Soils and Rocks

An International Journal of Geotechnical and Geoenvironmental Engineering

www.soilsandrocks.com

ISSN 1980-9743
ISSN-e 2675-5475

Brasília municipal solid waste landfill: a case study on flow and slope stability

José Fernando Thomé Jucá[1#], Alison de Souza Norberto[1], José Ivan do Santos Júnior[1], Fernando A. M. Marinho[2]

CASE STUDY

Keywords
MSW Landfill
Slope stability
Hydraulic and mechanical parameters
Leachate; Pore liquid pressures

Abstract

For geotechnical and environmental reasons, landfills are positioned above the regional water table and thus are formed in unsaturated conditions. This condition can be different if the drainage system and the rain regime of the site are such that they create a level of internal liquid in the landfill. During January and February 2019, excessive movements occurred in the slopes of the Brasília sanitary landfill. A geotechnical investigation indicated that the raised leachate level caused by the clogging of the drainage system contributed to the landfilled waste movements. The limit equilibrium analysis was used to predict the relationship between leachate level and slope stability. In order to understand the process that led to the rupture, flow and stability analysis by limit equilibrium were performed. The parameters associated with flow, water retention capacity, and shear strength were obtained based on literature evaluations. In addition, data from tests were used, which allowed to define more accurately the distribution of pore pressures of liquid that led to the failure. This study allowed to define the cause of failure and also to establish the role of the drainage system in maintaining the stability of the landfill. The studies indicated that although the gain of shear strength of landfill due to the unsaturated condition is negligible, the process of flow in unsaturated medium, associated with climatic aspects, are fundamental for a medium- and long-term analysis.

1. Introduction

Slope stability analysis for Municipal Solid Waste landfill has been the focus of many technical publications; however, few papers have addressed the influence of leachate on the landfill stability, considering the climatic aspect and hence, the unsaturated conditions of the waste mass, which occur up to the leachate level in the landfill and from there the conditions of the waste mass become saturated. This paper presents a case study of a landfill failure that involved a small movement of waste induced by an excessive pore liquid pressure, caused by the obstruction of the drainage system.

Excessive infiltration of rainwater, without adequate control, increases the waste saturation and raises the level of internal leachate in the landfill, inducing a reduction in gas permeability. If the generated gas finds it difficult to escape through the roof or be captured by the gas capture system, this pressure can add to the liquid pressure. It is exactly this combination of reduced gas permeability, as result of saturation, that makes it difficult to assess the role of gas pressure in instability processes. Merry et al. (2006) present a theoretical study to define the effect of gas pressure generation along the landfill. This effect is significant when the saturated hydraulic conductivity of the landfill is less than approximately 10^{-6} m/s. If there is complete saturation of the landfill, the excess gas pressure would be approximately 0.6 kPa per meter of landfill height. The authors suggest that to take this effect into account in the stability analyses, the simplest way is to use a specific weight for the liquid higher. According to Merry et al. (2006) and based on the data shown later in the text, the saturated hydraulic conductivities of landfills can range from 10^{-8} m/s to 10^{-4} m/s. Under these conditions, saturated waste, Merry et al. (2006) indicates that the equivalent specific weight of the liquid, to take into account the gas pressure in the stability analysis, can reach up to 110 kN/m^3. The heterogeneity characteristics of the landfill can generate an inhomogeneous pressure distribution of liquid and gas. Not even a well-distributed monitoring system can guarantee the correct determination of liquid and gas pressures in the landfill. The use of resistivity to detect

#Corresponding author. E-mail address: jucah@ufpe.br
[1]Universidade Federal de Pernambuco, Technology Center, Department of Civil and Environmental Engineering, Recife, PE, Brasil.
[2]Universidade de São Paulo, São Paulo, SP, Brasil.

Submitted on May 18, 2021; Final Acceptance on July 15, 2021; Discussion open until November 30, 2021.
https://doi.org/10.28927/SR.2021.067321

regions with the greatest presence of water has been very efficient (e.g. Rosqvist et al., 2007; Dumont et al., 2016).

During January and February of 2019 excessive movements occurred in the slopes of the Brasília sanitary landfill. A geotechnical investigation indicated that the raised leachate level caused by the clogging of the drainage system contributed to the landfilled waste movements. In this work, the slope stability analysis was carried out analyzing the influence of rain and the consequent generation of leachate considering the flow in unsaturated medium. The back analysis of the study of the Brasília MSW landfill slope stability aimed to identify the reasons for the excessive movements of the landfilled mass.

A back-analysis was performed considering information from site observations and data from an electro-resistivity survey. This case led to a general assessment of the design procedures for the landfill that included the flow analysis associated with the equilibrium stability analysis. The flow analysis took into account the precipitation and local evaporation, and the analysis was carried out for a period of two years after the completion of the landfill. The analyses made it possible to evaluate the change in the stability scenarios, through the variation of the factor of safety (FoS), associated with the pore pressure profiles developed according to the climatic conditions. The case shows that the amount of leachate present in a landfill is critical and should always be kept low, based on an efficient drainage system. The organic matter present in the Brasilia landfill is around 47% in volume. In the biodegradation process, part of this organic matter is transformed into liquids and gases at different times that vary according to the amount of waste and its degradation capacity. In other words, the contribution of organic waste to the total volume of leachate leaving the landfill is difficult to accurately estimate. However, if the landfill is isolated from incoming rain, the volume of liquids generated could be only 10% of the volume of biodegradable organics, depending on its moisture and density. Thus, it is precipitation and its infiltration into the landfill that control the generation of leachate.

2. General aspects of the landfill

The municipal solid waste landfill of Brasília is located at the Administrative Region of Samambaia, in the Federal District, between the Melchior stream and the DF-180 highway, close to the sewage treatment stations Melchior and Samambaia, at 30 km from the center of Brasília. Brasília is 1087 m above sea level and has a tropical climate, with hot and humid springs (September to December) and summers (December to March) and cold, dry autumns (March to June) and winters (June to September). The average annual rainfall is 1443 mm and presents an annual average relative humidity of 68%, ranging from 49% in August to 79% in December. Temperature ranges between 22°C and 40°C. Annual rainfall varies widely, from months without rain to periods of intense rain of 400 to 500 mm per month, as shown in Figure 1.

The Brasília Landfill project was conceived and adapted to the planialtimetric conditions of the land surface, considering aspects such as vegetation, available areas, access, and distance to rivers, streams, and springs. The implantation of the Brasília Landfill began in 2015 and is taking place in 4 sequential phases. Phase 1 contemplates the implementation of an initial area of approximately 110,000 m^2, located on the east side of the waste disposal area itself. Phase 2 is located in the central portion, Phase 3 in the southwest region, which should also be used as a soil storage area during the implementation and operation of the Phases that precede it, and finally, Phase 4 should be performed over the previous Phases. At the end of the construction, the landfill will occupy a total area of 320V and will have accumulated an amount of 8.2 million tons. The general arrangement of the landfill with the identification of the phases can be seen in Figure 2. The characteristics and properties of the subsoil were studied through in situ geotechnical investigation. For Phase 1, it was carried out based on 23 Standard Penetration Tests (SPT). The subsoil consists of a top layer of sandy clay 3m thick and SPT of 5, followed by a layer of sandy silt 6m thick and average SPT of 12. The water level varied between 3.50 m and 6.70 m, from the foundation level.

The MSW of Brasilia receives around 2200 t of waste daily. The predominant composition of the waste is food and garden waste (47%), followed by plastics (15%), paper and cardboard (11%), and clothes and wood (7%), the rest being sand, gravel, and stones. The geotechnical and environmental monitoring of the Brasília MSW landfill was carried out after the excessive movements in January 2019 through the installation and maintenance of monitoring instruments, such as: vector piezometers and superficial landmarks, which are intended to monitor parameters linked to the stability and safety of the landfill. Groundwater monitoring wells as well as surface water monitoring are used to assess the region's water quality. Routine visual inspection is also carried out

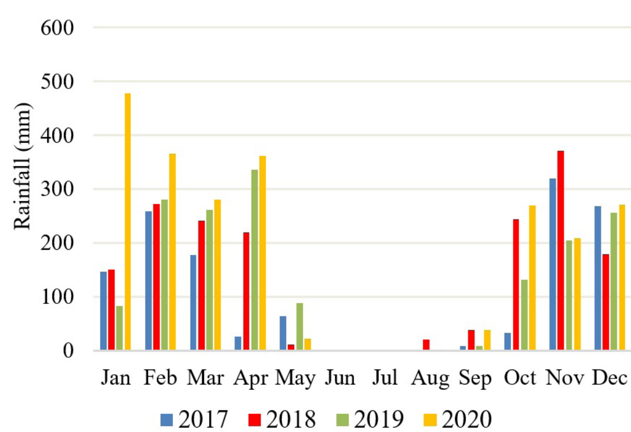

Figure 1. Rainfall at the Brasília Landfill between 2017 and 2020.

