary condition with surface run-off and to the bottom was attributed a free drainage boundary condition.

Mechanical, chemical and thermal loads as well as consolidation, shear strength, and lateral earth pressures were not considered at this stage. Layer slope was also disregarded.

3 Results and discussion

Simulations for scenario 1 resulted in maximum daily flow equal to 0.172 cm/d which occurred on the first day while minimum daily flow took place on the last day (365 days) and reached 0.152 cm/d. At the end of the simulation the cumulative bottom flux summed 33.08 cm. Those values account for the hydraulic heads that may be expected above the liner system. The evolution of flows can be seen in figure 5.

Fig. 5. Simulated bottom flux and cumulative bottom flux.

The negative sign in values of figure 5 indicate the direction of flow downward.

The volume of leachate which achieves the liner at each month was calculated by simply multiplying the heads times the projected surficial area of the cells. Figure 6 shows the comparison among measured and calculated volumes for the year of 2018.

The simulated and measured volumes present an explicit different among each other. Measured values showed no clear trend during 2018 but increased from August to October. One may be led to believe that from this point leachate generation is linked with precipitation which is only emphasized by the values recorded in December. The simulated results on the other hand

displayed a diminishing path over time ranging from 2,680 m³ in January to 875 m³ in December.

Fig. 6. Measured times simulated leachate volumes in 2018.

The absence of data of former periods makes it difficult to understand the full scenario, however, some information can be extracted. The layers of a landfill switch from coarse to fine soils to enhance lateral flow and inhibit vertical flow [10] since one of the main criteria for design is the protection of groundwater. Besides that, soil layers are rather unsaturated or variably saturated for long periods, influenced by evapotranspiration and precipitation.

The measured volumes can be explained by practice. According to [11] MSW are a porous media that is composed of macropores and a matrix in which preferential flows occur regularly and accelerate the percolation. That might be happening to the landfill, as seen in figure 6 when precipitation apparently affect the bottom flow very quickly.

The real embankment is non uniform and heterogeneous displaying a range of thickness for each layer of soil and MSW besides varying degrees of compaction. Also, solid waste consolidation is likely to be reducing its permeability. This hypothesis is supported by the high organic content, the average 3.0 m thick MSW layer and the stresses posed by the number of layers of the cell.

Computed values are based on several simplifications of the porous medium and for fluid flow as for instance the retention curves and unsaturated permeability were obtained considering water as the pore filling fluid. However, the real fluid features different properties from that of water with a trend for clogging.

One shall keep in mind that a landfill is a particularly challenging work of engineering with multiple loadings such as mechanic, hydraulic, chemical and thermal and so its long-time behaviour may deviate from design.

Although results may seem to disagree at a first glance, a yearlong assessment of cumulative volumes shows better concordance as is displayed in figure 7.

Cumulative measured leachate volume through 2018 accounts for 12,942 m³ whilst the cumulative calculated volume reached 17,299 m³. The difference corresponds to an overestimation of about 33.7%. This result is in good agreement with other works also carried out with

HYDRUS 1D such as [12] that reported an overestimation of 26.4% in a landfill located at Rio de Janeiro, and [13] which while simulating leachate production in a waste rock dump in Sweden found an overestimation of about 100% which was partially credited to the limitations of the model.

Fig. 7. Cumulative measured vs simulated leachate volumes.

The output from simulations seemingly are reliable and reasonable and since overestimation is well suited in this case it is coherent to state that this landfill has been properly executed.

Even so the difference between measured and computed values are quite high. This contrast may rely on the assumptions and limitations formerly discussed.

When compared to precipitation the cumulative measured leachate volume is up to 17% while calculated volume is approximately 22.7%. Though those values look high they encompass real and expected leachate pumping and do not relate to the rates that breakthrough the liner system.

A second scenario was carried out to investigate the effect of layers step-by-step, i.e., by summing the layers of the landfill from cover to bottom layer where the collection system lays. That is thirteen sets were created with the first containing only the cover and last one being equal to the scenario 1 (figure 8).

