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Numerical modelling to show variation in the amount of leachate in a solid waste column in the sanitary landfill sites of the Mejía and Ambato cantons

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Abstract. The leachate generated by the direct disposal of solid waste into the soil of terrace number one of the Romerillos sanitary landfill site contaminates the environment. This is visible from an average distance of up to 20m with the presence of dry vegetation cover showing infiltration by leachate and soil pollution in the surface and underground. Meanwhile, in the soil of terrace number one of the Ambato sanitary landfill site, the contaminated environment is visible from an average distance of 33m with the presence of dry vegetation cover. At both the Romerillos and the Ambato sanitary landfill sites, a quantification study of codified (Matlab) and spatial (ArcGis) variability of the characteristics, such as hydraulic load, pressure load and percentage of leachate, was carried out. Field data was collected for the Matlab simulation. For 10 specific GPS Navigator sampling points, the variables studied included infiltration speed, porosity, infiltration distance, Van Genuchten parameters and time. Estimation graphs were created for each variable at 10, 20, 30 and 40mins. Through the observation of the graphs obtained in Matlab, it was determined that the variable hydraulic load is inversely proportional to depth. It was also established that the behaviour of the pressure load is directly proportional to depth and percentage of leachate was inversely proportional to depth. All the variables analysed showed a normal behaviour due to the silty-clay soil type in the "Romerillos" sanitary landfill site and sandy-loam in the Ambato sanitary landfill site.

Keywords: Infiltration, leachate, simulation, hydraulic load, pressure load, percentage of leachate.

1. Introduction

Landfill sites are vital for the final disposal of solid waste which is continuously produced by human activities. They solve this one problem and generate others, such as biogas production and leachate, due to the way in which they are managed. Pressure can cause cracking and fissures in the terraces, letting in water due to precipitations that cause a greater quantity of gases and contaminating leachates to be released into the surrounding environment (Muñoz, 2008).

Leachate, a liquid effluent, is generated by an excess of moisture in the compacted waste in such a way that it exceeds the field capacity. This liquid has a high organic load, fecal coliforms, a certain concentration of heavy metals, low pH and other such parameters (Muñoz, 2008). Infiltrations accumulate in the soil causing contamination; Naula et al (2016) determined that: "One of the most important resources that we have are soils and ensuring that they are not contaminated is of great interest to the whole of society" (Naula et al, 2016).

In recent times, mathematical models have been proposed in order to reveal the phenomenon of infiltration related to soil characteristics. The Richards Equation is a model that is connected to this issue, as it allows one to calculate the amount and percentage of leachate that exist in the soil; "it suggests a relationship between humidity, hydraulic conductivity and suction in an unsaturated porous medium for different times" (Sierra et al, 2006).

With enough information, the application of the Richards Equation produces accurate results in order to estimate the infiltration, whereby data can be obtained to generate the hydraulic functions of the unsaturated soils. This acts as an improvement that more adequately considers the interaction of the infiltration processes and runoff. Sierra points out that "if field or laboratory data are scarce, other soil parameters can be used to define their hydraulic functions" (Sierra et al, 2006).

Our study aims to understand the comparison of the amount of leachate present in the sanitary landfill sites of the Mejía and Ambato cantons from a conceptual point of view. This permits one to determine the behaviour of the soil given the leachate pressure at a certain depth and time applicable to the case study. For the development of the general objective, the following specific objectives were proposed: a) to identify the areas that show leachate retention in the soil by means of spatial information on a distribution colour scale, b) to propose a model that uses curved graphs to describe the pressure load, hydraulic load and leachate content for simulations of 10, 20, 30 and 40 minutes, and; c) to develop the numerical solution in order to model the infiltration behaviour in the soil caused by leachate using mathematical software for the case study.

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2 Materials and Method

For the development of this study, the following activities were realised:

- A bibliographic review was carried out to determine the mathematical models to be used in the study.
- The sanitary landfill sites (Mejía and Ambato) were visited to identify areas that have leachate retention in the soil.
- Using GPS, the coordinates of the place and sampling points were taken, in which the area was later surveyed with the use of the ArcGis and Matlab programmes.
- The results obtained from the two sanitary landfill sites were analysed.

2.1 Field phase

Activity 1. Delimiting the study area.

The work was carried out at the sanitary landfill sites of the Mejía and Ambato cantons.

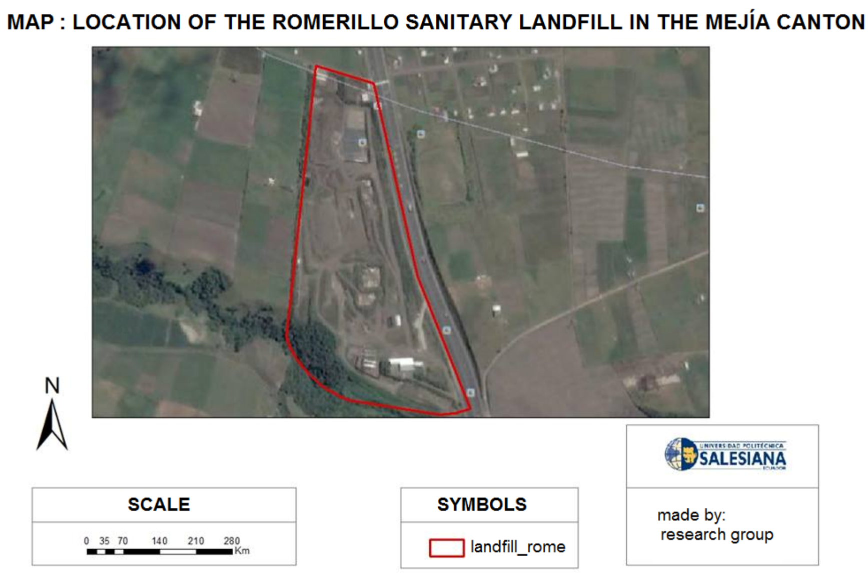

Fig. 1. Location of the sanitary landfill site in the Mejía canton.

