A Review of the Methodology for the Evaluation of Stability of Landfills in Chile

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The assessment of the physical stability of operational landfills is of vital importance as a control tool, as it allows demonstrating the safety of the facility, identifying the most relevant variables, and defining control thresholds. In this context, and based on the author's experience in national practice, the current approach used in the analysis of physical stability of national landfills is presented, highlighting the importance of operation on the different variables that determine a certain condition of physical stability for the facility and its different sectors.

Once the current analytical approach is outlined, this article discusses its various limitations, proposing recommendations to address the main shortcomings, especially regarding the determination of resistant parameters of the waste. In this sense, reference limit curves are presented for the results of dynamic cone penetration tests carried out in national landfills, in order to qualitatively estimate these resistant parameters.

KEYWORDS: Analysis of physical stability; landfill; resistant parameters of the waste.

1 INTRODUCTION

Managing the increasing amount of generated waste poses a significant challenge in modern societies, raising issues related to environmental impact, sustainability, and the urgency to implement effective recycling and final disposal practices.

One of the most commonly alternatives used for disposing of municipal solid waste is landfills, which, according to World Bank (2018), currently account for 40% of the total generated waste. Additionally, this institution projects the generation of approximately 3,04 billion tons of waste of all types by the year 2050.

This study critically examines the current approach used in stability analyses applied to landfills in Chile, highlighting its limitations and proposing recommendations to address them. Furthermore, it analyzes various operational practices of the landfill that may influence its stability. Finally, alternative approaches based on international experiences are presented with the aim of improving the stability analyses of landfills, thereby enhancing their operational safety based on credible technical foundations that adequately represent what occurs within the waste mass.

2 SOLID WASTE MANAGEMENT IN CHILE

According to data from the World Bank (2018), Chile holds the title of being the main generator of Municipal Solid Waste (MSW) in South America, with an average of 1,15 kg/person/day. Regarding the total generation of MSW, the Metropolitan Region contributes significantly, representing 41% of the 8.1 million tons produced nationwide in 2023 (SUBDERE, 2023).

Regarding the composition of MSW in Chile, measurements indicate that it consists of 53% organic matter, 13% paper and cardboard, 2% textile material, 9% plastics, 7% glass, 2% metals, and 14% other elements not classified within the mentioned categories (CONAMA, 2010).

In 2023, a total of 93 facilities for the final disposal of MSW were recorded, classified as Landfills, Manual Landfills, Dumps, and Garbage Sites (SUBDERE, 2023). The percentage distribution of these facilities is presented in Figure 1.

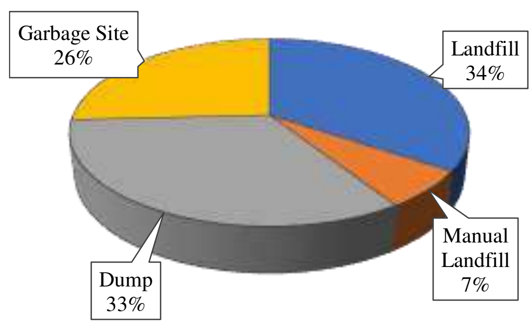

Figure 1. Percentage distribution of types of final disposal facilities for MSW.

A landfill is defined as a solid waste disposal facility that handles MSW. It is designed to minimize impacts on public health and safety, as well as the environment. Its operation involves liner systems, leachate and biogas control systems, mechanical compaction of waste in layers to reduce volume, and daily cover use, complying with corresponding regulations (unlike a dump or garbage site) (SUBDERE, 2023)

In response to the need to enhance the safety of waste disposal facilities, laws and decrees have been implemented since the late 1960s. Table 1 presents the main national regulations associated with sanitary landfills, with DS N°189/2008 standing out.

Table 1. Summary of waste regulations in Chile.

Year	Laws and decrees
1967	DFL N°725 (MINSAL), establishes the health code.
1994	Ley 19.300 (MINSEGPRES), on general environmental bases.
2008	DS N°189 (MINSAL), regulates basic sanitary and safety conditions in landfills.
2009	DS N°6 (MINSAL), regulates the management of waste generated in healthcare facilities.
2009	DS N°4 (MINSEGPRES), regulates the management of sludge generated in wastewater treatment plants.
2016	Ley 20.920 (MMA), establishes the framework for waste management, extended producer responsibility, and promotion of recycling.