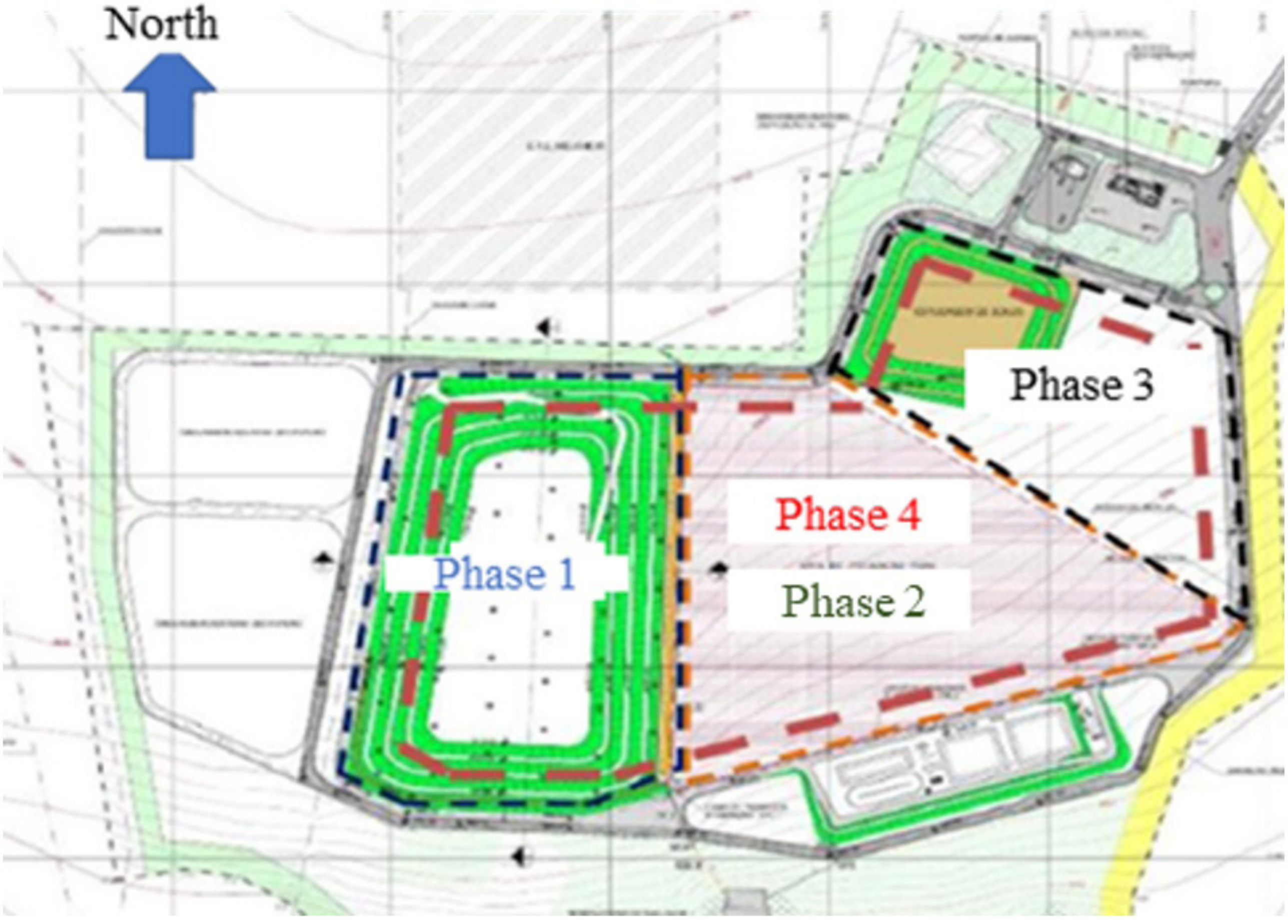

Figure 2. Locations of the construction phases of the Brasilia MSW landfill.

to check features that may indicate stability and security problems.

3. Characteristics of the base liner and drainage system

In Phase 1, the landfill base liner was built with a thickness of 1.5 m of compacted clay soil, aiming a hydraulic conductivity equal to or less than 10^{-9} m/s. Overlying the base liner, a 2 mm HDPE geomembrane was installed, textured on both sides, with seams made by thermal fusion. The mechanical protection of the HDPE geomembrane, both at the base and on the slopes, was carried out by means of a soil layer with a thickness of 0.5 m.

The leachate drainage system at the base of the Phase 1 of Brasília MSW (BMSW) landfill was implanted above the mechanical protection layer, where a HDPE geomembrane was used, and following the declivities defined in project, with 3.5% in the South-North direction and 0.7% in the East-West direction. The drainage system implanted is herringbone type with a main drain working with secondary drains that collect the leachate to the accumulation ponds. Vertical draining wells is also installed, starting over the main drains. The latter should also work as a gas drainage system. These drains were filled with limestone, which had no restrictions for its use in Brazilian technical standards. During the landfill operation, some problems occurred with the drainage system causing clogging or reduction in hydraulic conductivity to flow the leachate. Some studies have explained this problem by the use of limestones (about 50% of calcium carbonate) with significant concentration of fines (unwashed stone), although reports of similar problems have not been found in Brazilian landfills (Carvalho & Pfeiffer, 2019). Limestone was the main cause the problems, other minor causes may have been caused by movements in the drainage system. On the other hand, limestone was present in horizontal drains as well as vertical leachate drains and gas drains. There were excavations in specific places to investigate the clogging of liquid drains that confirmed as hypotheses raised about the effects of using limestone in drainage systems On the other hand, in the south area of Phase 1, the drainage system also indicated problems of low gradients, because the low slope of the drainage system induces lower flow velocities, accentuating the observed clogging problems. This area corresponds to the places where leachate overflow problems, excess of pore liquid pressures, and excessive movements in the landfill slope were observed.

4. Characteristics of the landfill soil cover

The cover system plays a key role in the water balance of landfills. This system controls the surface water and also the water that infiltrates and/or evaporates, thus having a direct influence on the volume of liquid (leachate) that is captured by the drainage system. This entire system is responsible for the variation of water content and pore pressures of liquids within the landfill and consequently, the landfill stability. The interaction between the roofing system and the atmosphere goes beyond the entry and exit of water. The atmospheric air (N_2 and O_2) penetrates the landfill due to variations in atmospheric pressure, leading to a series of biochemical reactions that generate gases (CH_4, CO_2, H_2S, among others) that tend to escape from the landfill. Thus, in the same soil element of the roof, there is simultaneously a flow of liquid and gases associated with climatic variations, water content, soil suction, air permeability, and hydraulic conductivity (e.g., Jucá & Maciel, 1999; Marinho et al., 2001; Maciel & Jucá, 2011). In this way, the system also has the function of minimizing gas emissions to the atmosphere. Its execution must be done with extreme care, adapting the conditions of compaction and thickness to the characteristics of the landfill and the local climate. In the specific case of BMSW landfill, the material used in the execution of the cover system is a sandy silt. The estimated infiltration is about 50% of the rain, which allows an excessive intake of water to the landfill, increasing the volume of leachate, Melchior et al. (2010) reports in his article that there was an infiltration of 42% of rain in the compacted soil layer. In field tests with double rings, the water infiltration range varies from 15 to 20 mm/h. The layer thickness was initially designed to be 0.6 m, but it showed variations during execution and there was no compaction control.

5. The occurrence of slope instability

From February to April 2019, the south area of Brasilia landfill presented excessive movements associated with the excess of leachate that overflowed in different points of the slopes and through the existing gas drains. These excessive movements were also identified in the drainpipes and an intense erosive process of the covering soils.

Figure 3a presents an overview of phase 1 of the landfill construction with an indication of the region that suffered the failure, and positions where the leaks were observed. Figure 3b illustrates the tipping of one of the gas drains after the failure.

In Figure 4a, one of the gas drainage systems completely taken by the leachate is shown. In Figure 4b, the leachate leak is identified on the road.

