MONITORING HORIZONTAL DISPLACEMENTS IN LANDFILLS USING INSTRUMENTATION AND GEOSTATISTICS

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ABSTRACT

Geotechnical monitoring encompasses the inspection of vertical and horizontal displacements, pore pressures, shear resistance, leachate, and gas flows. Moreover, the monitoring includes visual inspections, ensuring environmental preservation and the safety of the landfill site. Accordingly, this research aims to evaluate and spatialize the magnitude of horizontal displacements over a period of 1 year in a landfill located at Fazenda Logradouro II, district of Catolé de Boa Vista, in the municipality of Campina Grande, state of Paraíba - Brazil. The horizontal displacements were monitored with surface markers through weekly measurements conducted with a total station. After calculating the displacements, spatialization was performed using geostatistics with heat maps (Kernel density estimation), and the computed data was verified against literature data. The results indicated that cumulative horizontal displacements, horizontal displacement speed, and actual displacements are smaller than the values reported in the literature. The spatialization of displacement data using geostatistics has proven to be effective in better visualizing the distribution of displacements in regions of the sanitary massif. The displacement data do not behave uniformly due to waste heterogeneity and other operational factors such as compaction and the execution of the cover soil layer. Thus, geostatistical analysis can be considered as a technique that can help predict and manage these displacements, improving the stability and useful life of the landfill.

KEYWORDS: *Landfill, Horizontal displacements, Geostatistics*

I. INTRODUCTION

Environmental monitoring of landfills is crucial and should be carried out during the planning, operation and post-operation of a landfill. The main purpose of this monitoring is to ensure the preservation of the environment, the health of the local community, the stability of the structure, and the effectiveness of the drainage systems for percolated liquids and gases. Therefore, it is essential to establish a complete environmental and geotechnical monitoring system. This system is developed to ensure the stability of the landfill and the effectiveness of the environmental control and protection measures during the useful life of the enterprise [1].

In the process of geotechnical monitoring, it is essential to analyse various elements, such as vertical and horizontal displacements, pore pressure, shear strength of the waste, leachate and gas flows, and climate [2]. Additional influencing factors include the findings of visual inspections, geological data of the site, quantity and characteristics of incoming and landfilled waste, waste cell geometry, operational quality, and closure stage.

Surface markers are strategically positioned on the landfill surface to monitor horizontal and vertical displacements [3]. These markers are constructed of precast concrete and equipped with a reference pin for accurate topographic measurements. Each marker is uniquely identified to ensure traceability and accuracy of the data collected.

The superficial markers are situational on one of the sides of shedding, along the final covering layer, close to the slopes. These markers enable easy observation on the offsets, provide essential information to all decisive actions employed to the efficient landfill control. This means that the superficial marks are more critical in the geotechnical monitoring of the landfill area by precision data on the displacements and decision support regarding the stability and safety of the structure [1].

The implementation of a dynamic monitoring system makes it possible to obtain real-time data on the evolution of displacements, allowing for continuous analysis of the movements of the landfill. This monitoring is essential to effectively assess the stability of the landfill slopes. The frequency of topographic readings should be adjusted according to the registered displacements, to identify and allow for the immediate detection of significant changes that may require corrective actions. any significant changes that may indicate the requirement for corrective actions [4].

To improve field monitoring, it is possible to utilize geostatistical methods for spatializing data and effectively evaluating the extent of influence of each surface marker. This approach enables the identification of geostatistical surfaces exhibiting the highest noise levels in recorded displacements. The objective of this research is to assess and spatialize the magnitude of horizontal displacements over one year at a landfill located in Campina Grande, State of Paraíba, Brazil.

The paper is organized into five distinct sections. First, the research process is detailed, including the description of the monitoring and data processing techniques. Then, the results obtained from the analysis of the data collected in the field, which were processed using geostatistical methods, are presented. These results are then discussed in detail, highlighting the importance of applying geostatistics and spatialization of displacements in the geotechnical monitoring of landfills. Finally, the paper concludes with concluding remarks on the findings and the relevance of the study.