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Fig. 2. Location of the sanitary landfill site in the Ambato canton.

Activity 2. Perimeter survey of the study area

With the support of a GPS navigator, the WGS 84 17 S coordinates were taken. The sampling points were identified at the two study sites.

Activity 3.

Once the sampling points were defined, the necessary variables for the Matlab simulation were measured in the field.

2.2 Simulation phase

Activity 1: Measurements in the field

The coefficients of the equations were determined by:

- **Infiltration speed**

Sampling was done with: a homemade infiltrometer, tools such as a cylinder and plastic sheath, and a sample of leachate, all of which helped determine the infiltration rate.

- **Hydraulic conductivity**

To calculate the hydraulic conductivity, a soil gravimetry test was performed to ascertain soil texture and verify hydraulic conductivity in the already established tables.

- **Lower suction head**

In the laboratory, the suction curve h (θ) was determined by the hanging column methods. For this, the following was taken into account:

- Sample of soil with leachate

The input data are texture, soil density, field capacity or moisture content, 15cm suction and wilting point or moisture content at atmospheric pressure and soil density.
The granulometric characteristics of the soil were determined by soil textures.

- Porosity

Porosity was determined in tables according to soil type, which is identified by the shape it takes.

Activity 2: Codification in Matlab

The variables measured in the field and variables after bibliographical consultation were included in the script that related the Van Genuchten (soil characteristic) and Richards (pollutant infiltration on a surface) models by obtaining curves regarding hydraulic load, pressure load and percentage of leachate based on their relationship. To develop the numerical solution for the infiltration behaviour in the soil caused by leachate, we used mathematical software based on the Richards equation with which the simulations for the different simulation scenarios were obtained in the Matlab R2014a programme. Below, a Matlab 10-minute script is presented. This was used to determine the graph of the three variables mentioned for the Ambato sanitary landfill site (see supplementary material).

Activity 3:

Once the simulation had been carried out, a database was generated with the numerical results obtained.

2.3 Equations to be used

In the study, we used the following equations:

2.3.1 Darcy equation:

The movement of fluid is given from higher to lower potential. Darcy's law (1856) states:

$$q = -K\nabla H \qquad \textbf{(1)}$$

Where: q is the flow rate per unit area [m/s], K is the hydraulic conductivity [m/s], H is the hydraulic head.

In the unsaturated area, hydraulic conductivity is a function of water content in the soil, expressed as K = K (2), whilst in the saturated zone, K is independent of 2 (Vargas et at, 2010), therefore Darcy's law for the unsaturated zone can be expressed as:

$$\vec{q} = -K(\theta)\nabla H \qquad \textbf{(2)}$$

And in each direction as:

$$q_x = -K(\theta)\frac{\partial \psi}{\partial x} \qquad \textbf{(3)}$$

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$$q_y = -K(\theta)\frac{\partial \psi}{\partial y} \quad \textbf{(4)}$$

For the element shown, the movement of the water in a one-dimensional direction is determined, where qx is the input waste and qx + Δx is the output waste. Taking into account the concept of mass conservation, one obtains:

input mass - output mass = net mass

$$\text{input mass} \quad m.entrada = p \cdot q_x \ \Delta_y \Delta_z \Delta_t \quad \textbf{(5)}$$

$$\text{output mass} \quad m.\ salida = p \cdot (q_{x+\Delta x}) \ \Delta_y \Delta_z \Delta_t \quad \textbf{(6)}$$

$$\text{net mass} \quad m.\ neta = (p \cdot q_x - p \cdot q_{x+\Delta x}) \ \Delta_y \Delta_t \quad \textbf{(7)}$$

Combining the continuity equation and that of Darcy, we obtain the general flow equation:

$$\frac{\partial \theta}{\partial} = \frac{\partial}{\partial x}\left[K(\theta)\frac{\partial \psi}{\partial x}\right] + \frac{\partial}{\partial y}\left[K(\theta)\frac{\partial \psi}{\partial y}\right] + \frac{\partial}{\partial z}\left[K(\theta)\frac{\partial \psi}{\partial z}\right] + \frac{\partial K(\theta}{\partial} \quad \textbf{(8)}$$

2.3.2 Richards equation

The Richards equation is the numerical integration of variations in humidity, tension and hydraulic conductivity. The equation that governs the flow in the unsaturated zone (Castañeda et al, 2004) is obtained by combining Darcy's law with the continuity equation, which for a vertical flow in one dimension is written as:

$$C(h)\frac{\delta h}{\delta t} = \frac{\delta}{\delta z}\left[K(h)\left(\frac{\delta h}{\delta z} - 1\right)\right] \quad \textbf{(9)}$$

Where: C (h) is the specific moisture capacity (L-1); K is hydraulic conductivity (LT-1); z is the vertical coordinate (L), positive going down; h is the pressure height (L), a function of the volumetric water content θ (L3 L-3). To obtain the solution of the vertical flow equation in one dimension, it is necessary to specify the appropriate initial and edge conditions. The initial condition is given by the pressure height h throughout the profile and the edge conditions that can be applied are the potential condition or flow condition (Radcliffe et al, 2010).

2.3.3 Van Genutchen equation

The Van Genutchen equation indicates the characteristic curve of the soil:

$$\theta(\psi) = \theta\tau + \frac{\theta s + \theta r}{[1 + (\alpha|\psi|)^n]^{1-1/n}} \quad \textbf{(10)}$$

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Where: $\theta(\psi)$is the water retention curve [L^3L^{-3}], $|\psi|$ is the suction pressure ([L] or cm of water), θs is the saturated water content [L3L-3], $\theta r$is the residual water content [L^3L^{-3}] [L3L -3] (Bautista et al, 2015).

2.3.4 Results analysis

We proceeded to the analysis of the results obtained by the Matlab tools according to each of the established variables.

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3. Results

3.1 Place: Romerillos Sanitary Landfill Site.

Table 1. Texture of the soil type.