6. Post failure investigation

6.1 Back-analysis

6.1.1 Mechanical and hydraulic parameters of the landfill

The observational method associated with flow and stability analysis (limit equilibrium) provides a very efficient and simple tool for identifying the causes of failure or malfunctions in geotechnical structures. The geotechnical problems related to landfills of municipal solid waste (MSW) present intrinsic difficulties due to the characteristics of the material with which it is dealing. Back-analysis of failures requires knowledge of the parameters involved in the behaviour

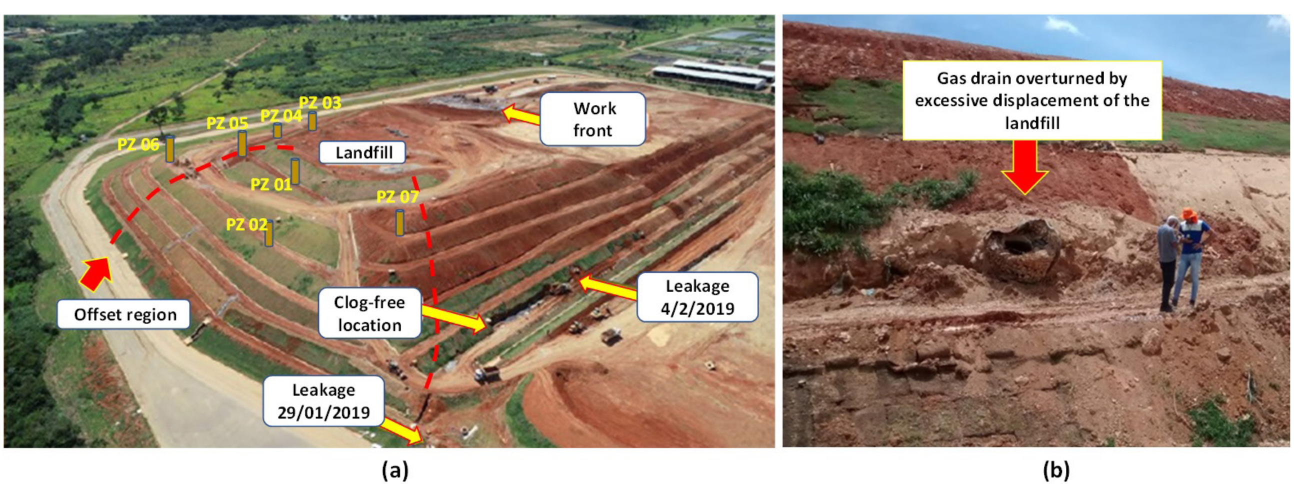

Figure 3. Region where the rupture movement occurred: (a) aerial view of the landfill with the location of leachate leaks and failure zone; (b) tilt of the vertical gas drain.

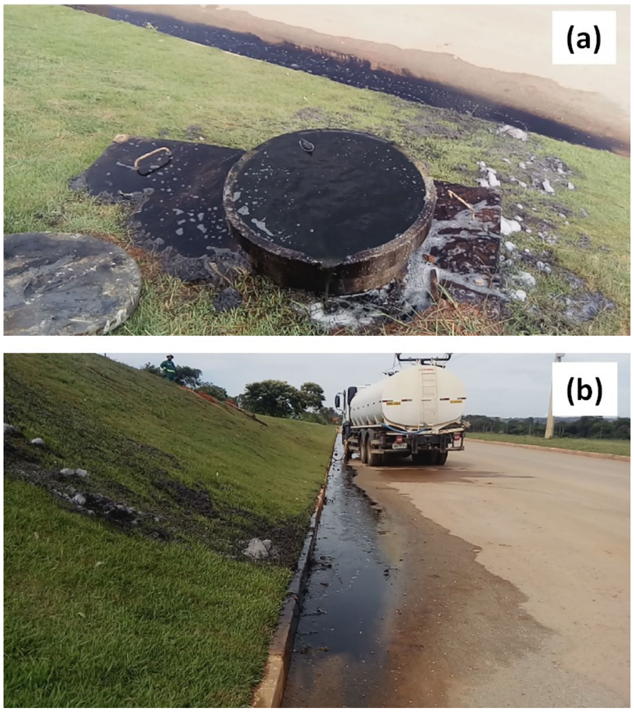

Figure 4. Leachate leaks: (a) gas drainage with leachate; (b) flow of leachate along the road.

of the materials. These parameters, which are predominantly mechanical and hydraulic in nature, govern the behaviour of the landfill. Associated with this are the biochemical aspects that affect the material and the drainage system. The failure mechanism must also be defined, establishing whether the failure occurred in a drained or undrained condition, or if there is a combination of the two mechanisms. Geometric characteristics of both the landfill section and the failure surface may also generate uncertainties in the analyses.

Thus, in order to carry out a back-analysis, it is necessary to define, with maximum accuracy, the parameters less susceptible to variations or the ones we are more confident about. In the case of MSW landfills, this is a task that is always subject to criticism. In the present study, which is based on a case of excessive movement of a MSW landfill, an attempt was made to establish a procedure that would allow not only to identify the predominant cause for the excessive movements but also to create a procedure that allows a conceptually more consistent definition of the project. It should be noted that the adopted procedure aims to be relatively easy to be adopted in engineering practice.

MSW landfills are located in positions that tend to leave the waste in an unsaturated condition. In other words, they are above the ground water level. This condition can change if there is any deficiency in the drainage system associated with an intense rainfall regime that creates an internal level of liquid. Based on data from the literature, the variation of the saturated hydraulic conductivity of the landfill in depth

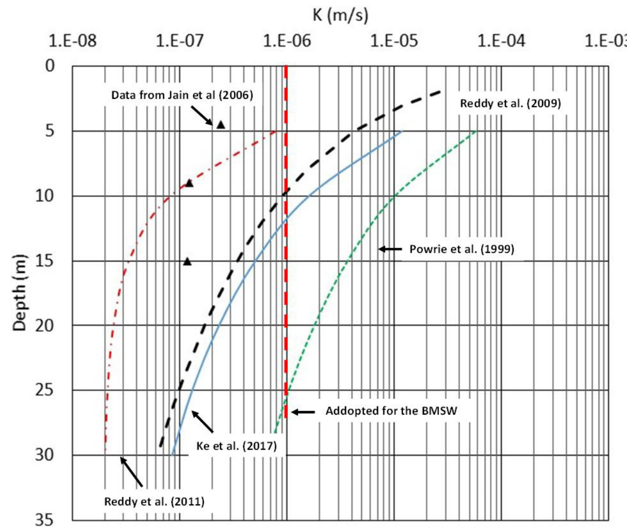

Figure 5. Variation of saturated hydraulic conductivity of MSW with depth according to literature and the value used for the present analyses (data from Jain et al., 2006; Ke et al., 2017; Powrie et al., 1999; Reddy et al., 2009, 2011).

was defined and the shear strength parameters were also based on literature as a start point for the back analysis.

6.1.2 Hydraulic parameters

Any embankment, whether carried out with solid urban waste, from mining tailings or even soil from a controlled borrow pit, is subject to climatic conditions. The infiltration of water plays a fundamental role in the stability of these structures and the project must take into account the climatic aspects of the site. Infiltrations are linked to seasonal climatic variations and can affect the stability of the structure in the medium and long term. These landfills are generally designed to remain unsaturated. This unsaturated condition, in the case of landfills of solid urban waste, does not contribute significantly to the strength of the material, which indicates that the gain of strength due to the unsaturated state is in general negligible. However, the unsaturated condition of municipal solid waste creates a different flow pattern than it would be if the material were saturated.

In this case, an unsaturated flow analysis is essential, taking into account appropriate parameters. The determination of the variation in hydraulic conductivity with saturation or suction (called permeability function) is not usually obtained through laboratory tests. Its determination is made through models that make use of the saturated hydraulic conductivity and the water retention curve (van Genuchten, 1980). In the specific case of BMSW, no data were available on saturated hydraulic conductivity and water retention curve, and an evaluation based on the literature was necessary. Figure 5 presents data on hydraulic conductivity as a function of the depth of the solid waste landfill, for several studies found in the literature (e.g., Powrie et al., 1999; Jain et al., 2006;

Reddy et al., 2009; Reddy et al., 2011; Ke et al., 2017). Based on these studies, a single value of 10^{-6} m/s was adopted as the hydraulic conductivity value.