Fig. 8. Annual volume of expected leachate for the year of 2018 simulating progressive clustering layers.

The first simulation which only accounts for the cover almost reached 50,000 m³. The second simulation showed a considerable decrease when compared to prior one, however, the magnitude is still much greater than that achieved by the entire profile.

As can be seen in simulations 3, 5 and 7 the presence of intermediary layers composed of sandy silt tend to reduce the percolation and favour lateral flow. This effect is of less extent when evaluating simulations 9, 11 and 13. That is so probably because with an increase on the number of layers the interactions with atmospheric boundary conditions became more complex. Deeper layers as less impacted by evapotranspiration and may accumulate fluid.

As formerly mentioned, an estimate of leachate levels is based on water balance in the profile. Figure 9 presents the results for the hydrologic years 2017-2019.

Potential evapotranspiration (*E_{tp}*) fluctuates with a minimum as much as 54.2 mm in Jun-18 and a maximum 160.3 mm in Jan-18. Precipitation also varied with its minimum in Jul-18 and maximum in Jan-18. The leachate levels rise from Oct-17 until Jan-18 and then decrease continuously. This pattern in levels is ought to be related to the size of the layered profile as prior noticed in figure 8. The profile may be functioning as a reservoir for long periods as the decreasing leachate levels path indicate.

Fig. 9. Water-budget for the entire period simulated.

The lack of data constrains interpretations, but it is a preliminary attempt to calculate a water balance and investigate the hydraulic behavior of this landfill. So future studies shall consider longer periods of analysis.

As in any study concerning leachate estimation this work has many limitations. It is likely that an analysis of mechanical loads can bring some lightning to the ideas presented herein. Consolidation is a phenomenon of primary significance and shall be added in future works.

In this manner a wide field and lab experimental work is supposed to be carried out to achieve more accurate intel and better describe the retention curves and unsaturated hydraulic permeability.

Despite limitations the calculated results seem to be reasonable and reliable whether compared to measured values. Further, HYDRUS 1D demonstrated a great potential to be used as tool for estimating fluxes in

landfill sites even so it is a one-dimensional model. Besides that, the numerical package can be coupled with other codes to simulate geochemical reactions.

4 Conclusions

This work was a brief survey to investigate the production of leachate in a landfill located in Timbó, Santa Catarina, the south of Brazil. This paper estimated the generation of leachate in a landfill by means of HYDRUS-1D. The software requires input data to simulate water flow, such as geotechnical and hydraulic soil parameters, which are often not available. For this reason, there are limitations linked to their application and feasibility. The cells studied were represented as a one-dimensional profile constituted of thirteen layers, a sequence intercalated of cover soils and MSW with the bottom layer corresponding to the drainage/collection system.

Computed bottom flux varied between 0.172 and 0.152 cm/d along the year of 2018 and the cumulative bottom flux achieved 33.08 cm. Cumulative measured bottom flux reached 0.247 cm. No direct relationship was established between calculated and measured data over time, nevertheless, the cumulative values rather agree reasonably. In comparison to measured data from the collection system there was an overestimation of approximately 33% which is consistent with results reported in other works.

An assessment of a water balance done over the hydrologic years of 2017-2019 are yet inconclusive, but it is suggested that the profile is functioning as reservoir.

Considering that the simulations are coherent, and the porous media is stable then measured leachate flux data suggest that other phenomena besides hydraulic gradients may impact fluid flow.

A second analysis was based on the evaluation of progressive clustering of layers starting with a single layer (cover) until all layer were finally simulated. This approach allowed the demonstrate the effect of multiple layers on percolation. In this sense the economic feasibility of overlapping many waste layers can questioned against the global hydraulic behavior of the cell profile.

Further, the landfill seems to behave properly even so especially because the collection system operated under the calculated estimates and no leaking or excessive settlement has been reported.

Finally, HYDRUS 1D proved itself a valuable tool for accurately estimating leachate production in a landfill.

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