Texture	Hydraulic conductivity	Porosity
Sandy	5(2.5-2.5)	38(32-42)
Sandy loam	2.5(1.2-7.6)	43(40-47)
Sandy loam	1.3(0.8-2.0)	47(43-49)
Silty loam	0.8(0.25-1.5)	49(47-54)
Silty clay	**0.25(0.03-0.5)**	**51(49-53)**
Clay	0.05(0.01-1.0)	53(51-55)

Source: Dorner, J. (2017)

Table 2. Values required for the simulation.

L = 200	length [L]
s1 = 0.0225	Infiltration speed [L/T]
s2 = 0	lower suction head [L]
T = 10, 20, 30, 40	maximum time [T]
qr = 0.218	Constant
f = 0.52	porosity
a = 0.0115	van Genuchten parameter [1/L]
n = 2.03	van Genuchten parameter
ks = 31.6	saturated conductivity [L/T]

Source: Matlab R2014a

Table 3. Data obtained in the simulation

VARIABLE	TIME (min)	MINIMUM	MAXIMUM	SD	AVERAGE	CV (%)
Hydraulic load	10	-190	-137.37	37.22	-163.69	23
	20	-195.32	-142.075	37.65	-168.70	22
	30	-197.14	-149.38	33.77	-173.26	19
	40	-199.28	-155.65	33.85	-178.45	23
Pressure load	10	-189.15	-135.27	38.10	-162.21	23
	20	-183.2	-140	30.55	-161.60	19
	30	-189.15	-143.19	32.50	-166.17	20
	40	-183.65	-148.87	24.38	-165.61	16
Leachate content	10	0.53547	0.33476	0.14	0.44	33
	20	0.56227	0.32912	0.16	0.45	37
	30	0.5591	0.32348	0.17	0.44	38
	40	0.5856	0.3202	0.16	0.45	39

Source: Matlab tool results

Table 3 shows the descriptive statistics of the variables obtained from the Matlab simulation, grouped by simulation time (hydraulic load, pressure load, percentage of leachate).

In general, they presented higher variation coefficients in the 10-minute simulation for both pressure load and hydraulic load. However, the decrease in CV in the leachate percentage variable was evidenced during the time of 10 minutes.

3.2 Curved graphs obtained in Matlab

Through the relationship of the Van Genuchten and Richards models, the graphs were obtained from ordinary differential equations (Giráldez et al, 1995). The results were presented graphically by curves of different colours at a certain depth, in addition to the viability of each of the parameters analysed. Below, each of the variables grouped according to time is shown.

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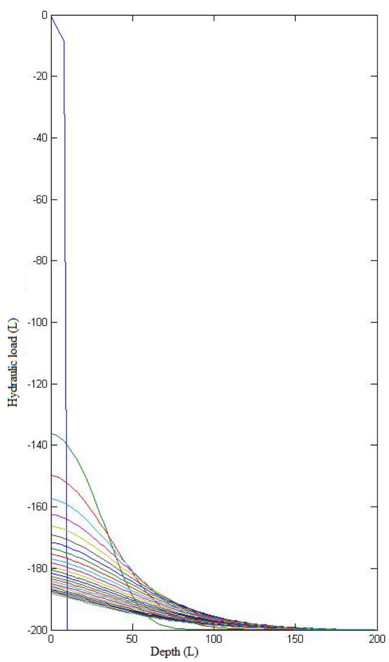
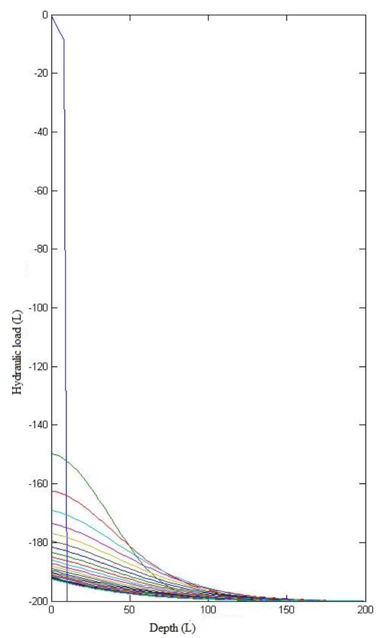
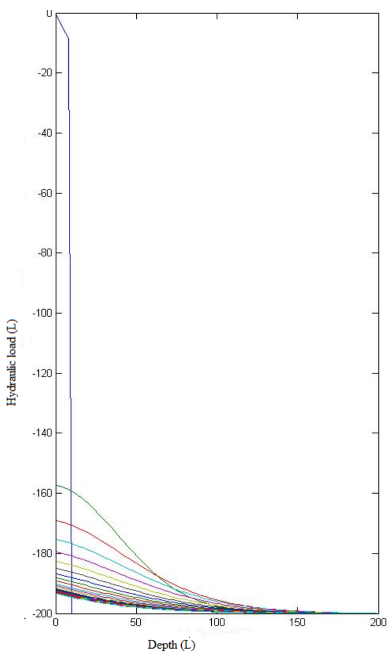
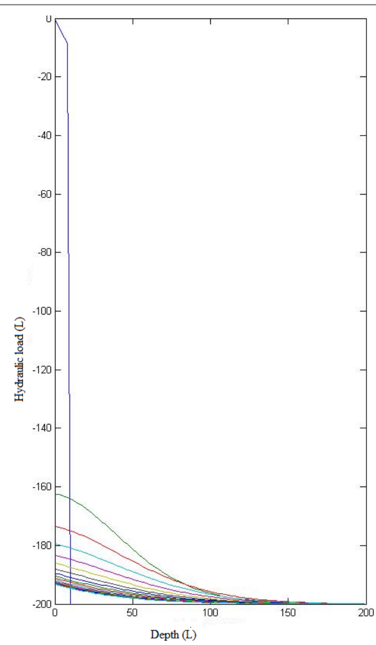
	
10 minutes	**20 minutes**
	
30 minutes	**40 minutes**

Fig. 3. Trend of the Hydraulic Load at different soil depths.Figure 3 indicates the behaviour of the hydraulic load variable at certain depths and times. The hydraulic load indicates the volume of leachate found in the soil.