3 CURRENT APPROACH TO STABILITY ANALYSIS IN NATIONAL LANDFILLS

The current approach considers stability analysis using the limit equilibrium method (LEM) under static and pseudo-static (seismic) conditions. Geotechnical characterization of materials, as well as pore pressures, is carried out through field campaigns and laboratory tests to generate input values for the required parameters. With this type of analysis, factors of safety (FS) are determined, which must comply with the requirements established by DS N°189/2008.

3.1 Analysis methods

In the most general case, methods of physical stability analysis can be divided into deterministic and probabilistic, where the difference lies in how the necessary parameters are selected. Thus, in a deterministic analysis, single values are used for the necessary input parameters, yielding unique results. On the other hand, in a probabilistic analysis, these parameters are varied according to probability density functions, generating different combinations of parameter values, thereby obtaining multiple results that are also probabilistically distributed.

One way to assess the physical stability of landfills is through a dynamic analysis or stress-strain analysis, in which stresses and deformations are calculated and compared against tolerability limits. Additionally, by applying the shear strength reduction method (SRF), these results can even be expressed in terms of a safety factor (Ering and Babu, 2016). This type of analysis involves extensive processing time, making it neither feasible nor practical to conduct it probabilistically. In fact, dynamic analysis isn't the approach currently used in the analysis of physical stability of national landfills, due to limitations in defining specific parameters, industry resources, and the absence of such requirements within current national regulations.

The current national approach involves conducting the analysis of physical stability using the limit equilibrium method (LEM), either deterministically or probabilistically. The LEM analyzes the equilibrium of a potentially unstable mass, comparing the forces tending towards movement with the resisting forces opposing it along a certain failure surface. In this method, for the selected theoretical failure surface and a defined combination of input parameters, a safety factor (FS) is determined according to Equation 1.

$$FS = \frac{\int \tau_R \; ds}{\int \tau_S \; ds} \qquad \text{Equation 1}$$

Where,
τ_R : Resistant shear stress along the sliding surface.
τ_S : Applied shear stress along the sliding surface.

In the LEM to represent the shear strength (τ_R) of MSW, there is a tendency towards the application of the Mohr-Coulomb failure criterion (Coulomb, 1776). Since MSW is highly heterogeneous and difficult to model, this criterion appears to be appropriate and sufficient. This failure criterion is described in terms of effective stresses by Equation 2.

$$\tau = (\sigma - u)\tan(\varphi') + c' \qquad \text{Equation 2}$$

Where,
σ : Normal stress on the failure plane.
u : Pore pressure.
φ' : Effective friction angle.
c' : Effective cohesion.

The slope stability analysis method in a landfill must satisfy both the equilibrium of moments and forces (Shafer et al., 2000). Authors such as Palma et al. (2007) and Moreno (2013) recommend the use of analysis methods by Bishop (1955), Janbu (1968), and Spencer (1967). However, the most accurate methods generally are those of Spencer, Morgenstern-Price (1965), and Generalized Limit Equilibrium (GLE), as they ensure equilibrium of both forces and moments.

Despite the differences among these methodologies, primarily derived from the assumptions used to achieve static equilibrium, discrepancies in the obtained values for the safety factor are relatively small (Gutiérrez, 2017).

DS N°189/2008 establishes that the minimum safety factors (FS) resulting from the stability analysis of a landfill must be 1,5 and 1,3 for static and seismic conditions, respectively.

3.2 Field campaign

The field campaign aims to collect information that will be used in the stability study, and specifically in the LEM analyses, including the search and identification, through visual inspection, of possible signs of physical instability in the landfill, which includes detecting cracks and areas and slopes where leachate may be surfacing.

As part of this campaign, for defining the piezometric level to be used within the waste mass, measurements over time are taken of leachate levels in gas extraction wells and/or in test pits.

As part of this campaign, measurements of leachate levels in gas extraction wells and/or test pits are taken over time to determine the piezometric level within the waste mass. Additionally, dynamic penetration tests assess the resistance parameters of the MSW qualitatively.