Similarly, data from the literature were taken to assess which water retention curve (SWRC) would be adopted for studies at BMSW. Figure 6 shows SWRCs obtained from the literature. It is observed that the volumetric water content is the condition closest to saturation, although it does not reflect porosity, varies between 60% and 70%. In addition, the various authors obtained curves with bi-modal behaviour. The interpretation of the suction water content relationships in unsaturated soils has always deserved much discussion and little convergence of opinions. In urban solid waste this issue is even more complex, few studies show repeatability and easy interpretations. The question of linearity or not of this relationship can be strongly influenced by the composition of the residues and the moisture retention capacity of each one of these fractions. Higher percentages of organic matter and materials such as paper and cardboard have a higher retention capacity than materials such as glass, plastics and metals. Organic fractions degrade and can change this composition over time. Furthermore, this same composition can change other properties of the waste, such as its permeability and compressibility, modifying the suction – water content ratio of the waste. The adoption of the nonlinear model is more associated with samples obtained at greater depths (higher stress level and older or more decomposed) and better expresses the long-term behaviour. Based on the analysis of the curves from the literature, a bimodal curve was adopted for the present work as shown in Figure 6 and its parameters are shown in Table 1.

6.1.3 Shear strength parameters

Similarly, data from the literature were obtained for the shear strength parameters of urban solid waste to be adopted

Table 1. SWRC parameters adopted for the BMSW.

Parameters	BMSW
α_1	1.327 1/kPa
n_1	7.948
m_1	0.87418
θ_1	61.55%
α_2	0.1514 1/kPa
n_2	3.121
m_2	0.67959
θ_2	38.45%
θ_s	71.5%

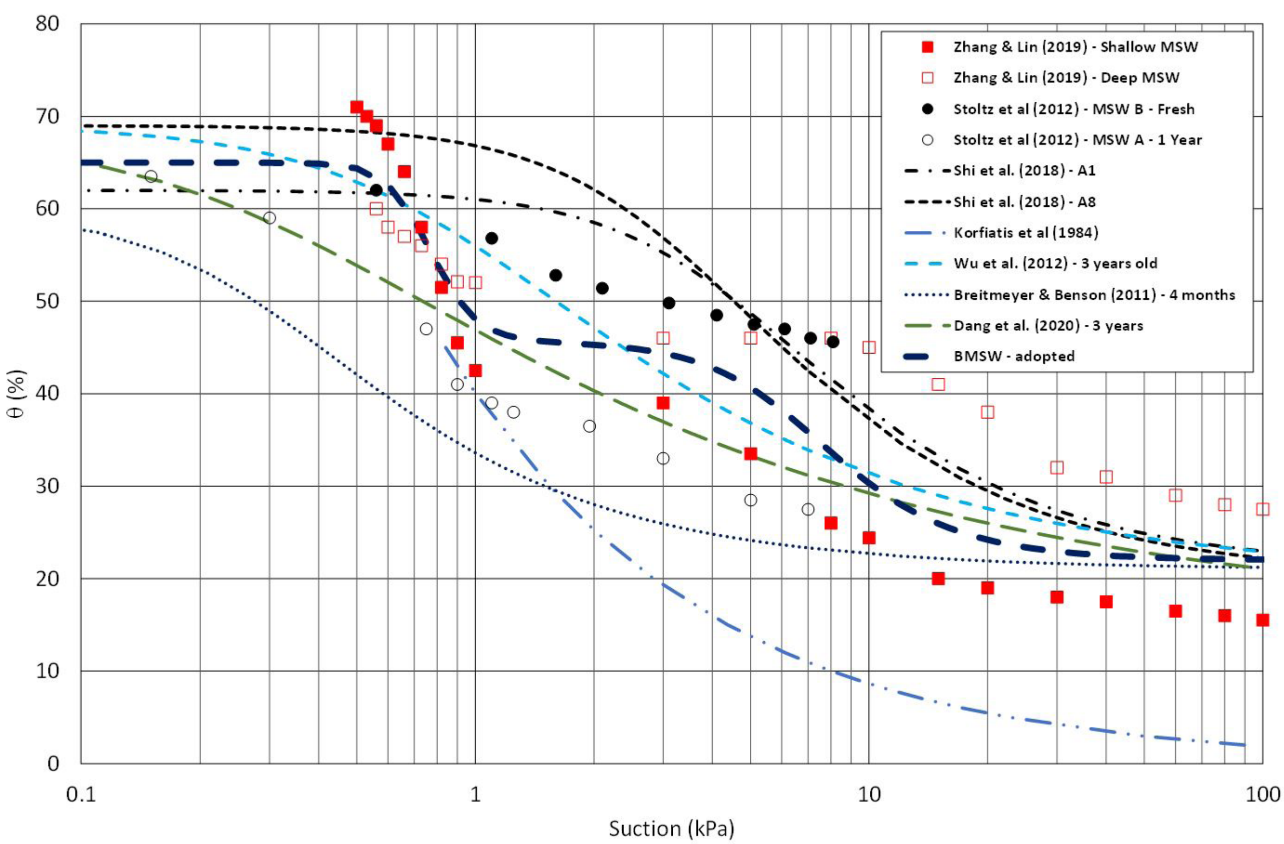

Figure 6. Soil water retention curve for MSW according to literature and the curve used for the present study (data from Breitmeyer & Benson, 2011; Dang et al., 2020; Korfiatis et al., 1984; Shi et al., 2018; Stoltz et al., 2012; Wu et al., 2012; Zhang & Lin, 2019).

for studies. In Figure 7, several shear strength envelopes found in the literature are presented, alongside the envelope used in this research.

6.1.4 Pore liquid pressure

In order to be able to carry out the back analysis, it is necessary to know or estimate the pore liquid pressure in the landfill. As in Phase 1 of the construction of the landfill, piezometers or water level meters had not yet been installed, it was decided to obtain an instantaneous picture of the moisture condition of the waste by performing an electrical resistance survey.

After the initiation of the failure process of the landfill in Phase 1, an investigation was carried out by means of electrical tomography, performed in the longitudinal and transversal directions of the landfill. These results, together with the data of the instrumentation, installed after the failure, were used to infer the pore liquid pressure distribution in the landfill at the time of failure. After a careful interpretation it was possible to have an approximate view of the level of leachate inside the landfill, which at the time of the test (January 2020) indicated a liquid level at about 10 m from the base layer of the first cell, as can be seen in Figure 8.

7. Back analysis of the failure

With the interpretation of the pore liquid pressure distribution and the shear strength parameters adopted it was possible to evaluate the failure using limit equilibrium analysis. The analyses were performed using the software Slope/w. The original slope presents a geometry of 1V:2H, with berms of 2 m wide, each 5 m. Figure 9a illustrates the final geometry adopted for the back analysis. The interpretation of the humidity zones identified in the electrical survey (shown in Figure 8) and converted to pore liquid pressure is indicated in Figure 9b. The conversion was based on the moisture distribution associated with the back analysis. That is, maintaining the moisture distribution and imposing pore-pressures that induce a safety factor equal to one.

In the analysis, software from the GeoStudio package was used, the Seep/W was used for the flow and climatic aspects modelling and the Slope/W for the stability analyses. The observed failure zone from the field is replicated in the analysis with a factor of safety of one, as shown in Figure 10, suggesting that the combination of parameters is in agreement with the failure mode. The rupture surface was delimited from the displacement observed in the field. Therefore, the BMSW landfill failure mode was due to excess of pore pressure.