II. METHODOLOGY

2.1. Study area

This study was carried out in a waste cell of the Sanitary Landfill in Campina Grande-PB (SLCG), located at Fazenda Logradouro II, district of Catolé de Boa Vista, in the municipality of Campina Grande, state of Paraíba - Brazil, (7° 16’ 44.4” S, 36° 00’ 44.0” W), as shown in Figure 1.

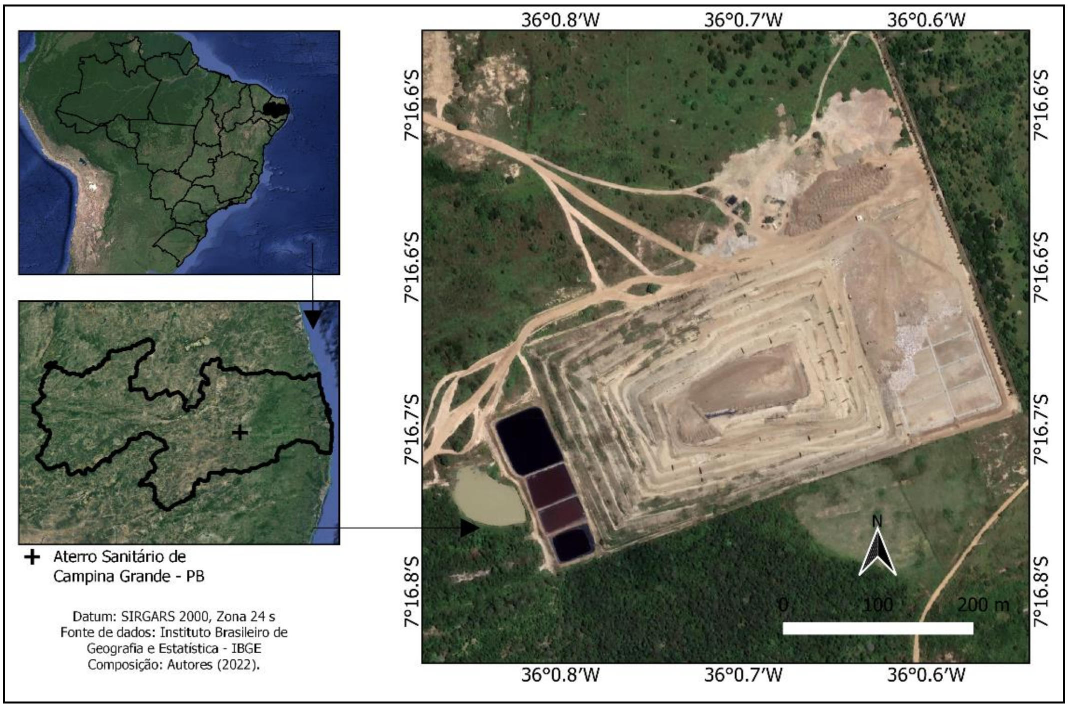

Figure 1 - Georeferenced map of the landfill in Campina Grande – PB

The SLCG waste disposal arrangement is shown in Figure 2. The landfill under study has two closed Cells, Cell 1 measuring 100 meters long by 220 meters wide and Cell 2 measuring 100 meters long by 100 meters wide, both with a height of approximately 40 meters, slopes with a 1:2 inclination and intermediate berms measuring 6 m wide.