Advantages of these tests include ease of use, obtaining landfill stratigraphy, and analyzing changes in waste strength over time through periodic testing campaigns (Palma, 1995). However, a drawback is their reliance on empirical correlations, challenging to apply to such variable materials as waste.

The earliest investigations into landfill dynamic penetration tests were led by Sowers (1968), revealing generally low resistance to dynamic penetration of waste, except in localized areas or when passing through cover material (Sowers, 1968; Olalla, 1991; Espinace et al., 1992; Palma, 1995; Zhan, 2008; Machado, 2010).

3.3 *Geotechnical characterization of materials*

To determine the mechanical properties of MSW, national practice often relies on bibliographic values, primarily derived from international experiences.

For landfill analysis, a homogeneous density value ranging between 1,04 and 1,12 t/m³ is commonly used (Espinace et al., 2007). However, the density inside a landfill likely tends to increase with depth due to bioconsolidation and the weight of the waste column itself; therefore, expressions have been developed to represent this effect as a function of the initial compaction degree of the waste (Zekkos et al., 2006).

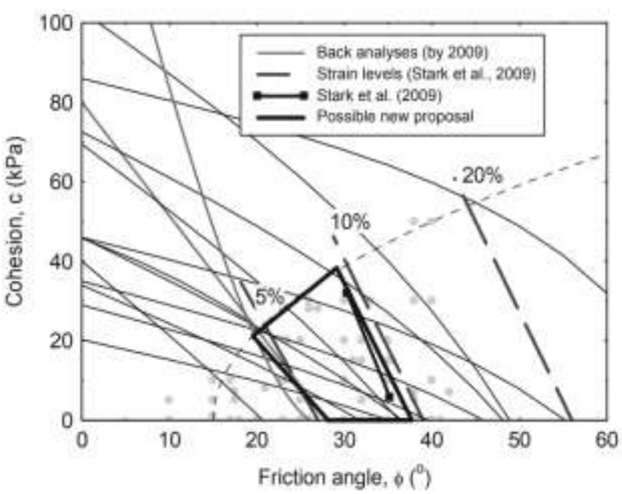

Figure 2. Recommended region of resistance parameter values for the analysis (Cañizal et al., 2013).

Regarding the resistance parameters, such as cohesion and friction angle of the Mohr-Coulomb failure criterion (Coulomb, 1776), it is common to use the region of values proposed by various authors, with the proposal by Cañizal et al. (2013) standing out. This proposal is based on laboratory and field test results, along with values calculated from the back-calculation of actual failures (see Figure 2).

4 LIMITATIONS OF THE CURRENT NATIONAL APPROACH TO PHYSICAL STABILITY ANALYSIS

The current approach has a series of limitations, which are described below.

4.1 *Use of limit equilibrium method and Mohr-Coulomb failure criterion*

The use of the Mohr-Coulomb failure criterion in LEM analyses appears to be the best option in terms of ease of use, as only three parameters attributable to MSW (resistance parameters and density), the location of the piezometric level, and seismic acceleration coefficients are necessary. However, with this analysis method and failure criterion, it isn’t possible to incorporate parameters and considerations necessary to reflect the complex phenomena that occur in landfills, mainly related to biodegradation and the effect of biogas.

4.2 *Determination of resistance parameters*

The determination of resistance parameters faces two main problems: obtaining values and their representativeness.

Regarding the obtaining of values, there are various methodologies from classical geotechnics, ranging from measurements through laboratory tests to the combined use of results from field tests with empirically determined correlations. However, for landfills, these methodologies are not directly applicable. In Chile, laboratory tests on waste aren’t generally carried out because commercial laboratories don’t make their equipment available to work with these types of materials, which is understandable given that they cause noticeable deterioration that is difficult to control.

On the other hand, the mechanical properties of waste are influenced by various factors, such as their age, composition, landfill operational methods, and cover material. The complexity of obtaining representative samples for laboratory tests makes it difficult to obtain reliable values of resistance properties.

As for the representativeness of the obtained results, whether in the field or laboratory, it is low due to the heterogeneity of MSW, so using single values isn´t recommended. A valid alternative is to perform probabilistic analyses, although in this case, the difficulty lies in defining appropriate probability distributions for each parameter, minimum and maximum values, and establishing the relationship between these values and the composition of the waste.

