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Unsaturated seepage analysis for an ordinary solid waste sanitary landfill in Costa Rica.

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Abstract. Sanitary Landfills in tropical areas are subjected to specific conditions such as high temperatures, intense precipitation, and highly organic solid waste with high biodegradation rates. Unsaturated seepage inside the cells of an Ordinary Solid Waste (OSW) Sanitary Landfill in Costa Rica, Central America was studied. It is essential to better understand the seepage behavior for this type of disposal infrastructure due to its physical and hydraulic properties high variation and degradation of the deposited materials, which are complex and exhibit high uncertainty. It is imperative that leachate movement inside the cells of the landfill is accurately estimated to design more efficient systems and optimize the sanitary landfill operation. Field exploration was performed to extract samples from the field representing different OSW ages. Then, a series of laboratory testing was performed to obtain the physical, hydraulic properties, and biodegradation behavior of the OSW and cover soil such as specific gravity of the solids, grain size distribution, Soil-water characteristic curve, K-curve, and Atterberg limits. Additionally, climatic conditions affecting the degree of saturation were assessed by performing a water balance. This information was utilized to estimate flow rates for different scenarios using a HELP model, an empirical model, and two different models using the Slide ™ software from Rocscience™ and later on compare them to actual field data available. The model that better predicted the actual flow rate was the HELP model.

1 Introduction

Design and operation of sanitary Landfills in tropical areas must consider high temperatures, intense precipitation, and highly organic solid waste with high biodegradation rates.

One of the aspects that must be considered is the understanding of Ordinary Solid Waste (OSW) behavior, both in terms of its mechanical and hydraulic characteristics. For instance, leachate generation can affect the water content, degree of saturation, internal pressures, and stresses in the cell.

An adequate study of leachate production and movement within the cell should consider aspects such as type of waste, cover soil, weather conditions, and in-situ geological and topographic conditions.

Unsaturated seepage within the cells of an Ordinary Solid Waste (OSW) Sanitary Landfill in Costa Rica, Central America was studied to better understand the seepage behavior for this type of disposal project due to its physical and hydraulic properties high variation, and degradation of the deposited materials, which are complex and exhibit highly uncertain. It is important to accurately estimated fluid movement inside the cells of the landfill to design efficiently and optimize the operation. A field study was conducted to gather samples from various ages of OSW (organic solid waste) found in the field. After that, a sequence of laboratory experiments was carried out to determine the physical, hydraulic characteristics, and biodegradation behavior of both the OSW and the covering soil. These laboratory tests involved measuring various properties like the solids' specific gravity, the distribution of grain sizes, soil-water relationships, K-curves, and Atterberg limits.

Additionally, climatic conditions affecting the degree of saturation were assessed by performing a water balance to determine the amount of leachate generated within the landfill. Knowledge of the potential leachate production is important for adequately assessing its collection system (e.g., pipes) and for making decisions on how to manage the waste-water treatment [1]. An accurate estimation of leachate generation depends on the meteorological conditions (intensity and distribution of precipitation and potential evapotranspiration), the hydraulic characteristics and initial conditions of OSW materials, and the biological processes within the sanitary landfill [2].

Unsaturated flow models have become relevant in recent years. Current models to analyze flow behavior in sanitary landfills under unsaturated conditions identified clear limitations mainly due to the variability of existing materials and their biodegradation processes [3].

Once the physical and hydraulic properties were determined, flow rates for different scenarios using a HELP model, an empirical model, and two different models using the Slide ™ software from Rocscience™

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were estimated and later on compared to actual field data available.

2 Sample preparation for testing

Representative samples were taken from different points for OSW of different ages by collecting material at different depths and using the information on the time of construction of the slopes and berms of the cell. Sampling locations are shown in figure 1.

