Construction And Test of An Instrumented 2D Channel With Rainfall And Insolation Control.

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Construction and test of an instrumented 2D channel with rainfall and insolation control

Bruno Rogério da Hora Lôbo · Sandro Lemos Machado · Edson Pereira Marques Filho

Abstract This paper presents the construction and testing of a large instrumented 2D channel for the simulation of the performance of compacted barriers under controlled conditions of insolation and rainfall. Details of the main apparatus devices and capabilities and the results of a long-term test performed on a capillary barrier (CB) are presented. The performed test aimed to simulate the CB behavior over a period of one year in typical semi-arid conditions. The channel behavior was considered very promising with its components functioning as expected and providing the desired information. Concerning the CB performance, it is shown that the upper clayey layer of soil presented undesirable shrinkage cracks that impacted the CB performance, mainly at the end of the period of evaluation. The obtained results point to the need to use of silty or low plasticity clayey soils in the CB design, despite the higher expected values of hydraulic conductivity, as well as the adoption of layers thicker than usual in order to preserve the integrity of the clayey soil near the interface with the bottom coarse soil layer.

Keywords Capillary barrier · Landfill final cover · Soil-Atmosphere interaction · Semi-arid

1 Introduction

Landfill cover layers constitute one of the main elements to be considered for an adequate landfill performance in field. They are of paramount importance in reducing the entry of liquids into the landfill cells (and therefore leachate generation), preventing gas emissions, and propitiating an adequate anaerobic environment for waste decomposition in cases where energy recovery from biogas is desired. Therefore, they directly influence the landfill management costs and the environmental impacts during the operation and after the closure of the landfill.

Cover layers are usually composed of low permeability compacted clayey soil with or without additives and they are often used because of their low cost, accessibility, durability, high resistance to heat and other factors (Wang & Huang (1984)). However, cover layer properties such as their susceptibility to shrinkage/swelling should be addressed (Daniel & Benson (1990); Shackelford (2014)). According to these authors, despite their acceptable performance, clayey soils usually present cracks in response to the drying/wetting cycles they undergo in field or because of the differential settlements of the waste mass, which lead to their loss of efficiency in the long term, especially in arid or semi-arid regions.

Capillary barriers (CB) are a relatively new concept, designed to reduce the downward flow to the waste while keeping high saturation levels in the clayey soil, which inhibits the upward flow of gases. They are normally composed of a granular soil layer superimposed by a clayey soil. Because of the contrast in their soil water retention curves (SWRC), the granular soil, which exhibits much higher water hydraulic conductivity compared to clayey soil when saturated, presents lower hydraulic conductivity for the suction levels normally obtained in field. The clayey soil has as primary function provisionally to store the infiltration water, releasing it into the atmosphere in periods of no rain. Therefore, its thickness must consider the rainfall/evaporation patterns of the region of installation and the effective storage capacity of the clayey soil.
Due to the growing interest in CB in recent years, much research work dealing with the CB soil-atmosphere interactions and modeling can be found. It can be said that the study of the capillary barriers started with the work of Yeh et al. (1985), who carried out a stochastic analysis of the unsaturated flow in heterogeneous soils, using laboratory and field observations. The authors concluded that according to the experimental evidence they could take advantage of the existing contrast between the hydraulic properties of the materials (fine/coarse soils). Years later, Ross (1990) and Kämpf & Montenegro (1997) evaluated the performance of several CB on an inclined surface. Until then, the variables that intrigued the researchers were only the hydraulic conductivity functions of the materials involved in the layer and their laying angle. The influence of evaporation and evapotranspiration on the performance of capillary barriers has been studied by several authors (Khire et al. 2000, Stormont 1996, Stormont & Anderson 1999, Webb 1997). The obtained results helped to consolidate CB as a cover alternative for waste disposal facilities, especially in arid and semi-arid regions. Considering the more recent works, the laboratory study of CB performance has gained impetus, as illustrated in the works of Vieira (2005), Tidwell et al. (2003), Oliveira & Marinho (2007), Tami et al. (2004), Silva (2011), Zhan et al. (2014). However, only few works focus on a 2D flow laboratory approach that considers the influence of the weather conditions on the expected CB performance and attempt to perform tests in environmental conditions that are close to the concern area (see Table 1). The use of instrumented 2D flow channels can supply valuable information concerning CB performance under controlled conditions. They allow the visual observation of the experiments and the monitoring of important variables such as the soil moisture content, suction, and temperature. This technical note presents the development and testing of an instrumented 2D channel with inclination control which can simulate rainy events and periods of insolation. The barrier performance is evaluated considering weathering data from the semi-arid region of Brazil, over the equivalent period of one year.