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The greater the depth, the lower the hydraulic load, so when performing the simulation at the different times (10, 20, 30 and 40 minutes) we can determine that: a) for 10 minutes and at a depth of 51.24cm, the hydraulic load is -179.79 and so on until it reaches a depth of approximately 178.87cm and hydraulic load of -190; b) for 20 minutes at a depth of 55.88cm, the hydraulic load is -195.32 and so on until arriving at a depth of approximately 140cm and hydraulic load of -142,075; c) for 30 minutes at a depth of 99.07cm, the hydraulic load is -197.14 and so on until it reaches a depth of approximately 161.68cm and hydraulic load of -149.38, and d) for 40 minutes of simulation, beginning at a depth of 118.64cm, the hydraulic load is -199.28 and so on until arriving at a depth of approximately 163.48cm and hydraulic load of -155.65.

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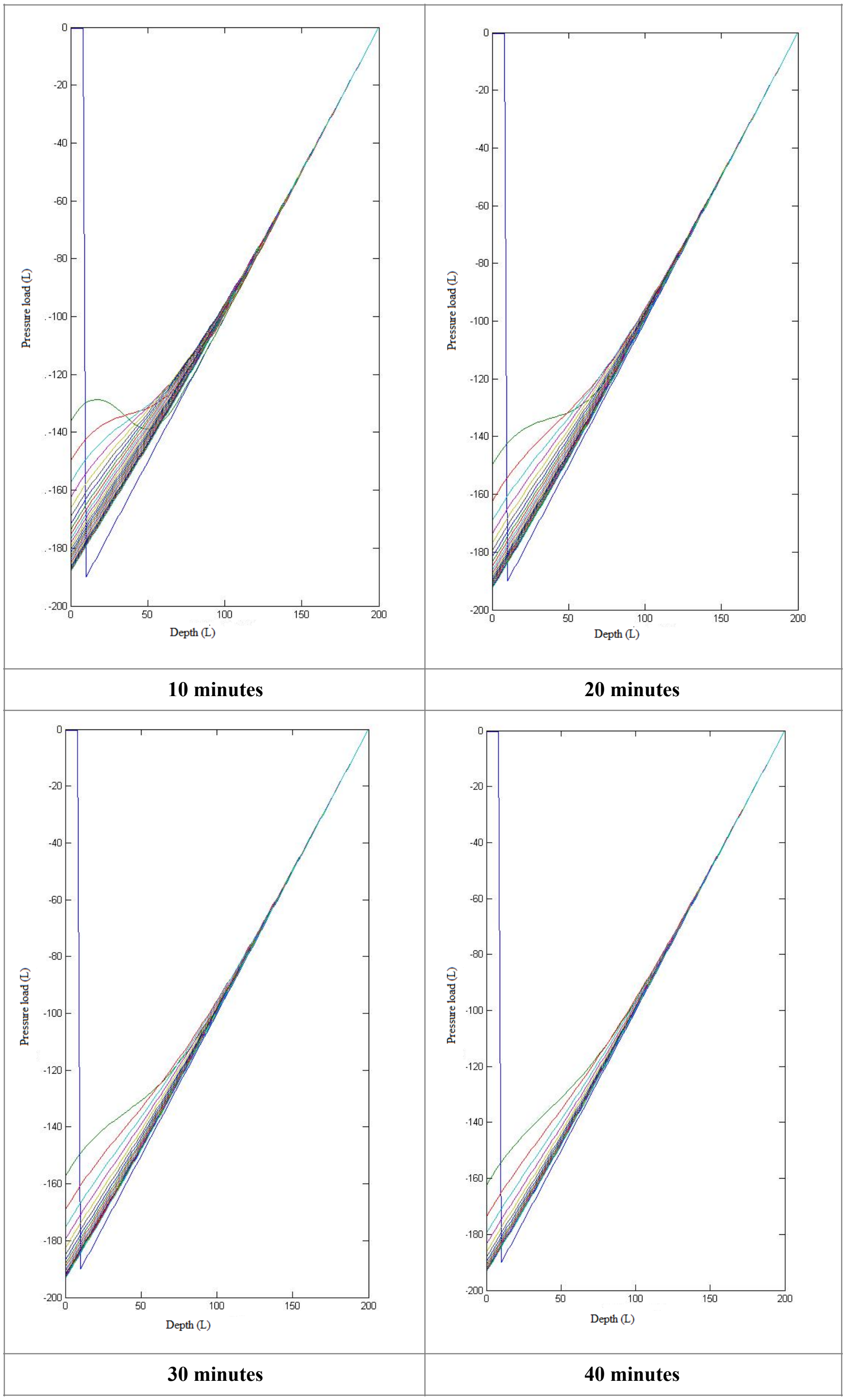

Fig. 4. Trend of the Pressure Load at different soil depths.

Figure 4 indicates the pressure exerted by the weight of the leachate in the soil at certain depths and times. It can be observed that in all the simulations, the pressure tends to increase as depth increases, so in the simulations we have: a) for 10 minutes, the pressure load is -189.15 at a depth of 2.417cm and so on until reaching a depth of