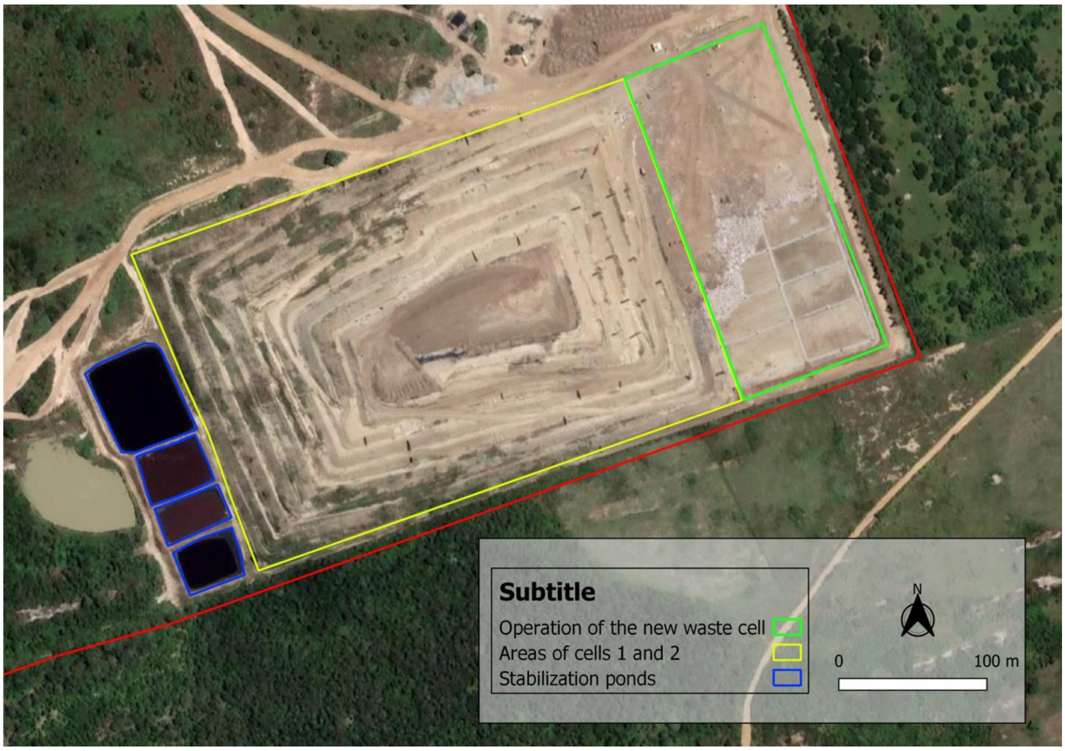

Figure 2 - Current arrangement of the landfill in Campina Grande – PB

2.2. Monitoring of horizontal displacements

Displacement monitoring was conducted using a Pentax total station R-205NE, surface markers, and fixed points (Figure 3) as part of a topographic survey. This monitoring facilitated the assessment of slope safety.

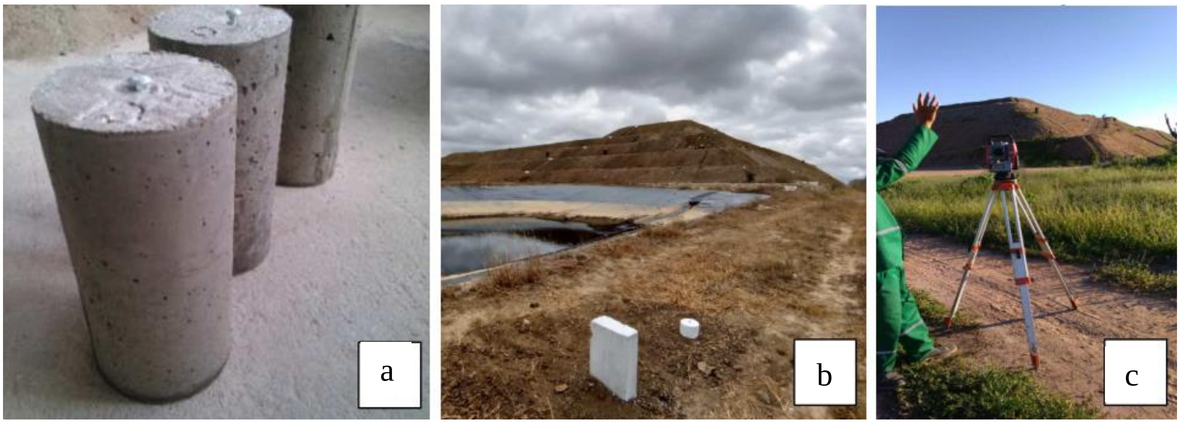

Figure 3 - Instrumentation used to monitor landfill displacements: (a) surface markers; (b) fixed point; (c) total station

The final compacted soil cover layer in Cell 1 of the SLCG was equipped with fifty-five surface markers. Additionally, four fixed markers were positioned in the non-deformable soil area adjacent to the waste cell, as illustrated in Figure 4.