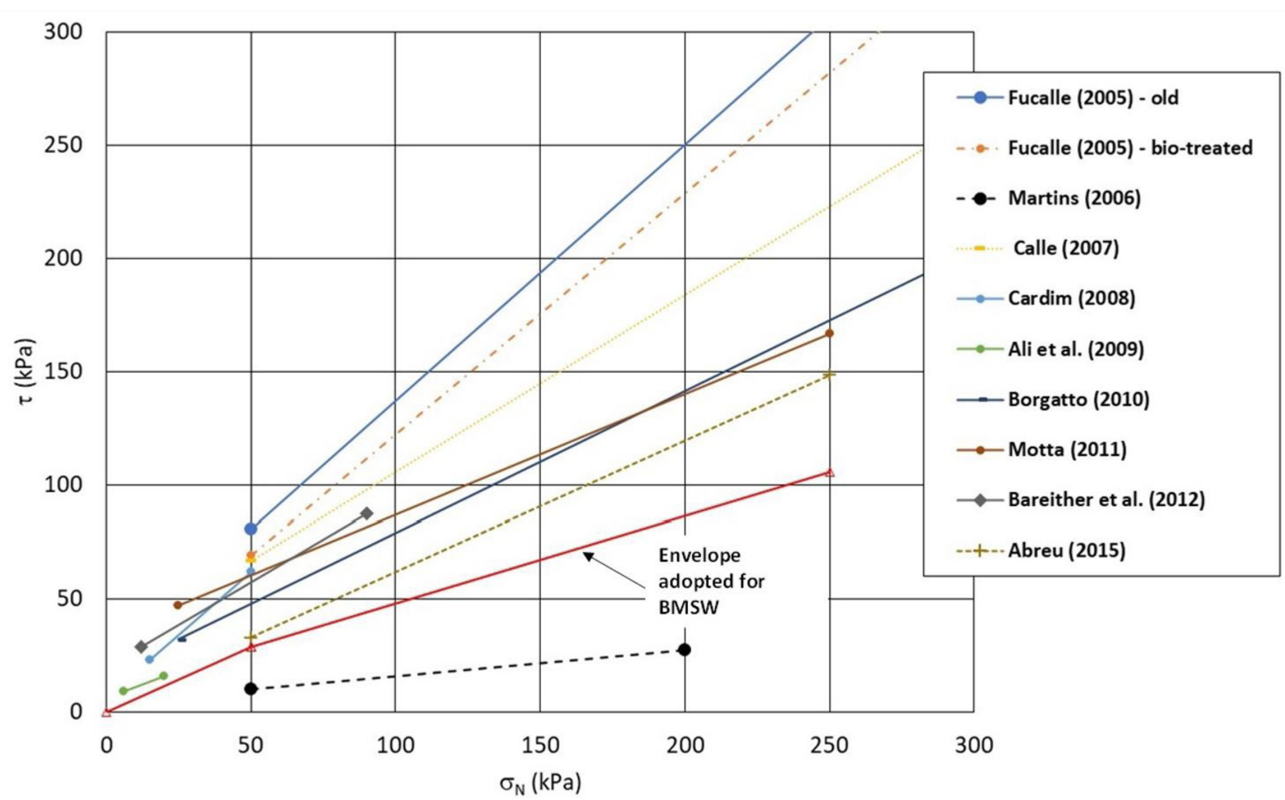

Figure 7. Shear strength envelopes for MSW and the bi-linear envelope used for the present study (data from Abreu, 2015; Ali et al., 2009; Bareither et al., 2012; Borgatto, 2010; Calle, 2007; Cardim, 2008; Fucale, 2005; Martins, 2006; Motta, 2011).

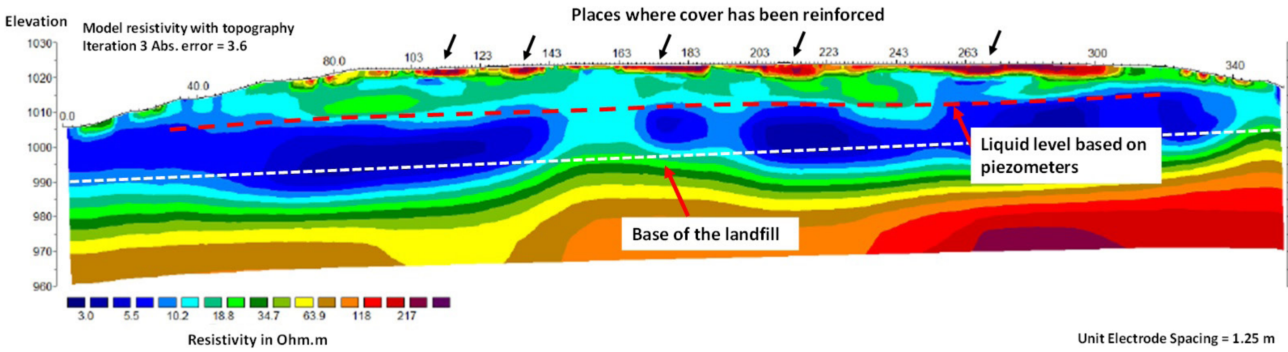

Figure 8. Geoelectric profile of Phase 1 after failure (Cunha & Borges, 2020).

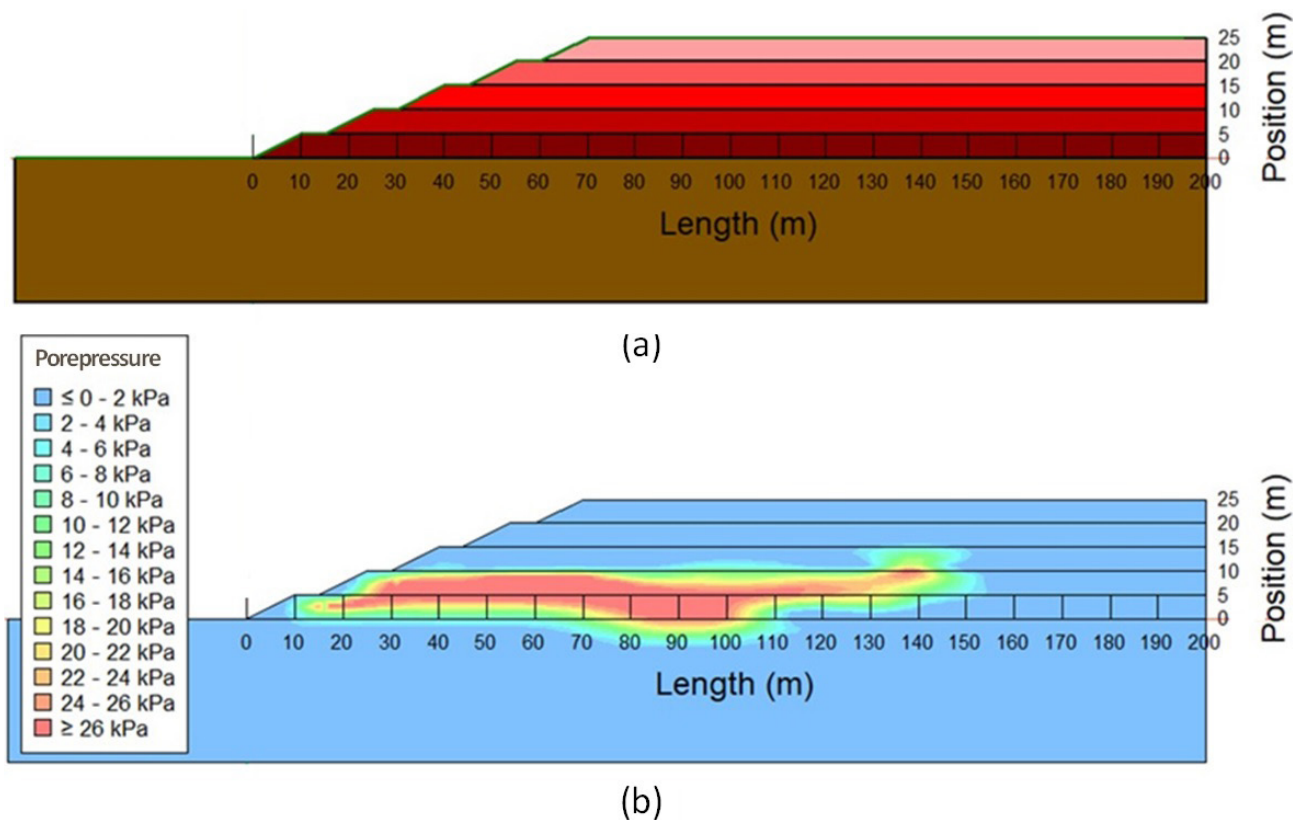

Figure 9. (a) section of the BMSW Landfill; (b) pore water pressure adopted to the back analysis.

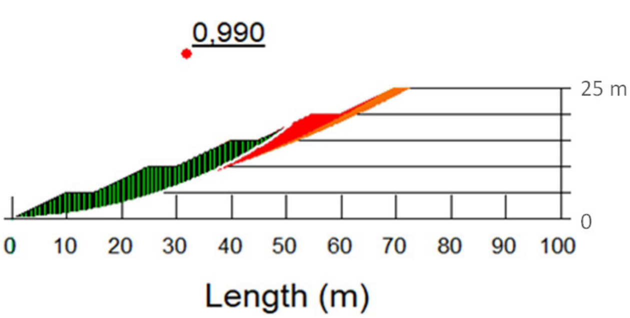

Figure 10. Surface equivalent to the field situation.

7.1 The local climate and the variation of the safety factor

In order to better identify the reasons for the increase in the pore pressure causing the failure, an analysis was carried out combining the effects of the climate and the analysis of stability by limit equilibrium. The climatic conditions of the place where the landfill is located were established, adopting precipitation data. Considering the location of the landfill, Penman-Monteith model was used to take evaporation into account. The study replicated the climatic condition for two years, with the initial condition of pore pressure being the equilibrium situation from the base of the landfill. In transient analyses the landfill is unsaturated, and therefore with a high gas permeability. Thus, gas pressure was not considered in the analyses.