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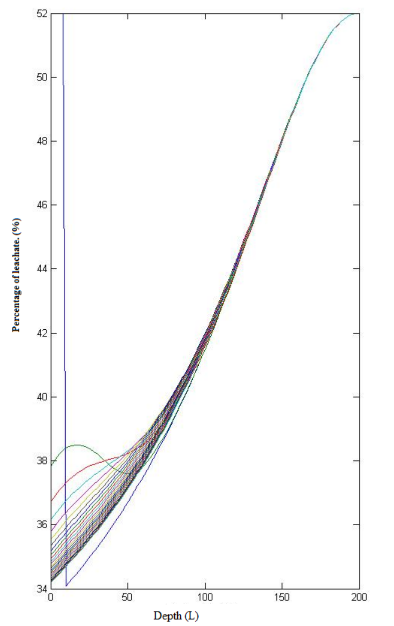
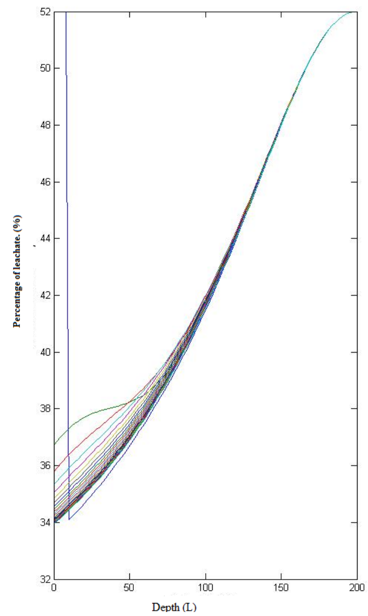
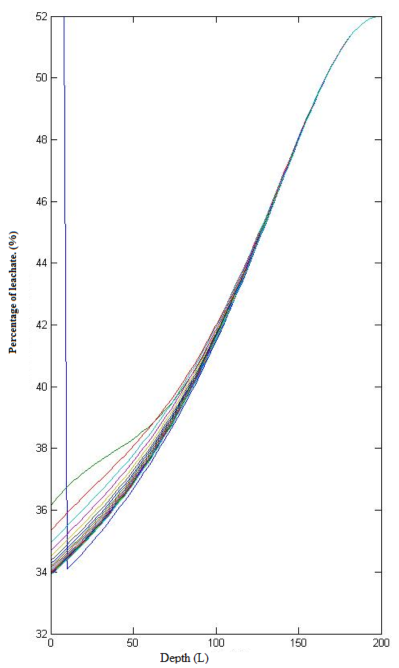
approximately 200.14cm and pressure of -135.27; b) for 20 minutes at a depth of 21.26cm the pressure load is -183.2 and this increases until reaching a depth of 200.00cm and pressure of -140 c) for 30 minutes at a depth of 46cm the pressure load is -189.15 and so on until reaching a depth of approximately 193cm and pressure of -143.19; finally c) for 40 minutes, at a depth of 2.158cm the pressure load is -183.65 and so on until reaching a depth of approximately 200 cm and pressure of -148.87.



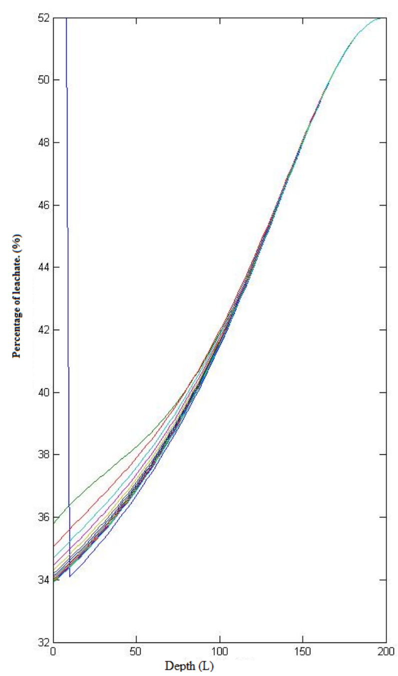
10 minutes



20 minutes



30 minutes



40 minutes

Figure 5. Leachate percentage trend at different soil depths.

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Figure 5 indicates the percentage of leachate present in the soil. It was determined that the soil reaches a saturation point, which means that the deeper the leachate filtration is, the simulation at the determined types shows us that the following occurs. a) In the simulation of 10 minutes, at 0cm there is 53% leachate, which was more or less true for all simulations. When the depth of the soil increases, the accumulated percentage of the leachate gradually decreases. At a depth of 70cm, there is a 49% accumulation of leachate. At 100cm, it is clear that the leachate decreases to 33% and this increases in relation to the depth of the soil. b) With 20 minutes of simulation, the percentage of leachate at 0cm is 52%. That percentage increases until we reach 70cm with a leachate accumulation of 56%. After 100cm, the accumulation of leachate begins to decrease (32%), and even more so at a depth of 120cm (29%). c) With 30 minutes, at 0cm there is 52% of leachate. As the depth of the soil increases, the accumulated percentage of leachate gradually decreases. At a depth of 70cm there is a 44% leachate accumulation. At 100 cm, the leachate decreases to 32% and then accumulation increases as depth increases. d) With the simulation of 40 minutes, at 0cm there is a 52% accumulation of leachate. When the depth of the soil increases, the accumulated percentage of the leachate gradually decreases. At a depth of 70cm there is a 39% accumulation of leachate. At 100cm, it can be seen that the leachate decreases to 32%.

3.2 Place: Ambato Sanitary Landfill Site

Table 4. Texture of soil type.

Texture	Hydraulic conductivity	Porosity
Sandy	5(2.5-2.5)	38(32-42)
Sandy loam	**2.5(1.2-7.6)**	**43(40-47)**
Sandy loam	1.3(0.8-2.0)	47(43-49)
Silty loam	0.8(0.25-1.5)	49(47-54)
Silty clay	0.25(0.03-0.5)	51(49-53)
Clay	0.05(0.01-1.0)	53(51-55)

Source: Dorner, J. (2017)

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Table 5. Values required for the simulation

L = 200	length [L]
s1 = 0.0332	Infiltration speed [L/T]
s2 = 0	lower suction head [L]
T = 10, 20, 30, 40	maximum time [T]
qr = 0.218	Constant
f = 0.44	porosity
a = 0.0115	van Genuchten parameter [1/L]
n = 2.03	van Genuchten parameter
ks = 31.6	saturated conductivity [L/T]

Source: Matlab R2014a

Table 6. Data obtained in the simulation.