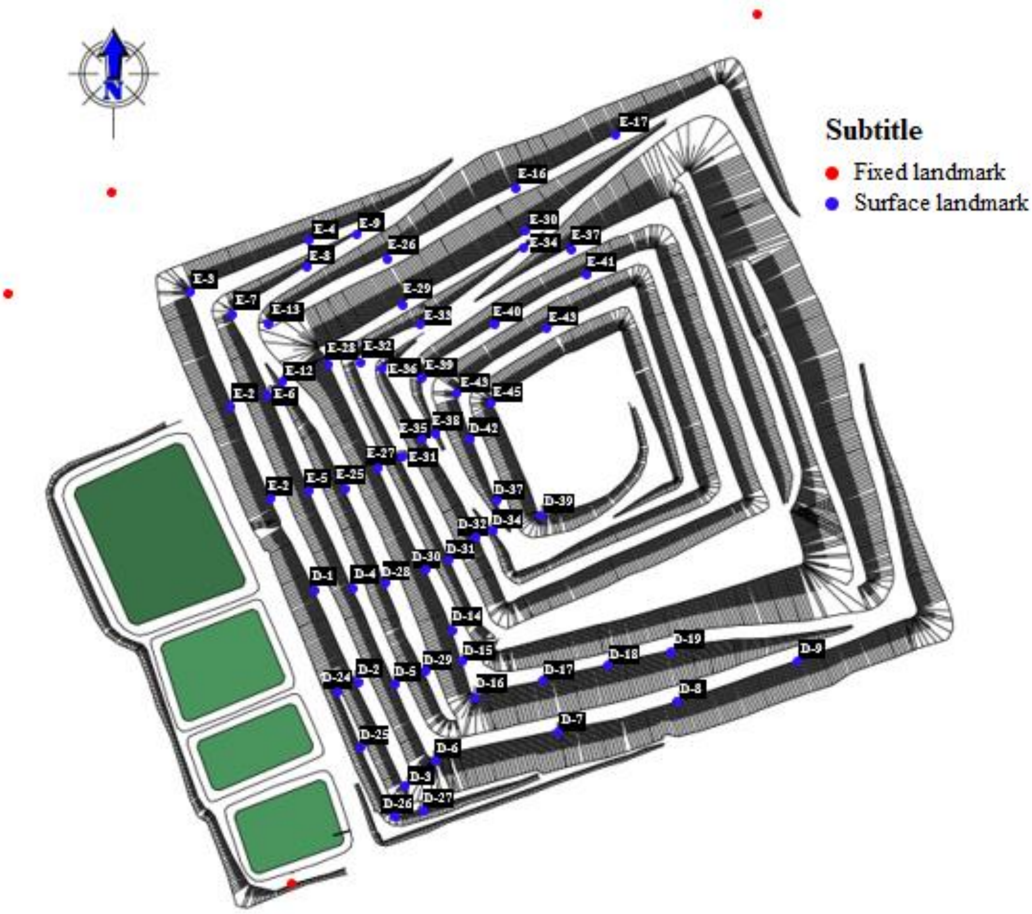

Figure 4 Distribution of surface markers in cell 1

After the waste disposal operation and the final covering layer were completed, surface markers were installed in Cell 1 to monitor horizontal displacements.

The monitoring of horizontal displacement involved taking weekly readings of surface marker locations using a total station, with fixed markers serving as reference points. Monthly data compilation included verification of accumulated horizontal displacement, speed, and actual displacements.

2.3. Geostatistics applied to monitoring vertical displacements

The use of Kernel density or heat maps in geotechnologies is a statistical method that estimates density curves based on quoted points. In this method, each observation (point) is weighted according to its distance from a particular point, called the nucleus [5].