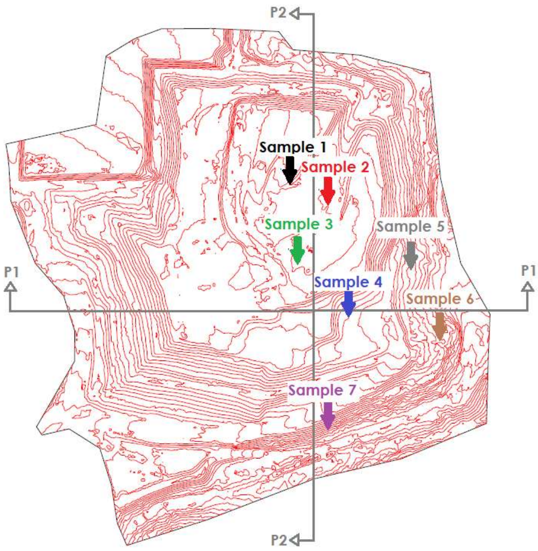

Fig. 1. Sampling points and surveying profiles

The OSW samples were placed on the surface to be stored and identified. The physical appearance of the materials sampled is shown in figure 2. The samples could not be used before processing for laboratory testing due to the presence of large particles, plastics, and glass bottles, as can be seen in figure 3.

Fig. 2. Appearance of the samples.

It was observed from the materials sampled and used in previous research projects by the authors, that the older the OSW the more similar it becomes to an organic soil consistency. Inert and partially degraded waste constituents such as rocks, metal, plastics, wood, and paper were also observed in the older OSW samples [4].

Gravimetric water content (ASTM D2216) [5] and organic matter content (AASHTO T267) [6] testing was performed on unprocessed samples (shown in figure 3). Then, the processing of the samples consisted of air-drying the material, and removing particles of plastic, metal, and glass, since it is not possible to perform conventional laboratory testing such as gran-size distribution and hydraulic conductivity using specimens containing particles so large. It was assumed that the seepage behavior is governed by the finer fraction, therefore, this elimination of larger particles would not affect significantly the results, causing a conservative estimate. The material after processing is shown in figure 4.

Fig. 3. Samples before processing

Fig. 4. Samples after processing

Information on the age and the type of laboratory test performed for each sample is presented in Table 1. Because this research was focused on a seepage analysis and the volume of available sampled material was limited, priority was given to hydraulic conductivity testing.

3 Test results

Results for gravimetric water content and organic matter content are shown in Table 2. The data exhibit a tendency to decrease in the values for both parameters as the age of the OSW increases. This can be associated with the degradation of the materials and the leachate production capacity which decreases with an increase on the time of biodegradation.

Table 1. Age and to each sample

Sample	Age	Laboratory Tests performed
Soil cover	-	Soil classification Hydraulic conductivity
1	Fresh	Hydraulic conductivity
2	6 months	Hydraulic conductivity
3	1 year	Soil classification Hydraulic conductivity
4	2 years	Hydraulic conductivity
5	3 years	Soil classification Hydraulic conductivity
6	4 years	Hydraulic conductivity
7	5 years or more	Soil classification Hydraulic conductivity

Table 2. Gravimetric water content and organic matter content

Sample	Gravimetric water content (%)	Organic matter content (%)
Soil cover	37.49	-
1	124.70	25.41
2	102.51	52.42
3	79.84	45.30
4	47.38	44.11
5	49.65	35.42
6	82.32	41.87
7	57.46	33.42

3.1 Classification of materials by size

A series of laboratory index properties analyses were performed on the processed materials to obtain the grain size distribution, Atterberg limits, and plasticity index for the cover soil and sampled OSW. The liquid limit, plastic limit, and plasticity index (ASTM D4318) [7] were obtained for samples 3, 5, and 7, and the cover soil. The plasticity chart presenting the results is shown in figure 5. According to the laboratory results the cover soil has a liquid and plasticity index approximately 10% higher than the OSW, except for sample 5.

The greatest difference is between the cover soil and sample 7 because, during the sampling process, greater biodegradation of the OSW was observed. Due to the degradation of this sample, the soil cover had been almost completely mixed with the OSW which could explain the measured reduction in the plasticity of this material.

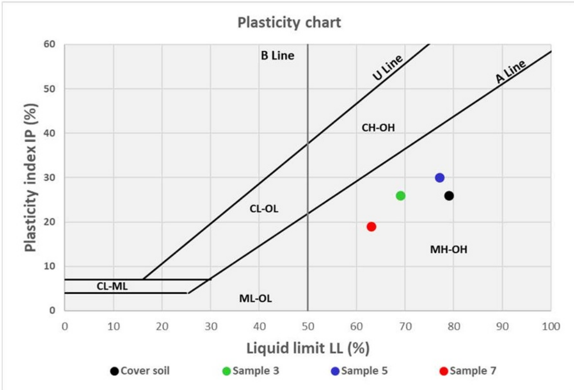

Fig. 5. Plasticity Chart showing PI and LL results

Grain-size distribution tests were performed on the same sampled specimens (ASTM D7928) [8] and the results are shown in figure 6. From these results, it can be observed that the older the material the higher the fine fraction, probably as a result of the longer biodegradation process experienced.