### Table 1 Experiments using 2D flow channel and variables measured.

| Reference        | Suction | Water content | Run-off | Bottom Drainage | Rainfall simulator | Radiance simulator | Relative humidity | Dimensions (m) |
|------------------|---------|---------------|---------|-----------------|-------------------|-------------------|------------------|----------------|
| Tami et al. (2004) | X       | X             | X       | X               | X                 | X                 |                  | 2.4 x 2.0 x 0.40 |
| Almeida (2011)   | X       | X             | X       | X               |                   |                   |                  | 2.0 x 1.0 x 0.60 |
| Sousa (2012)     | X       |               |         |                 |                   |                   |                  | 2.0 x 1.2 x 0.15 |
| Zhan et al. (2014)| X       | X             | X       | X               | X                 |                   |                  | 2.0 x 1.2 x 0.15 |
| Ng et al. (2015) | X       | X             | X       | X               |                   |                   |                  | 3.0 x 1.0 x 1.1  |
| Current study    | X       | X             | X       | X               | X                 |                   | X*               | X*             |

X* = Implemented in the test currently in course

### 2 Materials and methods

#### 2.1 Study area

Although the instrumented channel can be used to evaluate the behavior of distinct types of mineral barriers under different weather conditions, this research focused on the performance of capillary barriers under semi-arid climate conditions. Therefore, the weather conditions imposed to the channel in laboratory were based on surface meteorological measurements collected by INMET (National Meteorological Institute, Brazil) in the period of 2010-2018 in the cities of Barra, Irecê, Remanso and Petrolina. All these towns are located in the Brazilian semi-arid region which comprises a considerable portion of the Brazilian northeast states (see Figure 1). In this region medium to small towns predominate in which municipal solid waste is disposed of in dump sites and the presence of landfills is rare. The authors of this study believe that the research results can give impetus to the use of alternative and less expensive cover layers, which could provide adequate environmental safeguards and encourage the installation of landfills in the region.
2.2 2-D Flow Channel

The developed channel has the following internal dimensions: 4.0 m long, 0.40 m high, and 0.15 m wide. Figure 2 presents a schematic view of the channel with the instrumentation and the main apparatus devices used. Moisture content and suction probes were installed at depths of 35cm (sand layer) and 5cm, 15cm and 25cm (clayey soil layer). The instrumentation is described in section 2.6.1. As indicated in Figure 2, at the lower end of the channel, two discharge exits measure run-off drainage (ROD) and, eventually, the amount of water that passes through the barrier is collected by the bottom layer drainage (BLD).

In addition to allowing different slope configurations, a galvanized steel structure was installed in the channel top so as to simulate different weather conditions with variations in the intensity of solar radiance and rainfall (see Figure 3). Both systems are discussed in detail later and are also indicated in Figure 2.
2.3 The rainfall simulator and the rainfall regime

In order to simulate rains with different intensities and duration, a rainfall simulator (RS) was developed, inspired by two previous studies (Nissen et al. 2000, Vieira 2005). The RS has about 1500 needles, the same channel cross section and an internal height of 10 cm (see Figure 4). Rain intensity \( I \) was calibrated as a function of the water head inside the RS, which was a function of the flow rate entering the channel. The accumulated rainfall was a function of the time interval the channel was fed with water as well as of the water head inside the RS.