The original design of the landfill adopted a herringbone drain at the base of the landfill. This system, when it is compromised due to some type of clogging, generates a rapid increase in the pore pressure. As landfills, in general, are very subject to chemical processes that can speed up clogging, the use of horizontal blankets is recommended. The analysis carried out in the present study is in two dimensions, and therefore, it is only possible to consider obstructions in one section. Thus, only two analyses were performed: one with the drain blocked (case 1) and the other without obstruction (case 2). The analyses were made considering the horizontal blanket with 0.40 m height and adopting a saturated permeability of 10^{-3} m/s.

In case 1, the boundary condition adopted induced a full efficiency of drainage system, during the 2 years analysis. For case 2, a condition of variable obstruction was considered along the drainage system, simulating the clogging process that occurred in the field. The obstruction was induced over 30 m from the drain outlet. The hydraulic conductivity along the section considered obstructed varied from 10^{-8} m/s to 10^{-10} m/s, the obstruction being considered in a regressive way, being the largest obstruction at the exit point of the landfill drainage (10^{-10} m/s) and reducing to (10^{-8} m/s) at 30 m from the leachate exit. Using the software Seep/w (unsaturated flow considering local climate for two years) and Slope/w (limit equilibrium analysis), the analyses were performed for case 1 and 2.

Figure 11 shows the suction profiles over the two years of the analysis, for the case of the unobstructed drain (Figure 11a) and the case of the obstructed drain (Figure 11b). It should be noted that for the lower 4 m of the profile, the

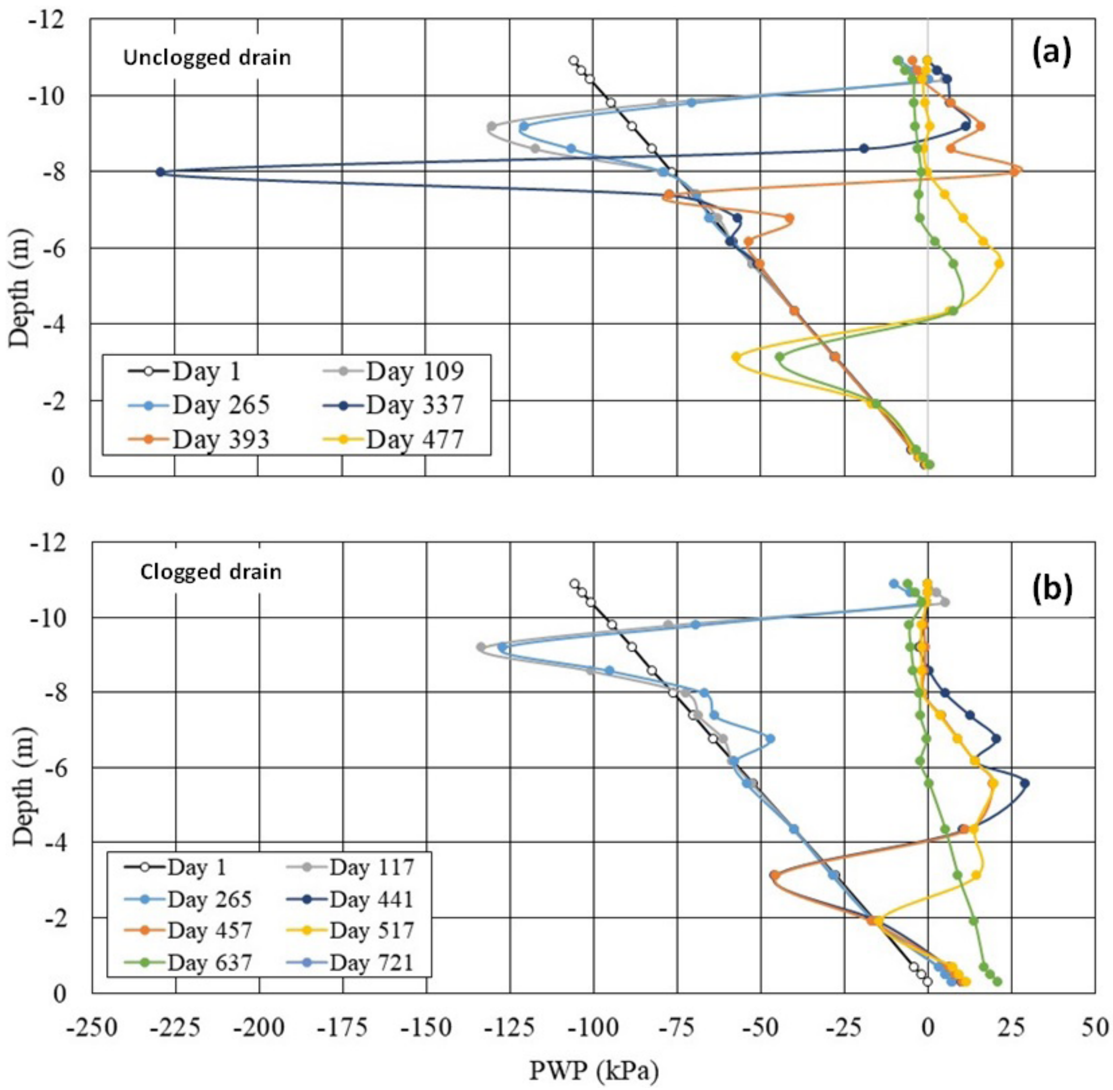

Figure 11. Pore liquid pressure profiles for: (a) unclogged drain; (b) clogged drain.

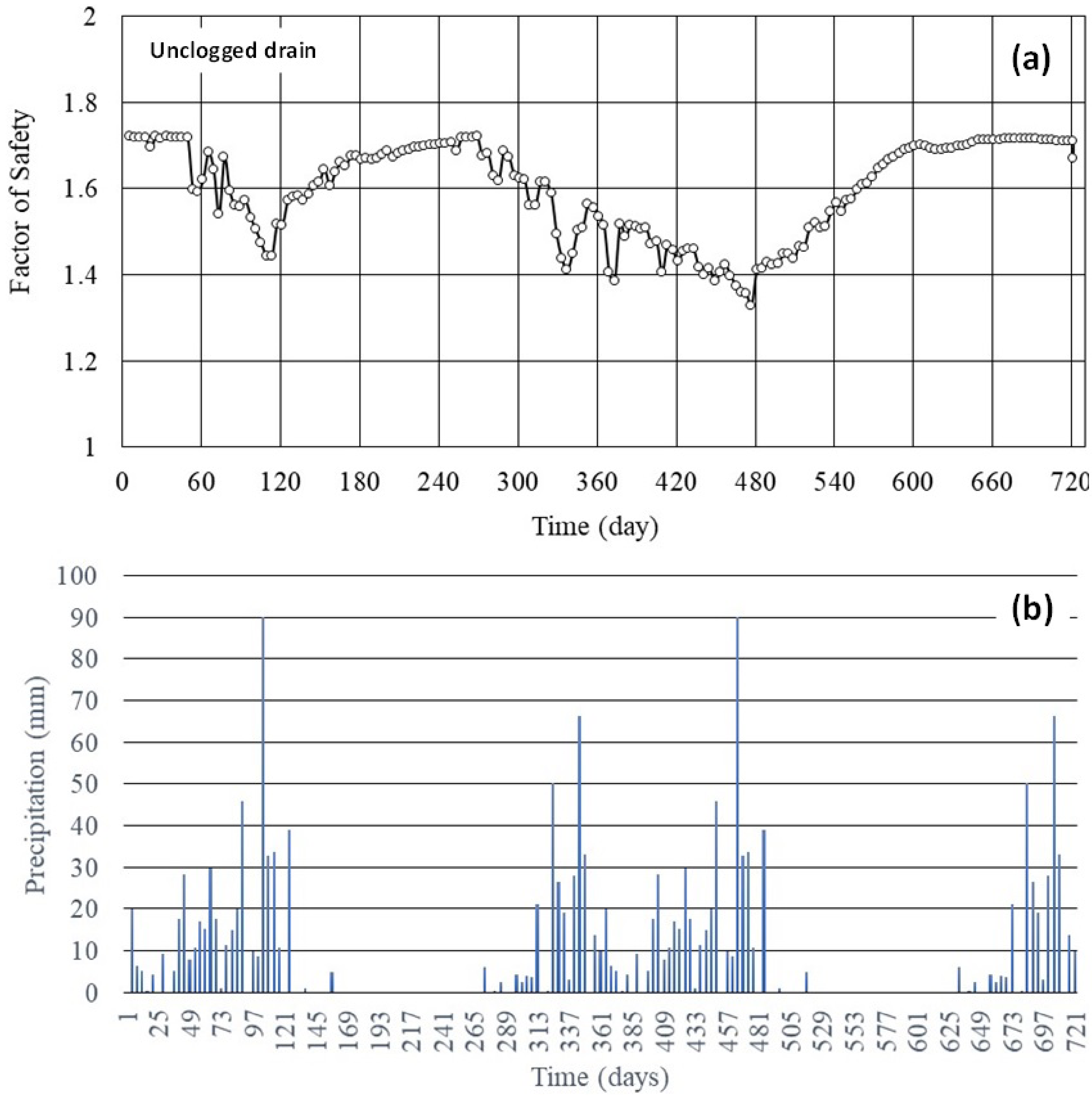

Figure 12. Evaluation of the Factor of Safety for an unclogged drain with time with the precipitation applied to the model.