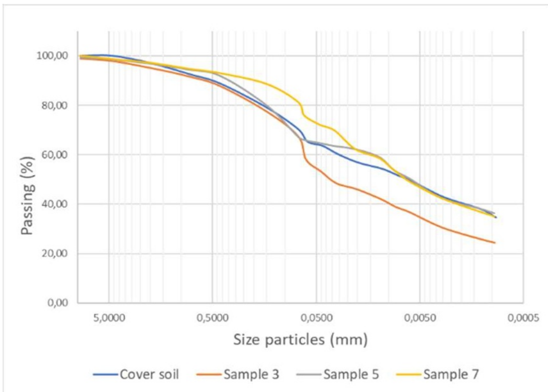

Fig. 6. Grain-size distribution of the studied materials

Additionally, the Specific gravity of solids was determined for all samples following the ASTM D854 [9] standard. The results of these analyses are shown in Table 3.

Table 3. Specific gravity of the solids test results

Sample	Gs
Cover soil	2.613
Sample 3	2.658
Sample 5	2.502
Sample 7	2.536

3.2 Hydraulic properties

To adequately model the unsaturated seepage within the sanitary landfill cell the hydraulic conductivity (k_s) values were estimated using constant head permeability

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laboratory tests (shown in figure 7) because the processed material exhibited short testing times using this type of test. Field densities were reproduced on the processed OSW specimens used for these tests.

Fig. 7. Constant head permeability test

To determine the saturated permeability of the OSW and cover soil, the samples were saturated for 48 hours prior to the start of the test. The results of the hydraulic conductivity for all the samples analyzed are summarized in Table 4.

Table 4. Saturated hydraulic conductivity test results

Sample	Age	Dry density (kN/m^3)	k_s (m/s)
Soil cover	-	7.88	6.285 x 10^{-5}
1	Fresh	7.26	3.467 x 10^{-4}
2	6 months	7.29	2.209 x 10^{-5}
3	1 year	7.28	6.041 x 10^{-5}
4	2 years	7.39	1.721 x 10^{-5}
5	3 years	7.40	2.926 x 10^{-5}
6	4 years	7.35	1.357 x 10^{-4}
7	5 years or more	7.55	4.004 x 10^{-5}

Furthermore, the Retention Curves were estimated using the filter paper method according to ASTM D5298 [10] procedure. With the suctions results and applying van Genuchten's model fitting parameters, the Retention curves of the analyzed materials were generated. Retention curves for all samples were obtained but only the cover soil, sample 3, sample 5, and sample 7 are presented in figure 8.

To define the van Genuchten parameters White et al (2015) [11] established functional relationships for landfill models. These relationships were established based on the variation of saturated volumetric water content (θ_s) and the collection of parameters from other research conducted in landfills. The van Genuchten fitting parameters used to create the Soil Water-Characteristic Curves are shown in table 5. The values of the saturated volumetric water content (θ_s) and saturated hydraulic conductivity (k_s) were estimated from the permeability tests. Using this information K-curves were also generated and used in Slide ™.

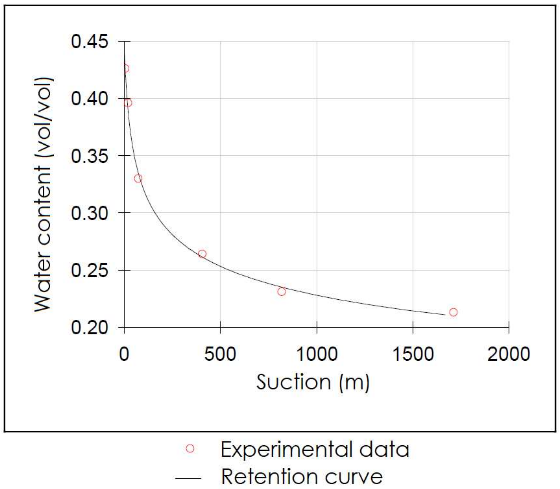

Fig.8. Retention curve of sample 3 (1 year)