VARIABLE	TIME (min)	MINIMUM	MAXIMUM	SD	AVERAGE	CV (%)
Hydraulic load	10	-200	-197.42	52.17	-198.71	33
	20	-195.77	-184.04	52.47	-189.91	30
	30	-200.68	-171.22	44.10	-185.95	31
	40	-187.74	-150.52	37.85	-169.13	33
Pressure load	10	-173.04	-180.11	45.33	-176.58	37
	20	-225.41	-197.65	49.74	-211.53	32
	30	-184.54	-206.41	32.85	-195.48	26
	40	-199.05	-214.33	36.65	-206.69	27
Leachate content	10	0.54301	0.36147	0.17	0.45	30
	20	0.55987	0.34782	0.16	0.45	37
	30	0.5501	0.35365	0.14	0.45	38
	40	0.57852	0.34417	0.15	0.46	42

Table 6, as in the previous case, shows the descriptive statistics of the variables obtained from the Matlab simulation, grouped by simulation time (hydraulic load, pressure load and percentage of leachate).

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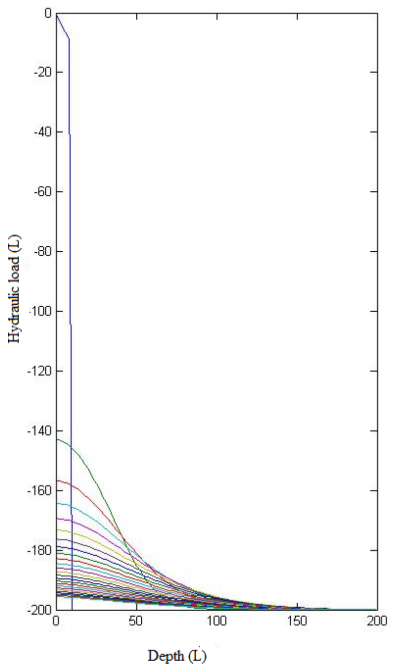
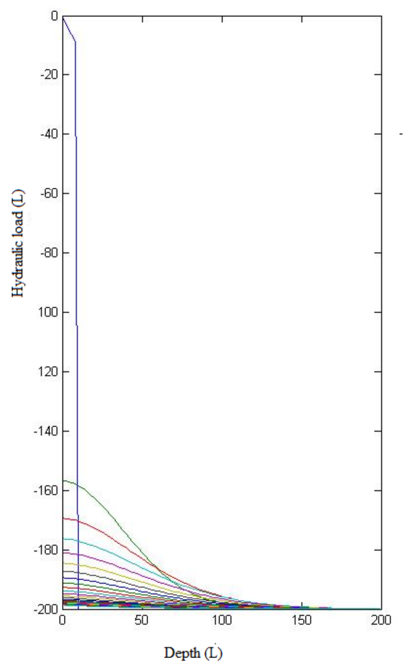
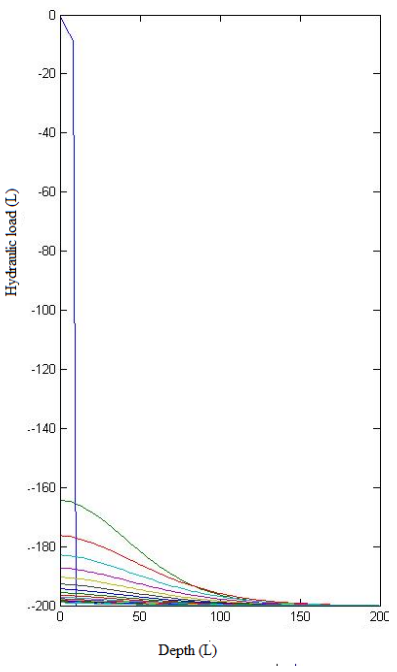
Graphs obtained in Matlab

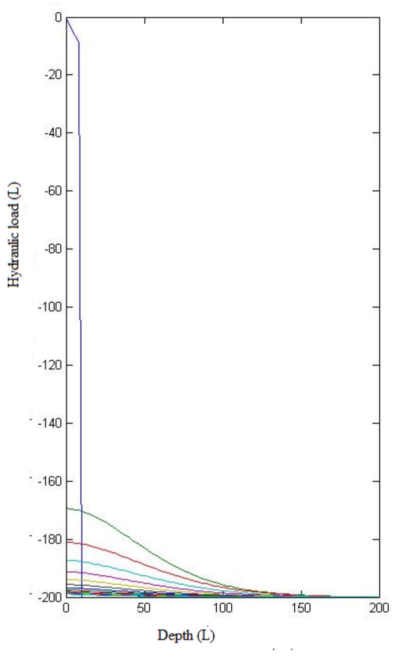
As with the Romerillos sanitary landfill site, the curved graphs were obtained from ordinary differential equations. These results were presented graphically by curves of different colours at a certain depth, in addition to the viability of each of the parameters analysed. Below, each of the variables grouped according to time is shown.





10 minutes	20 minutes





30 minutes	40 minutes

Fig. 6. Trend of Hydraulic Load at different soil depths.

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Figure 6 indicates the behaviour of the variable hydraulic load at certain depths and times. The hydraulic load indicates the volume of leachate found in the soil. The greater the depth, the lower the hydraulic load, so when performing the simulation: a) for 10 minutes after reaching a depth of 51.24cm, the hydraulic load is -200, and so on until a depth of 178 , 87cm and hydraulic load of -197.42; b) for 20 minutes at a depth of 55.88cm the hydraulic load is -195.77 until a depth of approximately 140cm and hydraulic load of -184.04; c) for 30 minutes at a depth of 99.07cm the hydraulic load is -200.68 and so on until reaching a depth of 161.68cm and hydraulic load of -171.22; and d) for 40 minutes of simulation, we started with a depth of 118.64cm and hydraulic load of -187.74 and so on until arriving at a depth of approximately 163.48cm and hydraulic load of -150.52.