Several experiments were carried out to calibrate the rainfall produced by RS for different combinations of water head and channel water fed duration. Figure 5(a) and 5(b) show the obtained rains for water heads of 2 and 8mm and water supply time of 1 hour. As can be observed, the produced rainfall is characterized by two transient portions located at the beginning and in the final part of the event, with a nearly stationary central portion. The rain intensity reached about a) \( I = 28\text{mm} \cdot \text{h}^{-1} \) and b) \( I = 70\text{mm} \cdot \text{h}^{-1} \) in the data presented in Figure 5, which can be considered as moderated/high to very high intensities according to the semi-arid rainfall pattern (see Table 2 and Figure 6). In this figure the presented results correspond to three different tests performed under the same conditions to evaluate the repeatability of the produced rain.

As the focus of the experiment was to evaluate the CB performance under weather conditions similar to those found in Brazil’s northeast semi-arid region, an analysis of the rainfall of the town cited above was performed. In the INMET dataset, hourly values of rainfall are available for Barra, Irecê, Remanso and Petrolina. Days with an accumulated rainfall of at least 1mm were considered rainy days and their data were used in the statistical analysis. Data from all the four towns were treated without distinction as they...
are in an area with the same climatic characteristics. Furthermore, statistical analysis of the main rainfall parameters proved to be similar, as presented in Figure 6.

The rainfall data (hourly basis) can also be seen in Table 2. In this case, some rain hourly average intensity intervals are shown along with the percentage of the annual accumulated rainfall they represent. As can be observed, about 75% of the yearly accumulated rainfall is composed of rains with an hourly rainfall less than 18.2mm.

Table 2 Hourly rainfall vs. Annual rainfall fraction.

| Hourly rainfall (mm) | Annual rainfall fraction (%) | Accumulated annual rainfall fraction (%) |
|---------------------|-----------------------------|------------------------------------------|
| 0 - 10              | 50                          | 50                                       |
| 10 - 18.2           | 25                          | 75                                       |
| 18.2 - 37.2         | 20                          | 95                                       |
| 37.2 - 68.2         | 5                           | 100                                      |

Table 3 presents the average rainfall for the different months of the year in the period analyzed. It is also shown the expected number of rainy days in each month. In the last four columns of Table 3 the rain distribution adopted for each month following the data presented in Table 2 is detailed. As an illustration, in January a total rainfall of 91mm is expected in the region, with 8 rainy days. This rainfall was then simulated using 10 hourly rainy events of 5mm (about 50% of the expected rainfall for these months) and one hourly event of 14mm and 25mm each, totaling 89mm. The adopted hourly rainfalls correspond to the middle of the intervals indicated in Table 2 and are marked as $I_5$, $I_{14}$, $I_{25}$ and $I_{45}$ in Table 3. Only one rainy event of 45 mm/h (representing the 37.2 - 68.2mm interval) was adopted in the simulations, following the frequency observed in field for this rain intensity.
Table 3 Monthly rainfall distribution.

| Month    | Average monthly rainfall (mm) | Rainy days | $I_5$ (mm/h) | $I_{14}$ (mm/h) | $I_{25}$ (mm/h) | $I_{45}$ (mm/h) |
|----------|-------------------------------|------------|--------------|----------------|----------------|----------------|
| January  | 91                            | 8          | 10           | 1              | 1              |               |
| February | 69                            | 8          | 11           | 1              | -              | -              |
| March    | 86                            | 9          | 7            | 2              | 1              |               |
| April    | 60                            | 7          | 9            | 1              | -              | -              |
| May      | 7                             | 3          | 1            | -              | -              | -              |
| June     | -                             | -          | -            | -              | -              | -              |
| July     | -                             | -          | -            | -              | -              | -              |
| August   | -                             | -          | -            | -              | -              | -              |
| September| -                             | -          | -            | -              | -              | -              |
| October  | 26                            | 4          | 3            | 1              | -              | -              |
| November | 55                            | 6          | 6            | 1              | -              | -              |
| December | 86                            | 9          | 6            | -              | -              | 1              |

The simulations in the channel started in the lower rainfall period, embracing the months of May to September. In order to optimize the simulations required time, the simulation of the dry season was interrupted after reaching stationary values in the installed suction and moisture probes and the rainy season, corresponding to the months of October to February, was started.