Through the utilization of the Kernel Density technique, displacement maps were generated to visualize varying density levels, delineated by distinct color gradients. The red gradient color scale denotes the intensity of the observed displacements, with warmer colors indicating greater displacement magnitudes. Furthermore, Table 1 presents the assessed frequency for each category of displacement.

Table 1 – Analysis period

Monitoring	Period	Analysis planes
Cumulative horizontal displacement	February 2022 – February 2023	Horizontal
Horizontal displacement speed	February 2022 – February 2023	Horizontal
Actual displacement	February 2022 – February 2023	Horizontal and vertical

Heat maps (Kernel density) were generated using the density tool on the QGIS software (QGIS 3.28.6).

III. RESULTS

3.1. Monitoring of accumulated horizontal displacements

The accumulated horizontal displacements have been recorded since February 2022. Figure 5 presents the accumulated values in millimeters.

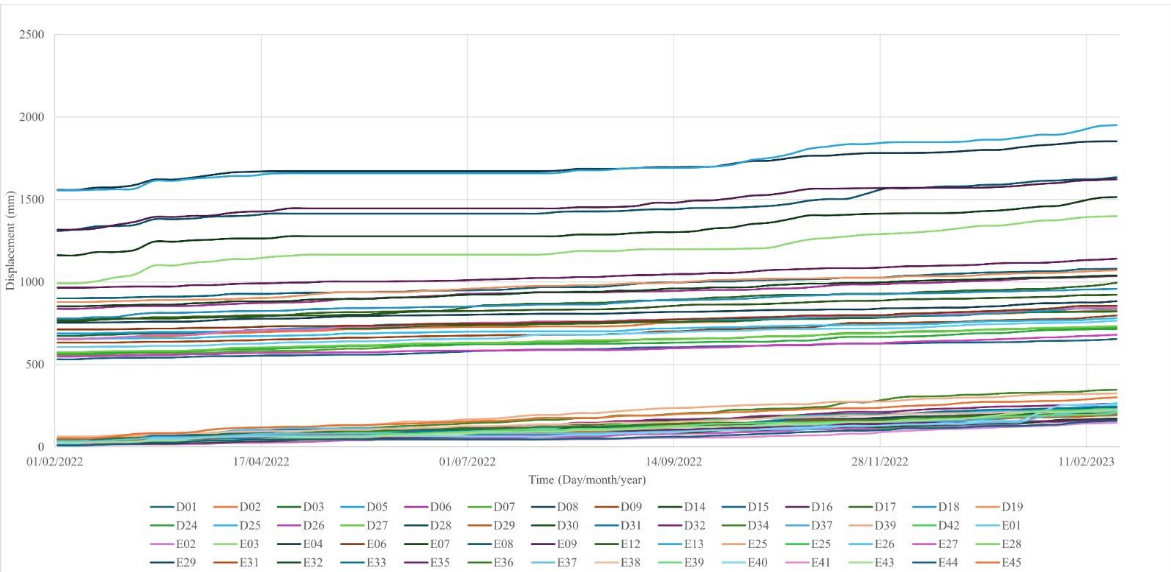

Figure 5 - Cumulative displacement during the monitoring period

Horizontal displacement speed is one of the main parameters available in the literature for assessing the stability of the landfill site. Figure 6 shows the monthly average values of displacement speeds during the monitoring period.