4.3 *Consideration of the effects or organic matter biodegradation*

The effects of biodegradation correspond to the generation of leachate and biogas. There is no clarity about the interaction between these two effects. Organic matter in landfills, necessary for biodegradation, is spatially located randomly inside the landfill, so the generation and accumulation of leachate and biogas isn't a uniform process. Additionally, the presence of cover or waste obstructs the flow of liquids and/or gas within the landfill.

In this sense, the presence of leachate can occur in the form of encapsulated liquids, similar to hanging nappe, or a homogeneous distribution, similar to a groundwater table in soils.

Regarding biogas generation, the difficulty arises in incorporating the pressures it exerts on the piezometric level, as there is no direct correlation between these elements.

Another relevant aspect is that when using the piezometric level as a reference, it isn't taken into account that leachates, due to the dissolved chemical species they contain, could have a different density than water, which may affect the accuracy of the calculations.

Chao et al. (2020) estimated that there are reductions in the safety factor (FS) of up to 44.5% when considering the generation of biogas and its interaction with the leachate level, considering leachate heights of up to 20 m.

4.4 Pseudo-static analysis

Being a seismic country, pseudo-static analysis plays a significant role in the design of landfills in Chile, sometimes being the predominant factor in defining slope geometries. However, given the nature of waste, which allows for large deformations, the evidence indicating that Chilean landfills did not experience serious failures during the 2010 earthquake, and the fact that major failures in Chile correspond to static failures generated by effects of biodegradation and sludge disposal, the representativeness and prominence of pseudo-static analysis is legitimate to question.

5 RECOMMENDATIONS TO ADDRESS LIMITATIONS OF THE CURRENT NATIONAL APPROACH TO PHYSICAL STABILITY ANALYSIS

To practically address some of the described limitations of the current national approach, alternatives and conservative considerations are proposed to safeguard, as the primary objective, the structural safety of the MSW storage facility. In this context, considerations for the location of the piezometric level are proposed, as well as empirical limits for the results of Dynamic Cone Penetration Tests (DCPT), the latter in order to qualitatively estimate the density and resistance parameters of the waste mass.

5.1 Limit curves for DCPT tests

Based on the analysis of results from forty DCPT tests conducted by GA Consultores in six national landfills, under different conditions such as normal operation, near failures, and areas with sludge co-disposal, lower and upper limit curves have been established for the normalized values of blow counts, every 30 cm of penetration, to a 60% of theoretical energy (N_{60}). These curves are plotted against depth (D) and are mathematically described by Equations 3 and 4, respectively. It is worth mentioning that energy normalization is carried out to bring the records of the forty tests to the same level of energy efficiency. Additionally, for the definition of the limit curves, a normal distribution equivalent to the mean ± one standard deviation was assumed, so that for each depth, 68% of the data falls within the limits (Figure 3).

$$N_{60,\ Lower\ Limit} = 4{,}938 \cdot e^{0{,}1181 \cdot D} \qquad \text{Equation 3}$$

$$N_{60,\ Upper\ Limit} = 10{,}529 \cdot e^{0{,}0861 \cdot D} \qquad \text{Equation 4}$$

Where,
D : Depth (m).

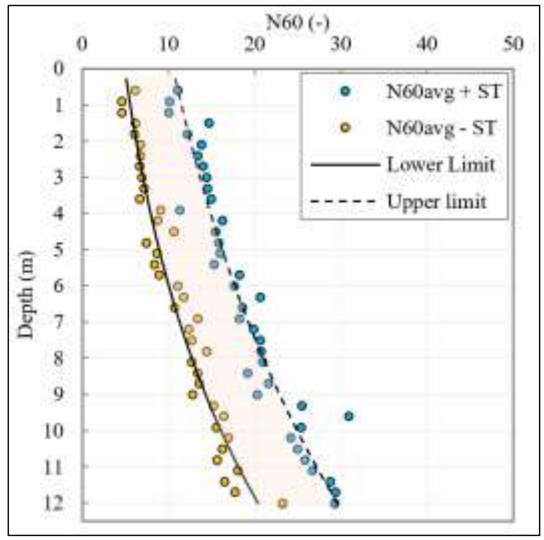

Figure 3. Lower and upper limits of the N_{60} value in DCPT tests.