2.4 Solar radiance simulator

A solar radiance simulator was developed to simulate the incidence of solar radiance on the soil surface. This sought to represent the equivalent average daily radiance incidence of the meteorological stations studied, based on data obtained from INMET. Data for the period 2010-2018 was used to calculate the average daily radiance for each month. To perform the calibration of the solar radiance simulator, the apparatus depicted in Figure 7 was used. It consists of a rectangular light fixture, a Philips™ HPI-400 W metal-halide lamp, a pyranometer model CMP-3 by Kipp and Zonen, with a sensitivity of $12.43 \times 10^{-6} V/Wm^{-2}$, and a device to change the elevation and horizontal position of the pyranometer.

![Fig. 7 Overview of the apparatus for calibrating radiance simulator. Apparatus from LaPO laboratory.](image)

Figure 8(a) presents the solar radiance intensity behavior as a function of the distance lamp/pyranometer. In this case, the measurements took place in the focus of the light fixture. As expected, there is a decrease in the radiance intensity as the distance to the pyranometer increases. Considering an average radiance intensity of 440 W/m² (average radiance intensity for a period of 14hs of insolation in the semi-arid region obtained from the weather stations data), a distance of 27 cm was adopted between the lamps and the CB soil surface. Figure 8(b) presents the surface distribution of the radiance intensity for a distance lamp/pyranometer of 27 cm. As can be observed, although the occurrence of solar radiance decrease at the
edges of the system, the solar radiance distribution was considered to be satisfactorily distributed and the distance between the light fixtures was adjusted to avoid this border problem in the experiments.

Based on the obtained radiance distribution on the surface and in order minimize the occurrence of shadow areas, a horizontal distance between light fixtures of 15 cm was adopted. Figure 9(a) presents a typical sunny period simulation, whereas as Figure 9(b) presents a close up view of the position of the light fixtures along the channel length. 8 metal-halide lamps were used in total.

As the channel was installed in a closed room, the periods when the lamps were off were considered equivalent to night periods in the field.

2.5 Tests performed with temperature and relative humidity controls

Although the daily average temperatures of the experiments (25.6 °C) could be considered close in the field in the target area (25.9°C), the experiments were performed in higher relative humidity (RH) values.
(71.0 – 85.5%) compared to field conditions (36.4 – 69.7%). In order to evaluate the RH influence on the obtained results, a second test is currently running with temperature and RH control. A dual inverter air conditioner and a pair of humidifier/dehumidifier are used to keep the room weather conditions close to the field conditions in the day and night periods.

### 2.6 Capillary barrier composition

The upper part of the studied capillary barrier is formed of a residual clayey soil (USCS classification: MH) from metamorphic rocks (granulite/gneiss). The inferior part of the barrier consists of a uniform fine to medium sand (0.06-0.6mm) (dune sand, USCS classification: SP). Table 4 presents the main characteristics of the soils used whereas their SWRC are presented in Figure 10.

**Table 4** Main physical properties of the materials used in the CB.

| Soil         | Gravel (%) | Coarse sand (%) | Medium sand (%) | Fine sand (%) | Silt (%) | Clay (%) | $L_L$ (%) | $P_L$ (%) | USCS |
|--------------|------------|-----------------|-----------------|---------------|----------|----------|-----------|----------|------|
| Clayey soil  | 2          | 6               | 10              | 11            | 18       | 53       | 72        | 42       | 30   | MH   |
| Dune sand    | -          | -               | 89              | 11            | -        | -        | -         | -        | -    | SP   |

Two methods were used to determine the clayey soil SWRC. For high suction levels the dew point method was used using the WP4C® apparatus (Meter Group, USA). For low suction values, a small Richard’s chamber (Machado & Dourado 2001) was employed, following the methodology proposed by Fourie & Papageorgian (1995).