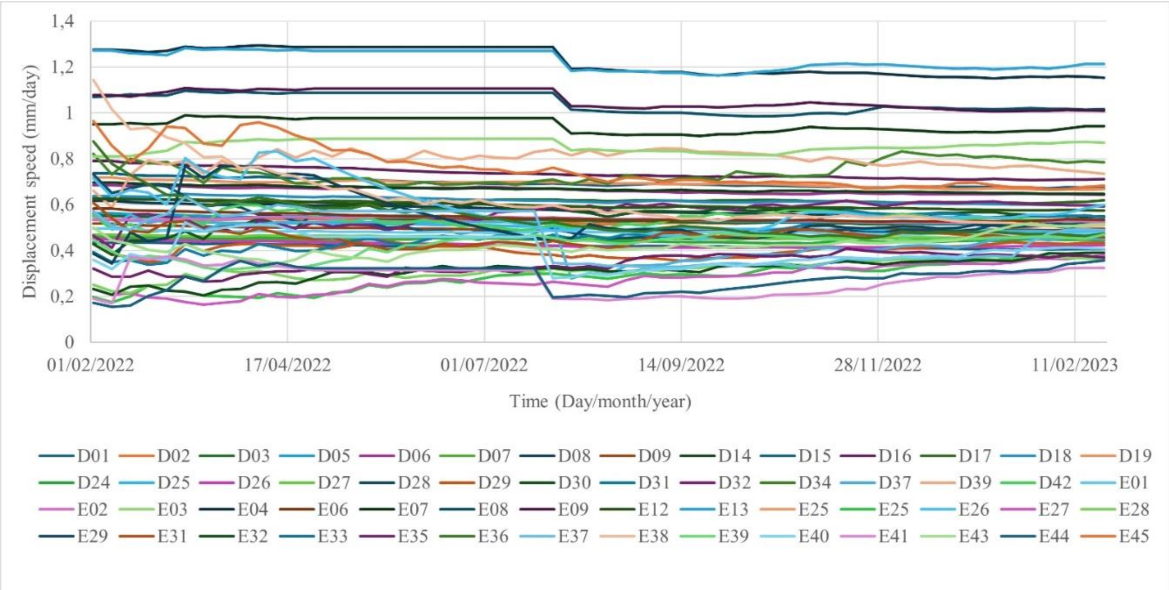

Figure 6 - Horizontal displacement speed during the monitoring period

Tracking historical actual displacement magnitudes is not feasible due to the three-dimensional variation based on the current positions of surface markers. Consequently, the magnitudes were segmented by quarters during the monitoring period, as illustrated in Figure 7.

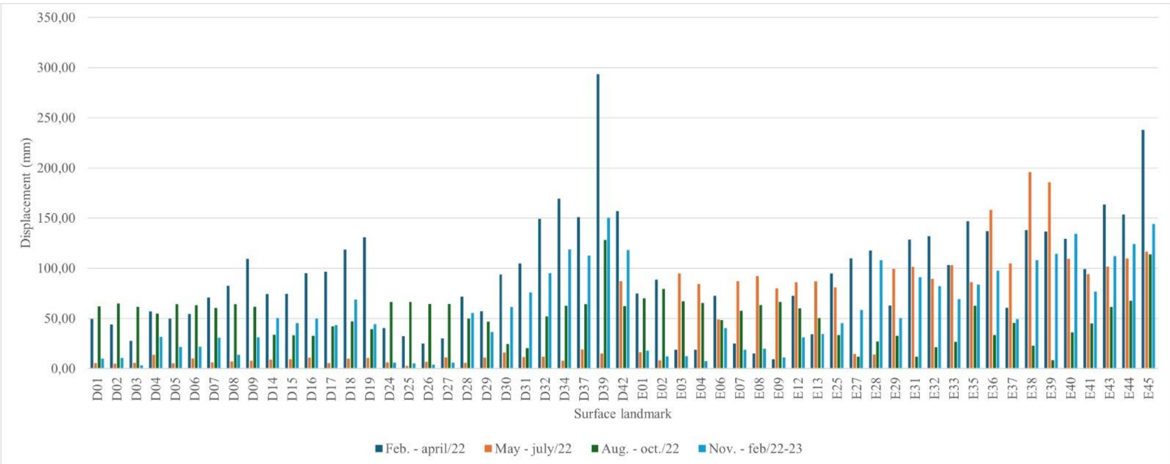

Figure 7 – Actual displacements magnitudes

3.2. Displacement distribution maps with geostatistics

The initial analysis pertains to the magnitude of accumulated horizontal displacements by the end of the monitoring period in Cell 1, specifically defined as February 2023. Figure 8 illustrates the spatial distribution of the data, highlighting the areas exhibiting the highest displacements observed over the monitoring period of the surface markers installed in Cell 1.