These limits establish a general trend for the N_{60} values in a Chilean landfill, which allows eliminating the influence of outlier data generated by highly rigid elements, as well as identifying points of low density. If the corrected results of the DCPT tests fall within these curves, it is valid to qualitatively assign the pairs of resistance parameters circumscribed to the region of values proposed by Cañizal et al. (2013) (see Figure 4) or another author suggesting similar values.

Studies have found that dynamic penetration test values exhibit dependence on waste characteristics such as age, organic material content, moisture content, high decomposition rates, and the presence of plastic fibers (Machado, 2010). These factors make it extremely difficult to establish precise and consistent correlations between N60, cohesion and friction angle.

Dixon (2005), suggest that there is no clear relationship between penetration resistance and the shear strength of municipal solid waste (MSW). However, Gomes (2013) posits that theoretically, penetration resistance can represent the overall strength of the waste at the strain levels imposed by the tests, correlating friction angle with N_{60} in terms of axial strain.

5.2 Definition of the piezometric level

In terms of on-site measurement and in a simplified manner, the most practical methodology is to use the measured leachate level, whether through test pits, piezometers, or biogas extraction wells, although it should be considered that it may not be a true measure.

In this regard, the execution of CPTu tests can also be considered, which allows the measurement of interstitial pressures at depth, determining whether the presence of leachate can be assimilated to a piezometric level or if they are encapsulated liquids. It should be noted that the sensor of this equipment would not allow the measurement of gas pressures.

As discussed in Section 4.3, it is still not fully understood how the interaction between leachate and biogas occurs, as well as the mineralogical composition of the leachate, which affects the definition of the piezometric level in a physical stability analysis by LEM. Therefore, to address this uncertainty, it is recommended to reduce the depth of the piezometric level in the modeling, to depths shallower than those measured in test pits, biogas extraction wells, and piezometers.

Additionally, it is important to consider that leachate level measurements are carried out in open drillings, which causes the evident release of biogas, not considering its contribution in the measured level.

6 EFFECT AND IMPORTANCE OF OPERATIONAL PRACTICES ON PHYSICAL STABILITY

The way a landfill is operated is extremely important in terms of physical stability, due to the conditions that arise within the waste mass, both favorable and unfavorable. Some of the operational practices described below are part of normal operation, while others necessitate prior specific health authorization for implementation.

6.1 Compaction of waste

Firstly, perhaps the most common operational practice involves on-site compaction of solid waste during deposition. This practice is mandated according to DS N°189/2008, where article 35 specifies the use of bulldozer-type mechanical equipment to ensure minimum safety and stability conditions. It requires the compaction of waste layers no more than 60 cm thick, with at least four passes of such machinery.

Authors such as Fasset et al. (1994) have differentiated the expected density in MSW according to compaction energy, categorizing it into three groups:

- Poor compaction, associated with little or no compaction.
- Moderate compaction, linked to older landfills.
- Good compaction, representing current practices.

According to these authors, MSW with good compaction achieve total density values ranging from 0,89 to 1,07 t/m3.

It should be noted that not perform this operational practice has a negative effect in terms of volume, as the waste remains disposed of at low densities, thereby reducing the remaining lifespan of the landfill.

In terms of physical stability, low density resulting from insufficient, or no compaction favors slope failures, as the degree of compaction tends to be directly proportional to the shear strength of the waste mass (Carvalho, 1999). This premise is particularly valid when comparing non-compacted or moderately compacted waste masses with those that have been well compacted.

Variations in density within the range associated with good compaction would not have a significant influence on physical stability. In this regard, Vajirkar (2004) conducted a sensitivity analysis to assess the influence of waste density on safety factors in slope stability analysis, finding that varying the total density of waste within a range of 0,96 to 1,28 t/m^3 resulted in the safety factor remaining practically constant.

Additionally, it's important to mention that low density values would increase the stabilization time of the waste mass, as total settlements would take longer to develop. Pavez (2020) indicates that total settlements of waste can be divided into three successive basic stages: initial compression, which occurs due to material rearrangement and compaction processes; primary compression, resulting from the dissipation of excess pore pressure produced by leachate and biogas; and long-term secondary settlement, caused by the combined action of mechanical compression and biodegradation of waste. Waste with low density values in its disposal will progressively compact under the weight of upper layers, a phenomenon that occurs almost instantly when waste is compacted with machinery.