![Experimental Sand, van Genuchten - Sand, van Genuchten - Clayey Soil, Dewpoint Patricia Meter - Clayey Soil, Machado e Dourado (2001)](image)

**Fig. 10** Water retention curve for Sand and clayey soil.

In the case of the dune sand, continuous vaporization technique was used in conjunction with tensiometers as described in Sousa et al. (2011): after saturation, samples were kept exposed to the atmosphere, and the water mass loss and suction increase were monitored. SWRC were obtained by fitting experimental data using Equation 1 (van Genuchten (1980)):

$$
\theta = \theta_r + \frac{\theta_s - \theta_r}{1 + (\alpha\psi)^n}^m
$$

where $\theta_r$, $\theta_s$ and $\theta$ are the volumetric residual and saturated water contents and the volumetric water content for a given suction, $\psi$, respectively. $\alpha$ is related to air entry suction of the soil and $n$ is a parameter linked to the soil pore size distribution. A value of $m = 1 - 1/n$ was adopted. The physical and hydraulic parameters of the soils are presented in Table 5.
Table 5  Physical and hydraulic properties of soils.

| Soil       | $\rho_s$ ($g\cdot cm^{-3}$) | $\theta_r$ ($m^3\cdot m^{-3}$) | $\theta_s$ ($m^3\cdot m^{-3}$) | $\alpha$ | $m$ | $n$ | $k_s$ ($cm\cdot s^{-1}$) | $R^2$ |
|------------|-----------------------------|--------------------------------|--------------------------------|-----------|-----|-----|-------------------------|-------|
| Clayey soil| 2.79                        | 0.110                          | 0.514                          | 0.0008    | 0.004 | 1.004 | 1.93 $\cdot 10^{-8}$ | 0.9805 |
| Dune sand  | 2.70                        | 0.003                          | 0.362                          | 0.2755    | 0.555 | 2.251 | 1.43 $\cdot 10^{-3}$ | 0.9876 |

2.6.1 Soil compaction and instrumentation of the capillary barrier

The CB bottom layer (dune sand) was densified using a static strip foot until reaching a dry bulk density of $\rho_d = 1.72 \ g\cdot cm^{-3}$ using the moist tamping technique (1% moisture) (Diambra et al. 2010). After being released into the channel, leveled in a loose state, the soil layers with initial heights of about 2cm were subjected to light pressure until reaching the desired dry bulk density. A final height of about 10cm was adopted for the bottom sand layer.

The upper clayey layer was compacted using a mini sheepfoot (Figure 11(b)) to achieve a $\rho_d = 1.41 \ g\cdot cm^{-3}$ (maximum dry density of the Normal Proctor energy). First, the soil was released into the channel and leveled to reach about 1 cm of thickness; then the strip foot was used to gently compact the layer allowing the final compaction using the mini sheepfoot roller. Figure 11(a) and 11(b) illustrate the compaction process.

The flow channel enables the monitoring of the soil moisture content and suction at different points in the barrier (see Figure 12). Temperature, electrical conductivity and moisture content were monitored using 5 TE™ moisture sensors (Meter Group, USA) in both soils. Moisture sensors were calibrated specifically for the soils used prior to the tests. Matric suction in the clayey layer was monitored employing MPS-6™ (Meter Group, USA) suction sensors, whereas low capacity tensiometers (LCT) were used in the dune sand layer. The MPS-6™ sensors are dielectric water potential sensors for measuring soil water potential and temperature. According to Decagon Devices™, the accuracy of the probes is about 10% of the reading for the suction range reached in the experiments. The LCT has a pressure range of 0-100 kPa (absolute pressure) and porous stone tips with air entry value of 100 kPa (Model 0604D04-B01M1, Soil moisture™ Equipment Corp.) and were calibrated using water columns in the laboratory (Sousa et al. 2011). In order to avoid porous stone tip desaturation, LCT were removed, saturated and reinserted in the channel on a regular basis and before each rainy event.
3 Results and Analysis

The experimental CB performance evaluation started on September 9th, 2020 and after reaching equilibrium conditions with the environment, indicated by constant readings of matric suction and moisture content, the simulation of the rainy period was initiated (first rainy day occurred on day 145, February 9th, 2021).