Table 5. van Genuchten model fitting parameters

Parameter	Cover soil	Sample 3	Sample 5	Sample 7
θ_s	0.734	0.754	0.721	0.739
θ_r	0.160	0.160	0.160	0.160
α	2.567	2.567	2.496	2.567
n	1.900	1.900	1.900	1.900
m	0.474	0.474	0.474	0.474

4 Water balance

The water balance analysis was performed using the HELP V 4.0 (Hydrologic Evaluation of Landfill Performance) model which allows to inclusion of different layers of material and their thicknesses, weather information of the site, slopes, and drainage conditions. With this information, the model estimates the amount of evapotranspiration, runoff, leakage, and leachate collected.

The design of the module included a layer of cover soil, 5 layers of OSW ranging in age from “1 or less” to “5 or more” years in the sanitary landfill, a drainage net to protect the filter, a gravel filter, and a layer of polypropylene that separates the cell from the original in-situ soil with the same characteristics as the cover soil were included.

It was estimated that for the period of time evaluated, the amount of leachate generated in the study cell was 59076.1 m^3 and that the maximum daily collection data is 1327.2 m^3. In addition to the HELP V 4.0 model, the estimation of the amount of leachate generated was performed using the methodology proposed by Delgado A. (2018) [12], and the amount of leachate generated using this model was 70075.4 m^3. These data were compared with the records obtained from the sanitary landfill of a total of 53572.0 m^3 treated during the analysis time period.

One possible explanation of the calculated differences between the results is that the field data do not account for all the leachate generated, but only for the volume that was treated at the waste-water treatment plant.

5 Flow model

Seepage analysis models were constructed using the Rocsciense Slide® software. The model was elaborated using the same layers as the water balance with their respective physical and hydraulic characteristics obtained from the laboratory analysis. The van Genuchten fitting parameters were also included in the model so that the analyses can be performed in unsaturated and saturated conditions.

From the water balance analysis, the amount of leachate produced was defined for each layer of OSW based on the volume treated for each year and the area of the site obtained from the surveying records available at the site. Furthermore, each layer was assigned a leachate production rate (meters per year). The infiltration rate (meter per year) for the cover soil was obtained from the water balance.

With the flow model defined, the behavior of the flow in stationary conditions was analyzed considering that the flow inside the cell is in equilibrium. This condition can be generated when the drainage pipes are closed causing an accumulation of leachate inside the cell. A section of the profile used for the subsurface flow analysis at the Sanitary landfill in the stationary condition is presented in figure 9.

Utilizing these results, it is possible to estimate the volume of leachate produced in the time period analyzed and to compare it with the results obtained from the water balance and the available field data from the wastewater treatment plant.

The volume of leachate collected for the analysis period of one year and stationary flow conditions was obtained for the two profiles evaluated. For profile 1 (P1) the volume was 64517.0 m^3 and for profile 2 (P2) 60515.0 m^3. The differences between the values obtained can be justified by the dimensions of the profiles since the length and height vary due to topographic conditions. Despite the differences, a difference of 6.2% is considered adequate for the type of analysis performed. The results attained with the different methodologies used to calculate the volume of leachate are shown in table 6. Flow behavior considering the stationary condition for the scenario in which the leachate is between the drainage and the "five or more years" old OSW is exhibited in figure 10.

Following the analysis in a stationary condition, the analysis was performed in a transient condition using the same profiles. The infiltration rate was modified to use the maximum daily values obtained from the HELP model. In addition, different scenarios were analyzed by modifying the leachate level between the different OSW layers. For each case, the flow behavior was considered over a period of five days, and it was observed that the pressures inside the cell changed as the media became saturated.