section closest to the drainage system, there is an increase in the pore liquid pressure when the drain has its drainage limited by the obstruction. Although this phenomenon (increase of pore-water pressure) does not occur in the first year, the increase in the liquid pressure at the base of the landfill is clear in the second year. It should be noted that this was the time taken between the completion of the landfill and its failure.

By incorporating pore liquid pressure profiles over time in the stability analysis, there is an expected variation in the safety factor. This variation is linked to precipitation and evaporation, that is, to the local water balance, and the efficiency of the drainage system. Figures 12 and 13 show the variation of FoS over time, together with the rainfall adopted. In both cases, the response of the FoS to rainfall is clear. In the situation of the system without obstruction, the FoS reaches a value below 1.4, but at the end of the second year, it still maintains a FoS above 1.7.

In the case where the system undergoes a clogging process, the FoS already reaches a value below 1.4 in the first year, and this value suffers a degradation from the second rainy season, reaching values below 1.2.

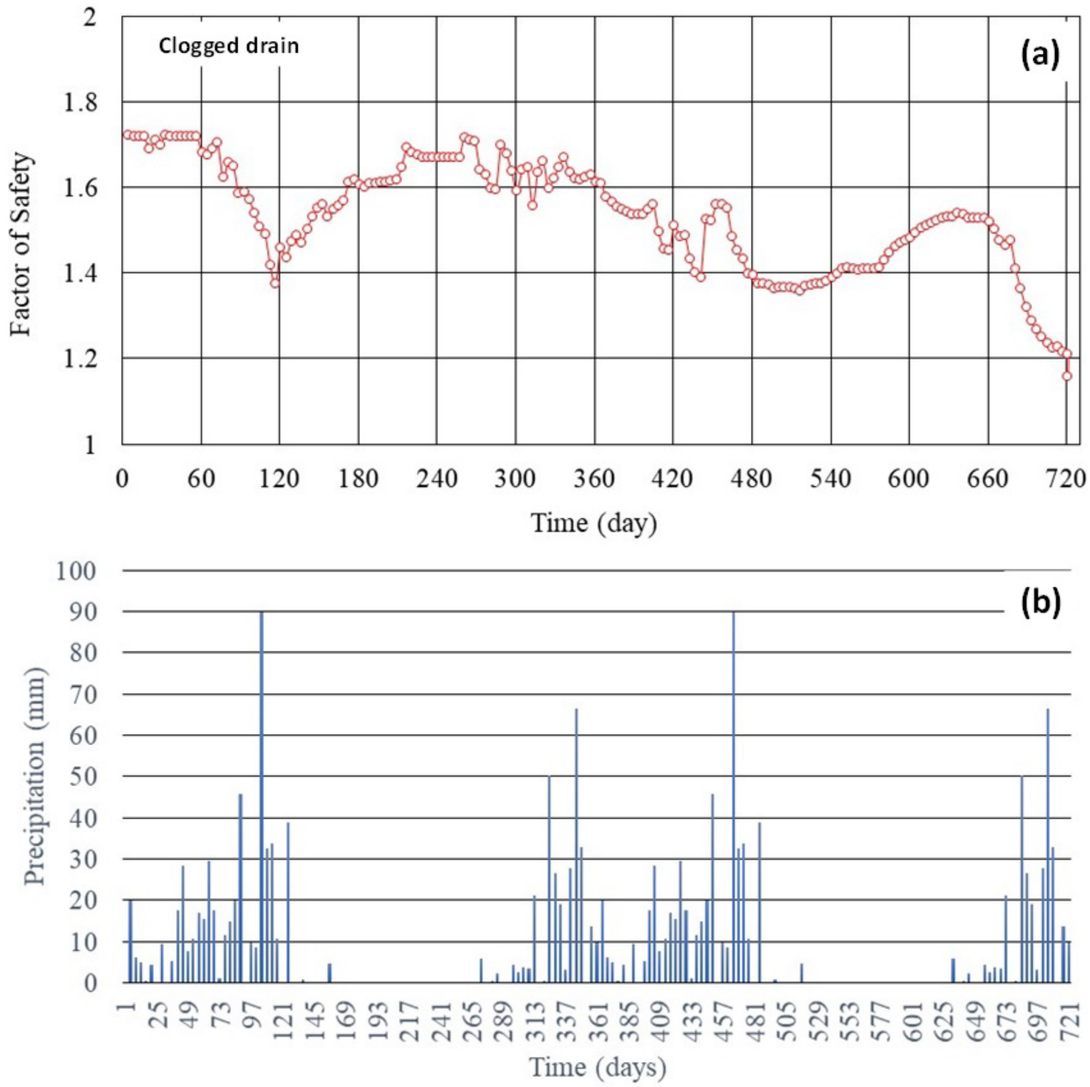

Figure 13. Evaluation of the Factor of Safety for a clogged drain with time with the precipitation applied to the model.

8. Conclusion

The present case once again brings to light important design aspects to be considered in municipal solid waste landfill projects. These aspects range from considerations about the internal drainage system to the cover system and its drainage project. In addition, analysis procedures—such as, climate association, flow in unsaturated media, and stability analysis must be incorporated.

Some specific observations and conclusions are:

- In many Brazilian landfills, control and testing data to obtain mechanical and hydraulic parameters are quite difficult. This paper presents alternatives for obtaining these parameters and makes an analysis that allows an assessment of the slope stability. However, it is emphasized that it is necessary to obtain specific parameters for the projects, taking into account the characteristics of the local waste and the soils, both those of the foundation and those that will be used from borrow pits;
- Drainage systems in the form of herringbone has severe limitations in its efficiency. This effect is accentuated due to climatic conditions, the cover system, and the operation of the landfill. In most cases, a draining blanket system is more effective. In a system with a horizontal blanket, the occasional obstruction still allows drainage by another section, so it is considered safer to adopt this type of drainage system;
- Although the present analysis was limited to two years, it was possible to evaluate the behaviour of FoS over this period. It is suggested that the behaviour for longer periods be evaluated, using local rainfall data and parameters obtained for the landfill itself;

- Some aspects are important to control the stability of the landfill in the long term, such as: a well-dimensioned and permanently maintained cover system; and a monitoring system that allows the assessment of any clogging of the drainage system or the formation of leachate pockets.

Acknowledgements

The authors are very grateful to the Regulatory Agency for Water, Energy and Sanitation of the Federal District (ADASA) and the Federal District Urban Cleaning Service (SLU – DF).

Declaration of interest

The authors have no conflict of interests regarding the matter included in this paper.

Authors' contributions

José Fernando Thomé Jucá: Writing, reviewing, editing, investigation. Alison de Souza Norberto: Writing, reviewing, editing, investigation. José Ivan do Santos Júnior: Writing, reviewing, editing, investigation. Fernando Antônio Medeiros Marinho: Writing, reviewing, editing, investigation.

References

Abreu, A.E.S. (2015). *Geophysical investigation and shear strength of municipal solid wastes with different landfilling ages waste* [Doctoral thesis, University of São Paulo]. University São Paulo's repository (in Portuguese). https://doi.org/10.11606/T.18.2015.tde-03082015-115017.

Ali, L., Ali, S., & Maqbool, A. (August 2009). Large direct shear test apparatus for in situ testing of municipal solid waste landfill sites. In *Proceedings of the GeoHunan International Conference*, Changsha, Hunan. https://doi.org/10.1061/41041(348)13.