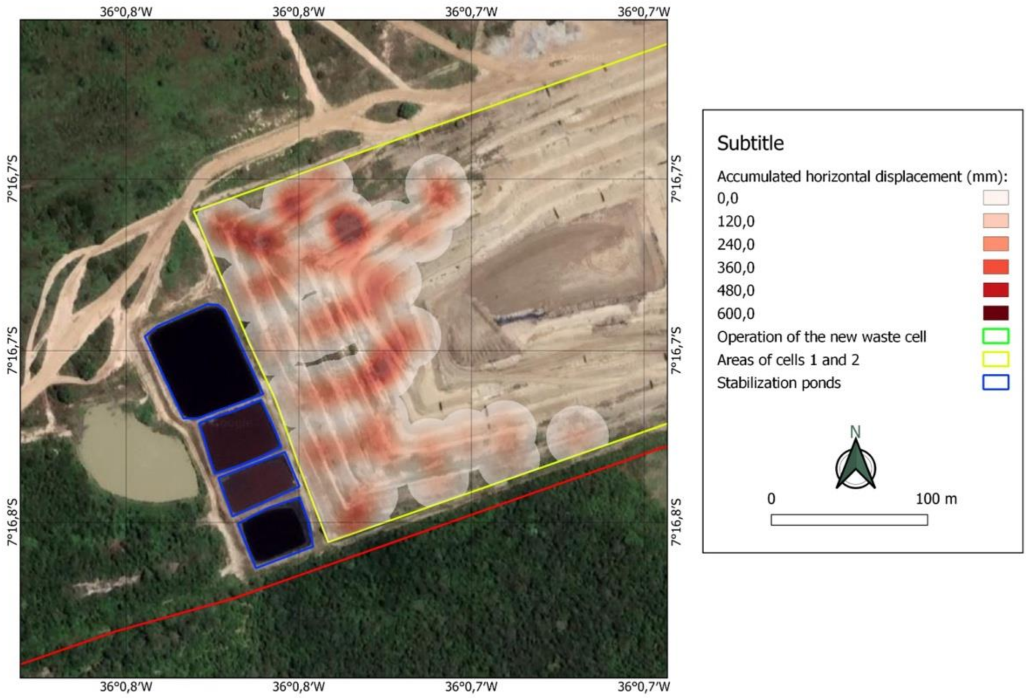

Figure 8 - Heat map of accumulated horizontal displacements

Figure 9 illustrates the areas within Cell 1 exhibiting the highest horizontal displacement speeds observed between February 2022 and February 2023.