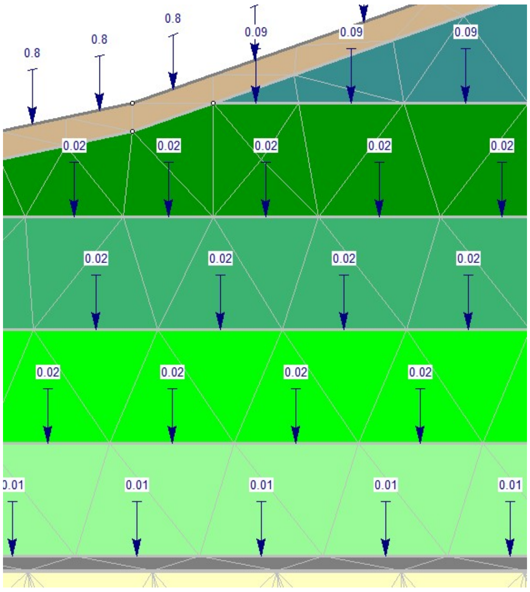

Fig. 9. Flow model using Rocsciense Slide® software

Table 6. Results of leachate production

Method	Leachate production (m^3/year)	% Difference to Slide®	
		P1	P2
HELP V 4.0	59076.1	9.2	2.4
Delgado A.	70075.4	7.9	13.6
Field data	53572.0	20.4	12.9
Slide P1	64517.0	-	-
Slide P2	60515.0	-	-

6 Conclusions

Index properties obtained from laboratory testing suggest that the more advanced the process of biodegradation the finer the particle composition of the OSW, which can affect the seepage through the media, thus producing changes in pore pressures and suction values within a sanitary landfill.

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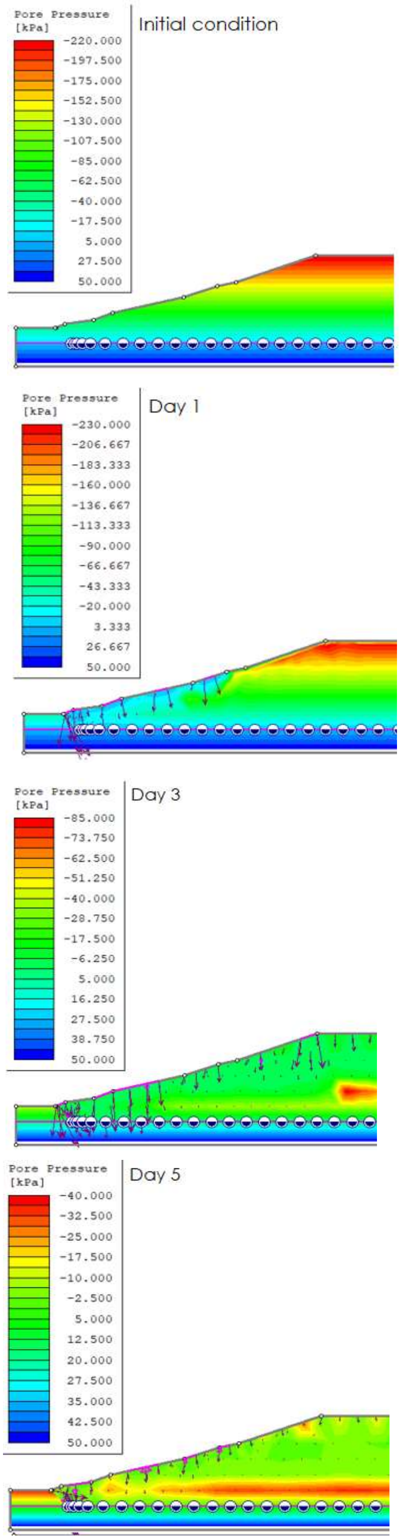

Fig. 10. Transient flow behavior

Saturated hydraulic conductivity values were estimated using the same in-situ density. These values were used to determine the Soil-Water Characteristic Curves by means of the van Genuchten model. These curves were utilized to perform an unsaturated seepage analysis within a sanitary landfill cell.

For the flow model, the water balance of the cell was performed by determining the amount of water that seeps into the cell and the amount of leachate generated during the analysis time period. These calculations were compared with the results of the stationary flow model, determining that the model yielded adequate results when compared to available recorded data.

The transient flow model allowed for a better prediction of the pore pressures and changes in suction as the degree of saturation changed according to the water balance estimated.

Additionally, it was observed that neither in the stationary nor in the transient flow model the sanitary landfill becomes fully saturated, thus justifying an unsaturated seepage analysis for this case.

The pore pressures and suction values estimated can also be used for slope stability analysis or to better understand the shear strength behavior of the OSW.

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