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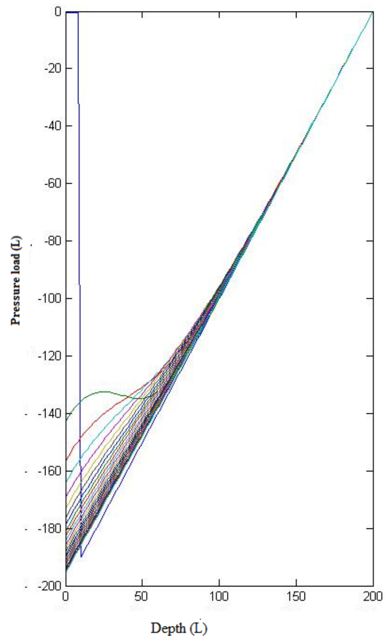
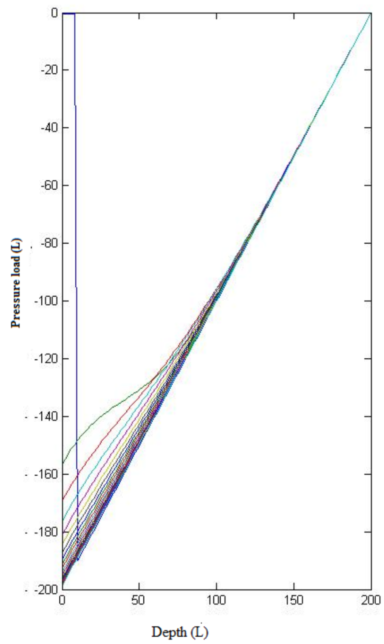
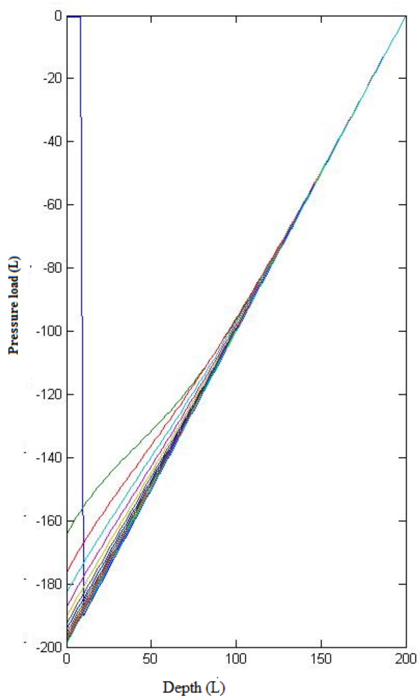


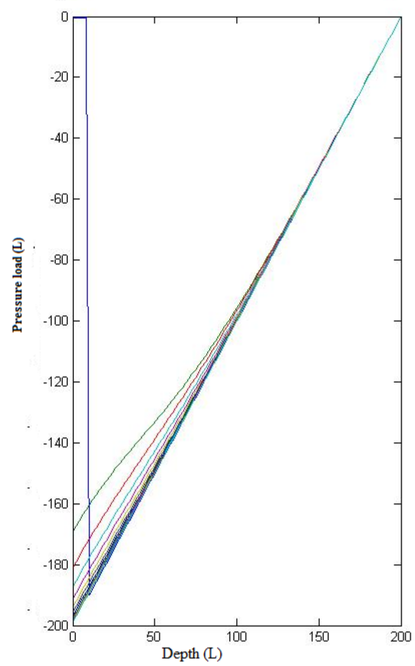
10 minutes



20 minutes



30 minutes



40 minutes

Fig. 7. Trend of the Pressure Load at different soil depths.

Figure 7 indicates the pressure exerted by the weight of the leachate in the soil at certain depths and times. It can also be observed that in all simulations, the pressure tends to increase as depth increases. Thus, in the simulations we have: a) for 10 minutes, the pressure load is -173.04 at a depth of 2.417cm and so on until reaching a depth of approximately 200.14cm and pressure load of -180.11; b) for 20 minutes at a depth of 21.26cm the pressure load is -225.41 and this increases until reaching a depth of 200cm and pressure load of

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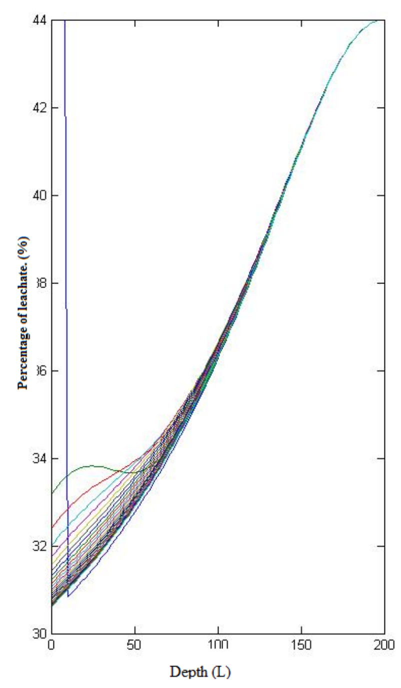
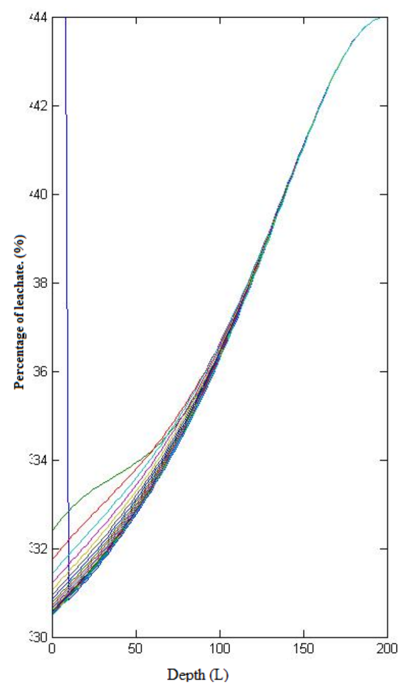
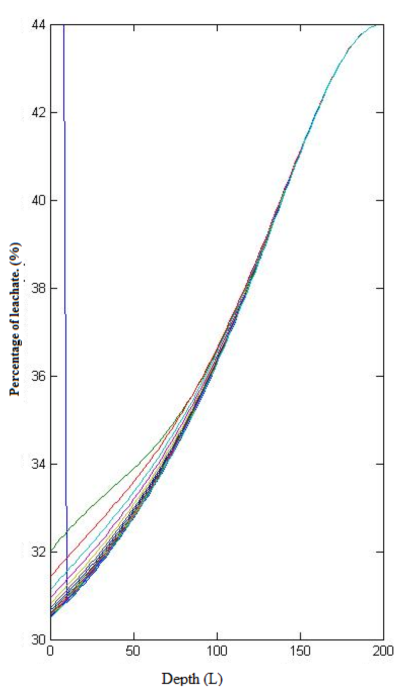
-197.65 c) for 30 minutes at a depth of 46cm the pressure load is -184.54 and so on until reaching a depth of approximately 193cm and pressure load -206.41; finally c) for 40 minutes, at a depth of 2.158cm the pressure load is -199.05 and so on throughout the simulation until reaching a depth of approximately 200 cm and pressure load of -214.33