6.2 Utilization of daily cover material

According to article 37 of DS N°189/2008, waste disposed of in a landfill must be covered with a layer of cover material at least 15 cm thick at the end of each day of operation or more frequently if necessary.

This operational practice is required by national regulation primarily to isolate the waste from the surrounding environment, control the proliferation of sanitary vectors, mitigate biogas emissions and unpleasant odors, reduce the risk of fires and the ingress of rainwater.

National regulation, as stated in article 39, also require that the daily cover not be removed at any time, and it may be necessary to establish vertical continuity between cells through drainage pipes. It is precisely in this provision where differences arise regarding the operation of some landfills in the country, as many of them have chosen to remove the daily cover when disposing of a new layer above, arguing that it hinders or greatly complicates the percolation of leachate liquids towards the basal drainage system. Landfill operators also cite two main reasons for not constructing drainage pipes: the difficulty associated with their implementation alongside deposition activities, resulting in a longer operational time; and the need to project many drainage pipes within a specific area to ensure adequate leachate percolation.

The concentration of leachate liquids at different depths is often modeled as hanging nappe, which negatively affects the physical stability of the waste mass, as pore pressures are generated that reduce effective stresses and, consequently, the shear strength of the mass. It should be noted that defining these nappes is extremely difficult with current control methodologies.

6.3 Co-disposal of sludge with MSW

The co-disposal of sludge and MSW in landfills involves the combined disposal of sludge from wastewaters treatment plants (WWTP) with MSW, where small amounts of sludge are mixed with the waste and spread at the working face. This operational practice is one of the most employed alternatives today for managing sludge generated in national WWTP (Pavez, 2020).

According to article 56 of DS N°189/2008, prior authorization from the competent health authority is required to carry out this operational practice, and a physical stability analysis validating its feasibility must be conducted. Similarly, DS N°4/2009, which is the regulation for the management of sludge generated in WWTP, in its article 16, also states that it is possible to dispose of WWTP sludges in a landfill with prior health authorization, along with specifying a maximum limit of 6% by weight for the maximum daily amount of sludge relative to the total waste deposited daily. In the same article, in concise terms, it is also established that the daily average moisture content of the sludge to be disposed of must not exceed 70%.

Pavez (2020) indicates that the co-disposal practice has positive factors, such as providing a secure disposal site for sludge, as landfills incorporate a basal liner system and leachate conduction or drainage. This same author indicates that this practice leads to an increase in the generation of leachate and biogas, which could be seen as a positive aspect in terms of physical stability, as it accelerates the biodegradation of waste and thus stabilizes the deposited waste mass. Additionally, another benefit is the opportunity to energetically utilize biogas production.

On the other hand, the co-disposal practice also brings negative factors for the physical stability of the landfill. With the mixture, the strength properties of MSW tend to decrease (Reinhart et al., 2003; Xiaojuan & Cheng, 2014). Additionally, if the increase in leachate and biogas generation is not properly managed, for example, due to clogging of the basal drainage system or insufficient biogas extraction wells, the level of interstitial pressures in the waste mass increases, thereby increasing the likelihood of landfill slope failures (Reinhart et al., 2003, 2005; Espinace et al., 2007; Altabella et al., 2016; Espinace & Farfán, 2016). In this regard, the provisions of DS N°4/2009 regarding the maximum daily amount of sludge to be disposed of and the maximum deposition moisture are aimed at controlling and minimizing the occurrence of these negative effects on the physical stability of the waste mass.

It is important to clarify that, although co-disposal has been defined here as the mixing of WWTP sludges with MSW, current regulations in Chile do not establish a procedure for the disposal of sludge and MSW, inferring that this must be adapted to the type of landfill, its infrastructure, and available equipment. Authors such as Shafer et al. (2000) recommend mixing sludge with MSW before disposing of them in the landfill, or directly disposing of sludge in thin layers so that they can fill the voids in the waste when compacted. In addition to these two alternatives, Reinhart et al. (2007) recommend other methods such as trench disposal within the landfill (without mixing) and mixing with additives (soil or other material), either for disposal in layers within the landfill or for use as cover material.