Concerning the clayey layer behavior during the dry season, the appearance of cracks was observed. This was already expected, however, some cracks extended far enough to reach the bottom sand layer. Figure 13 presents the main cracks observed in the clayey layer. Figure 13(a) and 13(b) were submitted to filters to improve crack visibility. The observed results indicate the need for the use of thicker clayey layers in the field mainly if the occurrence of differential settlements is considered. Another aspect to be considered concerns the geotechnical nature of the soil used. Due to the observed shrinkage cracks, it is plausible to speculate that a more adequate volumetric behavior could be obtained if silty or low plasticity soils are employed in the upper CB layer, although some loss of performance is expected in terms of hydraulic conductivity.

Figures 14 and 15 illustrate the CB performance in the period of testing in the monitoring profiles 1 and 2 indicated in Figure 2. As expected, shallower probes (5cm depth) presented higher and more abrupt
variations in moisture content and matric suction over time. Considering the monitoring profile 1, probes located at 25 cm depth were able to present a smooth transition and nearly constant values of moisture content throughout the whole period of the test, indicating that the CB clayey layer was able to temporarily store the infiltration water above this point. Concerning the probes located in the middle of the clayey layer (15cm depth), a suction decrease can be observed after day 170, indicating the accumulation of water at this depth. Considering the probes located in the sand layer, it is possible to observe an increase in the sand moisture content after day 248. Since the moisture content at the 25cm depth moisture probe remained almost constant, the authors believe that there was a lateral supply of water coming from the crack presented in Figure 13(a). This was supported by visual inspections of the sand layer.

One of the main shrinkage cracks, presented Figure 13(b), was formed close to the soil monitoring profile 2. The authors believe that this was the main reason for the differentiated behavior presented in the two studied profiles. In the case of the monitoring profile 2, all the probes present accentuated variations after rainy events, indicating a poor performance of the barrier in this region. The CB bottom drainage was activated on the days 127, 145, 193, 238, 243, 246 and 263. The total amount of water that leaked to the bottom corresponded to 5mm of rain or about 1.89% of the total rainfall applied to the barrier in the period.

4 Conclusions

This study involved the construction and testing of a flow channel apparatus to evaluate the performance of mineral cover barriers under different weather conditions. Concerning the apparatus developed, it can be said that a good overall performance was obtained, with the flow channel able to reproduce most of the main weather variables and monitor the CB performance in different profile positions. The use of suction measurement devices with different working principles and suction measurement ranges proved to be adequate to monitor two such different materials in terms of hydraulic properties. The employed moisture probes performed well both in coarse and clayey soils and the rain and the solar radiance simulators were
able to achieve the desired performance, producing nearly homogeneous conditions for the whole length of the channel superficial area. The flow channel demonstrated its great potential use in laboratory simulations of field conditions. A temperature and relative humidity controlled room will allow the device to simulate and control all the main environment variables that influence the performance of mineral barriers in the field.

With regard to the capillary barrier performance, the study has demonstrated that thicker than 40cm clayey layers are necessary in the field in order to prevent shrinkage cracks from reaching the bottom sand layer. The use of silty or low plasticity clayey soils is also preferred in order to avoid the occurrence of preferential flow paths. Despite the observed problems in the clayey layer, only about 1.89% of the total rainfall applied to the capillary barrier leaked to the bottom layer, which can be considered a good overall performance indicator.

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