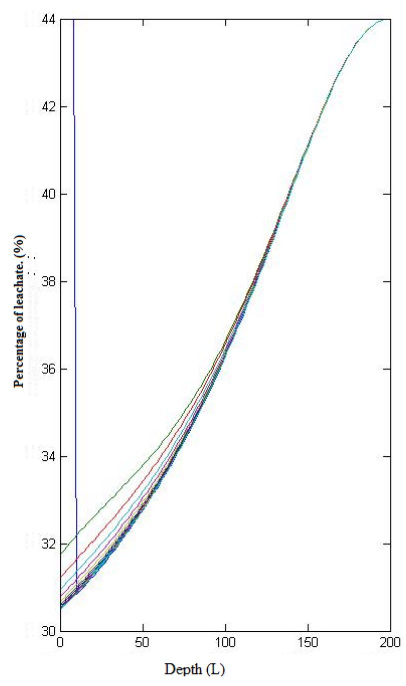
10 minutes



20 minutes



30 minutes



40 minutes

Fig. 8. Trend of the Leaching Percentage at different soil depths.

Figure 8 indicates the percentage of leachate present in the soil. It was determined that the soil reaches a saturation point, which means that the deeper the leachate filtration is, the simulation at the determined types shows us that the following occurs. a) In the simulation of 10 minutes, at 0cm there is 54% leachate, which was more or less true for all simulations. When the depth of the soil increases, the accumulated percentage of leachate gradually decreases. At the depth of 70cm there is a 51% accumulation of leachate. At 100cm, the leachate decreases to 36% and this increases in relation to the depth of the soil. b) With 20 minutes of simulation, the percentage of leachate at 0cm is 55% and that percentage decreases until we reach 70cm and a leachate accumulation of 56%. After 100cm, the accumulation of leachate begins to decrease (34%), and even more so at a depth of 120cm (30%). c) With 30 minutes, at 0cm there is 55% leachate. When the depth of the soil increases, the accumulated percentage of the leachate gradually decreases. At a depth of 70cm there is a 45% accumulation of leachate. At 100cm, the leachate decreases to 35%, and then accumulation increases as depth increases. d) With the simulation of 40 minutes, at 0cm there is a 57% accumulation of leachate. When the depth of the soil increases, the accumulated percentage of the leachate gradually decreases. At a depth of 70cm, there is a 38% accumulation of leachate. At 100cm, the leachate decreases to 34%.

4. Discussion

The importance of the study and Matlab simulation arises from the need to know the behaviour of the soil faced with pollutant infiltration (leachate) at a spatial level and therefore in a continuous field. For this, one must implement methods to construct said fields when the measurement of this variable is done with position points and on the surface.

According to the results obtained in the simulation, it can be seen that the behaviour of the parameters tested varies depending on the differing soil characteristics. Given the soil types of the Romerillos and the Ambato Sanitary Landfill Sites (silty clay and sandy loam texture, respectively), it was determined that as depth increases the soil changes its structure and horizons. It also becomes more compact in relation to the superficial soils.

In the simulation of 10, 20, 30 and 40 minutes and according to what was formulated by Chan and Pratley (1998), the behaviour of the soil with respect to the hydraulic load is inversely proportional to the depth of the soil, due to the soil characteristics. Consequently, data is obtained, where greater depths mean lower hydraulic loads for both sanitary landfill sites. The results obtained from the variable under study were similar at the different times and soil textures. We observed that when depth increased, volume of leachate decreased. Therefore, it was established that the volume of leachate is close to the surface of the soil.

Different functions are used for pressure loads and these were determined in the study by Southorn and Cattle (2004). They found that pressure loads are directly proportional to the surface of the soil; that is, the greater the depth of the soil, the greater the pressure, due to the pressure exerted by the fluid on the surface. In the simulations carried out at the landfill sites at the four established times, it was perceived that the soil's porosity and structure of the horizons change at greater depths. These are influential factors in the variation of pressure load, which is verified in the study by performing the two simulations with the two soil textures corresponding to the two landfill sites. We concluded that the greater the depth, the greater the pressure exerted by the leachate. In the simulations corresponding to 10, 20, 30 and 40 minutes in Matlab, similar behaviours were observed at each of the times. Visualised in the graphs, one can see that the pressure exerted by the weight of the leachate in the soil is greater as depth increases, because the pressure of the leachate is greater than air pressure.

During the simulations corresponding to percentage of leachate, a similar behaviour was observed at each of the times. One notes that as depth increases, percentage of leachate decreases due to soil infiltration. Alegre et al (1996) determined in their study that when leachates cannot pass through the soil, they are accumulated in the strata, which is harmful to organisms present in the soil such as plants and microorganisms. Likewise, organic

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matter present in this type of soil can be contaminated, which is the beginning of a chain of contamination by leachates present in the soil (Dorner et al, 2009).

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