Based on the experience gained by the authors of this article in the analysis of physical stability of landfills, it seems that the alternative of trench disposal of sludge may not be advisable, as it can create potential soft spots in the landfill, which can lead to significant sudden and localized settlements over time.

7 OTHERS APPROACHES TO PHYSICAL STABILITY ANALYSIS

In the realm of research and international practices, other approaches have been developed for stability analysis, both regarding numerical modeling and landfill characterization and monitoring. These approaches include the application of coupled models, conducting geophysical surveys, and incorporating monitoring systems.

7.1 Coupled models

A coupled numerical model is a type of model that combines two or more individual models to simulate physical phenomena or processes that interact with each other. Through coupled numerical models, a greater number of variables, parameters, processes, and interactions can be included with the aim of improving the representation and accuracy of what occurs. In the case of landfills, these models allow for the incorporation of the mechanical behavior of MSW, the influence of bioconsolidation, and the presence of fibrous materials in them.

MCDougall (2007) proposes a coupled hydraulic-biological-mechanical model based on the Cam-Clay model, incorporating settlements through an equivalent time method. Waste biodegradation is simulated through two stages of the anaerobic degradation process, considering the loss of organic solids through parameters related to the mechanical properties of the waste.

On the other hand, Hubert et al. (2016) develops a coupled model that encompasses the disciplines of thermodynamics, hydraulics, biology, and mechanics, based on the modified Cam-Clay model. This model considers the phenomena of hardening or softening associated with waste biodegradation, detailing the stages of the anaerobic degradation process.

Li et al. (2023), based on triaxial tests on MSW with different contents of fibrous materials, conclude that the reinforcement of these materials is the key factor affecting the mechanical properties of MSW. They propose a new plastic potential function that reflects the reinforcement effect of fibrous materials to establish an elastoplastic constitutive model that predicts the stress-strain response of MSW.

It is important to mention that this type of approach isn't part of current national practice, and it is even rarely applied internationally, mainly restricted to research studies conducted in the academic sphere. This is due to the large number of variables involved and the modeling time required, which increases the cost of characterization campaigns and desk studies.

7.2 Geophysical surveys

The geophysical characteristics of MSW are often different from those of the surrounding environment, which allows for the use of geophysical survey methods to characterize aspects such as the extent (depth) and volume of landfills. Generally, landfills are characterized by low densities and low seismic wave propagation velocities, which are related to the nature of the waste and its low compaction compared to the surrounding soil. Similarly, the electrical resistivity of landfills is usually low due to the high electrical conductivity of leachate and the temperature increase caused by waste biodegradation.

RAWFILL was a project co-financed by the European Union that took place between 2017 and 2021. The main objective of this project was to analyze and compare various geophysical survey methods applied to landfills. The findings provide a detailed assessment of the information obtained from each survey and are summarized in Table 2.

Table 2. Relevant information for each geophysical survey method.

Method	Relevant information for landfill characterization
Electrical resistivity tomography (ERT) or DC electrical resistivity	Cover layer thickness, waste zonation, leachate content, geology, groundwater table
Induced polarization (IP)	Cover layer thickness, vertical extent, waste zonation
Ground Penetrating Radar (GPR)	Cover layer thickness and utilities
Electromagnetic induction (EMI)	Lateral extent, utilities, waste zonation
Magnetometry (MAG)	Lateral extent, utilities, waste zonation
Seismics (Seismic refraction tomography, Multichannel analysis of surface waves, Microtremor refraction, Nakamura method (spectral ratio HVSR or HV))	Vertical extent, Geology

Source. Caterina et al. (2020).