Bareither, C.A., Benson, C.H., & Edil, T.B. (2012). Effects of waste composition and decomposition on the shear strength of municipal solid waste. *Journal of Geotechnical and Geoenvironmental Engineering*, 138(10), 1161-1174. https://doi.org/10.1061/(asce)gt.1943-5606.0000702.

Borgatto, A.V.A. (2010). *Study of the geomechanical properties of pre-treated municipal solid waste* [Doctoral thesis, Federal University of Rio de Janeiro]. Federal University of Rio de Janeiro's repository (in Portuguese). http://www.coc.ufrj.br/en/doctoral-thesis/349-2010/3891-andre-vinicius-azevedo borgatto.

Breitmeyer, R.J., & Benson, C.H. (2011). Measurement of unsaturated hydraulic properties of municipal solid waste. In *Proceedings of the Geo-Frontiers 2011: Advances in Geotechnical Engineering* (pp. 1433-1442). Dallas, TX. https://doi.org/10.1061/41165(397)147.

Calle, J.A.C. (2007). *Geomechanical behavior of urban solid waste* [Doctoral thesis, Federal University of Rio de Janeiro]. Federal University of Rio de Janeiro's repository (in Portuguese). http://www.coc.ufrj.br/pt/teses-de-doutorado/151-2007/1091-jose-antonio-cancino-calle.

Cardim, R.D. (2008). *Estudo da resistência de resíduos sólidos urbanos por meio de ensaios de cisalhamento direto de grandes dimensões* [Master's dissertation, University of Brasilia]. University of Brasilia's repository (in Portuguese). https://repositorio.unb.br/handle/10482/3290.

Carvalho, E.H., & Pfeiffer, S.C. (2019). *Studies of the causes of clogging on leachate drainage system in Brasilia landfill* (Technical report). Consortium Samambaia.

Cunha, S.L., & Borges , W. R.B. (2020). *Report ASB 01/2020 - Profile of electrical tomography acquired at the top of cell 01 of the landfill in Brasília on 01/21/2020*. Institute of Geology, University of Brasília.

Dang, M., Chai, J., Xu, Z., Qin, Y., Cao, J., & Liu, F. (2020). Soil water characteristic curve test and saturated-unsaturated seepage analysis in Jiangcungou municipal solid waste landfill, China. *Engineering Geology*, 264, https://doi.org/10.1016/j.enggeo.2019.105374.

Dumont, G., Pilawski, T., Dzaomuho-Lenieregue, P., Hiligsmann, S., Delvigne, F., Thonart, P., et al (2016). Gravimetric water distribution assessment from geoelectrical methods (ERT and EMI) in municipal solid waste landfill. *Waste Management (New York, N.Y.)*, 55, 129-140. https://doi.org/10.1016/j.wasman.2016.02.013.

Fucale, S.P. (2005). *Influence of reinforcement components in the resistance of municipal waste* [Unpublished doctoral thesis]. Federal University of Pernambuco (in Portuguese).

Jain, P., Powell, J., Townsend, T.G., & Reinhart, D.R. (2006). Estimating the hydraulic conductivity of landfilled municipal solid waste using the borehole permeameter test. *Journal of Environmental Engineering*, 132(6), 645-652. https://doi.org/10.1061/(asce)0733-9372(2006)132:6(645).

Jucá, J.F.T., & Maciel, F.J. (1999). Permeabilidade ao gás de um solo compactado não saturado. In *4º Congresso Brasileiro de Geotecnia Ambiental - REGEO 99: Vol. 1* (pp. 384-391). São José dos Campos, SP. (in Portuguese).

Ke, H., Hu, J., Xu, X.B., Wang, W.F., Chen, Y.M., & Zhan, L.T. (2017). Evolution of saturated hydraulic conductivity with compression and degradation for municipal solid waste. *Waste Management (New York, N.Y.)*, 65, 63-74. https://doi.org/10.1016/j.wasman.2017.04.015.

Korfiatis, G.P., Demetracopoulos, A.C., Bourodimos, E.L., & Nawy, E.G. (1984). Moisture transport in a solid waste column. *Journal of Environmental Engineering*, 110(4), 780-796. https://doi.org/10.1061/(ASCE)0733-9372(1984)110:4(780).

Maciel, F.J., & Jucá, J.F.T. (2011). Evaluation of landfill gas production and emissions in a MSW large-scale experimental cell in Brazil. *Waste Management (New*

York, N.Y.), 31, 966-977. https://doi.org/10.1016/j.wasman.2011.01.030.

Marinho, F.A.M., Andrade, M.C.J., & Jucá, J.F.T. (2001). Air and water permeability of a compacted soil used in a solid waste landfill in Recife, Brazil. In R.N. Yong and H.R. Thomas (Eds.), *Proceedings of the 3rd BGA Geoenviromental Engineering Conference* (pp. 437-442). Edinburgh.

Martins, H.L. (2006). *Avaliação da resistência de resíduos sólidos urbanos por meio de ensaios de cisalhamento direto em equipamento de grandes dimensões* [Doctoral thesis, Federal University of Minas Gerais]. Federal University of Minas Gerais's repository (in Portuguese). http://hdl.handle.net/1843/FRPC-6ZNJ2D.

Melchior, S., Sokollek, V., Berger, K., Vielhaber, B., & Steinert, B. (2010). Results from 18 years of in situ performance testing of landfill cover systems in Germany. *Journal of Environmental Engineering*, 136(8), 815-823. https://doi.org/10.1061/(asce)ee.1943-7870.0000200.

Merry, S.M., Fritz, W.U., Budhu, M., & Jesionek, K. (2006). Effect of gas on pore pressures in wet landfills. *Journal of Geotechnical and Geoenvironmental Engineering*, 132(5), 553-561. https://doi.org/10.1061/(asce)1090-0241(2006)132:5(553).

Motta, E.Q. (2011). *Shear strength evaluation of municipal solid waste with co-disposal of sewage sludge through large-scale direct shear testing* [Doctoral thesis, Federal University of Pernambuco]. Federal University of Pernambuco's repository (in Portuguese). https://repositorio.ufpe.br/handle/123456789/5382.

Powrie, W., Ceng, F., & Beaven, R.P. (1999). Hydraulic properties of household waste and implications for landfills. *Proceedings of the Institution of Civil Engineers: Geotechnical Engineering*, 137(4), 235-247. https://doi.org/10.1680/geng.1997.137.4.235.

Reddy, K.R., Gangathulasi, J., Parakalla, N.S., Hettiarachchi, H., Bogner, J.E., & Lagier, T. (2009). Compressibility and shear strength of municipal solid waste under short-term leachate recirculation operations. *Waste Management & Research*, 27(6), 578-587. https://doi.org/10.1177/0734242X09103825.

Reddy, K.R., Hettiarachchi, H., Gangathulasi, J., & Bogner, J.E. (2011). Geotechnical properties of municipal solid waste at different phases of biodegradation. *Waste Management (New York, N.Y.)*, 31(11), 2275-2286. https://doi.org/10.1016/j.wasman.2011.06.002.

Rosqvist, H., Dahlin, T., Linders, F., & Meijer, J.E. (2007). Detection of water and gas migration in a bioreactor landfill using geoelectrical imaging and a tracer test. In *Proceedings of the 11th International Waste Management and Landfill Symposium - Sardinia 2007* (pp. 267-274). Italy: CISA.

Shi, J., Wu, X., Ai, Y., & Zhang, Z. (2018). Laboratory test investigations on soil water characteristic curve and air permeability of municipal solid waste. *Waste Management & Research*, 36(5), 463-470. https://doi.org/10.1177/0734242X18766223.

Stoltz, G., Tinet, A.-J., Staub, M.J., Oxarango, L., & Gourc, J.-P. (2012). Moisture retention properties of municipal solid waste in relation to compression. *Journal of Geotechnical and Geoenvironmental Engineering*, 138(4), 535-543. https://doi.org/10.1061/(asce)gt.1943-5606.0000616.

van Genuchten, M. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal*, 44, 892-898. https://doi.org/10.2136/sssaj1980.03615995004400050002x.

Wu, H., Wang, H., Zhao, Y., Chen, T., & Lu, W. (2012). Evolution of unsaturated hydraulic properties of municipal solid waste with landfill depth and age. *Waste Management (New York, N.Y.)*, 32(3), 463-470. https://doi.org/10.1016/j.wasman.2011.10.029.

Zhang, W., & Lin, M. (2019). Evaluating the dual porosity of landfilled municipal solid waste. *Environmental Science and Pollution Research International*, 26(12), 12080-12088. https://doi.org/10.1007/s11356-019-04607-2.