In addition to the above, Flores Orozco et al. (2020), through the Induced Polarization (IP) method, demonstrated that the electrical conductivity of waste is primarily sensitive to the increase in fluid conductivity associated with leachate production and migration. Furthermore, images of the polarization effect expressed in terms of the complex component (σ´´) reveal the potential to characterize variations in the structure and biogeochemical activity of the landfill (Equation 5). In particular, they found that zones with high total leachable organic carbon contents (above 1500 mg/kg of dry waste) are associated with high polarization values (σ´´ > 10 mS/m, ϕ > 40 mrads), while areas with low total leachable organic carbon contents (less than 300 mg/kg of dry waste) exhibit low polarization values (σ´´ < 1 mS/m, 10 < ϕ < 25 mrads).

$$\sigma^* = \sigma^{\prime} + \sigma^{\prime\prime} i = |\sigma| e^{\emptyset i} \qquad \text{Equation 5}$$

Donde,
σ^* : Complex conductivity [mS/m]
$\sigma^{\prime}$: Real component of σ^* [mS/m]
$\sigma^{\prime\prime}$: Complex component de σ^* [mS/m]
ϕ : Phase angle [mrads].

Before the implementation of DS N°189/2008, there was no control over the volume of MSW deposited in landfills, and since the volume of this waste mass varies over time due to biodegradation processes, as mentioned earlier, the use of geophysical methods emerges as an effective alternative to estimate landfill volume.

In this context, Liu & Jin (2022) applied electrical geophysical methods, such as transient electromagnetic method and high-density resistivity, to estimate the distribution and volume of waste in the Anhui landfill (China) under various cover conditions (soil, geomembrane, and concrete). As a result, the resistivity value at the soil-waste interface was determined to be 29 Ω·m, facilitating the quantification of stored MSW volume.
Finally, it is important to highlight that there are inherent limitations to geophysical surveys, particularly regarding data interpretation and processing. In seismic methods such as multichannel analysis of surface waves and microtremor refraction analysis, the difficulty arises from the possibility of obtaining multiple depth shear wave velocity profiles for a single dispersion curve. This occurs because field measurements provide an empirical dispersion curve, requiring an iterative process to propose stratigraphic models. Each model produces a theoretical dispersion curve that is compared with the empirical one to find the best fit. In this context, having accurate stratigraphic information is crucial, which is challenging in landfills due to the heterogeneity of MSW.

7.3 Instrumentation

Monitoring through instrumentation installed in a landfill, along with comprehensive and critical interpretation of compiled data, is crucial for achieving safe and satisfactory performance of the facility.

Titov et al. (2021) proposed a comprehensive monitoring system based on the following components:

- Gas analysis: A network of sensors capable of detecting hazardous vapors.
- Geophysical sensors: A network of geophysical inclinometers designed to monitor the state of the landfill soil and control its internal deformations.
- Perimeter monitoring: Coherent Optical Time Domain

Reflectometry System sensitive to seismic activity in the monitored perimeter area, along with a network of long-range surveillance cameras.

- Data transfer: Collects information from various sensor types and transmits data using wireless technologies such as Low-Power Wide-Area Network.
- Analysis and forecasting: Intelligent analysis and prediction of landfill state dynamics based on a record of geological conditions, a network of previous gas emission events, and spatiotemporal dynamics of event flow.

On the other hand, Fay et al. (2023) introduced an innovative autonomous device for measuring biogas pressure in active landfills, enabling real-time monitoring and early detection of critical events such as underground fires or methane explosions. Equipped with advanced pressure sensors and wireless communication, it facilitates remote data transmission and access via the internet.

8 CONCLUSIONS

The analysis of the current approach used at the national level in studies of physical stability of landfills has revealed a series of limitations, of various natures, mainly related to the method and type of analysis, as well as the obtaining of input parameters derived from said method. Emphasis has been placed on the difficulty of conducting tests that are truly representative of the waste mass, often resorting to bibliographic values that were not necessarily determined for waste of composition and nature like those of the landfill being analyzed. In this context, limit curves of DCPT tests have been proposed based on the analysis of forty such tests in six national landfills. These curves establish a general trend that serves to qualitatively obtain input parameters for MSW, specifically the resistant parameters of the Mohr-Coulomb failure criterion.

Additionally, the importance of different operational practices on the physical stability condition has been highlighted, aiming to demonstrate the great variability of states and conditions that can be found in the same landfill, further complicating the possibility of conducting truly representative analyses.

Finally, other approaches used internationally and in research in the analysis of physical stability of landfills have been discussed. These approaches include the use of coupled numerical models to more accurately represent processes and interactions, geophysical testing to characterize the waste mass, and the implementation of instrumentation systems for effective and safe management of landfills.

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