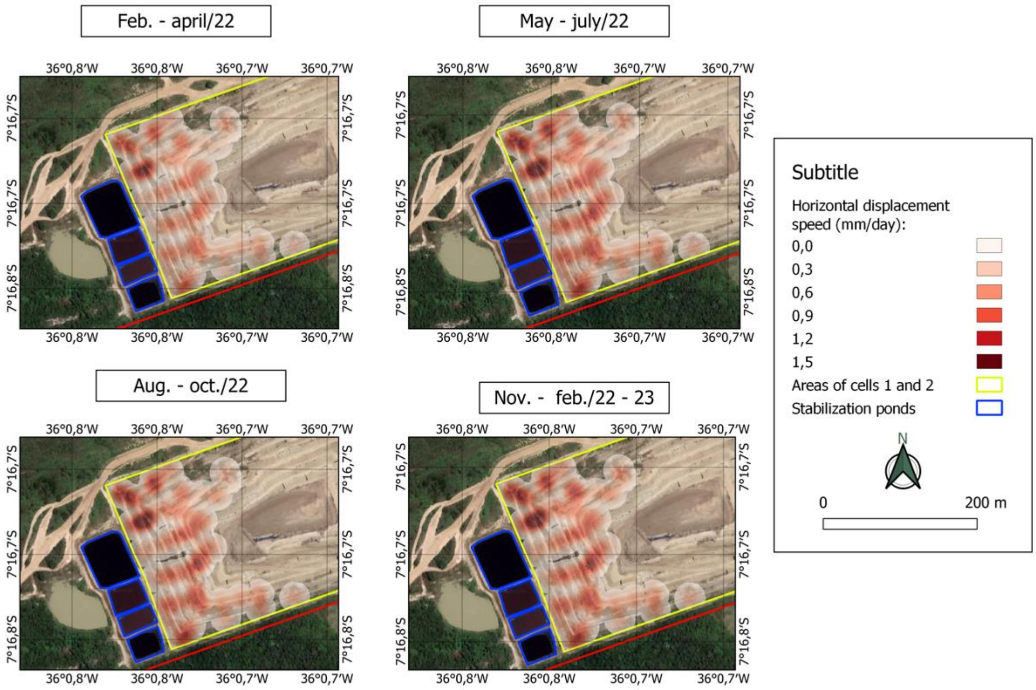

Figure 9 - Heat maps depicting the average speed of horizontal displacements over the monitored months

The actual displacements demonstrate the real values and areas experiencing the most significant displacements in the SLCG. Figure 10 shows the heat map of the actual displacements.

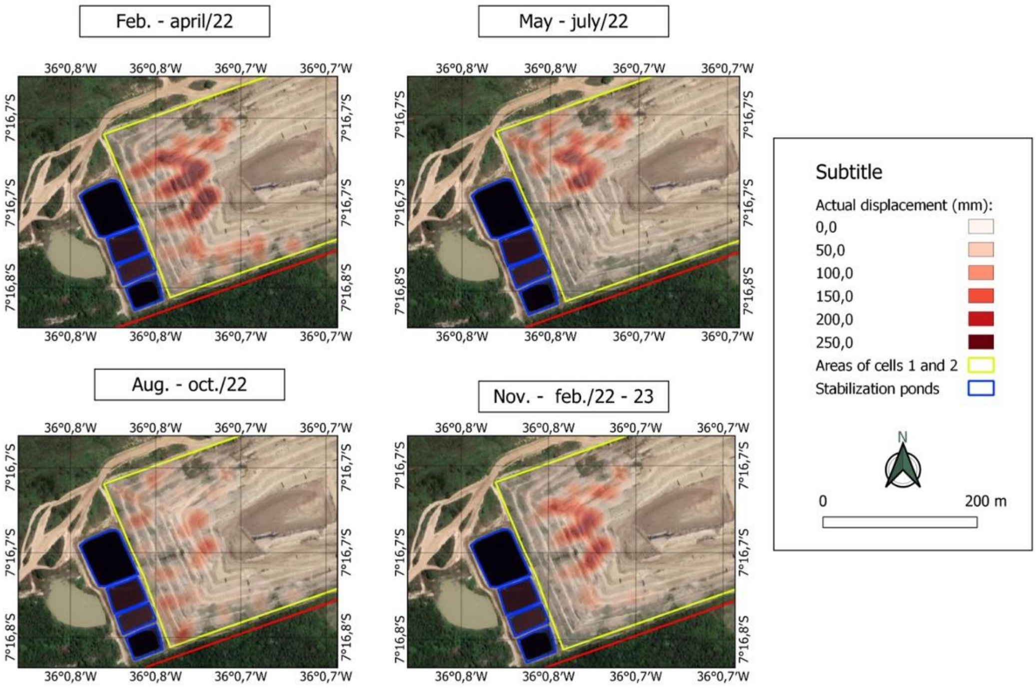

Figure 10 – Heat maps of actual displacements

IV. DISCUSSION

4.1. Monitoring of accumulated horizontal displacements

Figure 5 displays the accumulated horizontal displacements of the waste cell monitored over a one-year period from February 2022 to February 2023. Overall, the landfill does not exhibit homogeneous horizontal displacement in terms of magnitude. The difference between the first and last day of monitoring did not exceed 2000 mm. This variability is typical for landfills due to the heterogeneity of the waste and other operational factors, such as compaction and the non-uniform execution of a soil cover layer.

The data presented in Figure 6 illustrates the average speed of horizontal displacements observed between February 2022 and February 2023. Given the absence of established standards for reference values on horizontal displacements in landfills, it is advisable to consider the risk level classification recommended by various authors (Table 2).

Table 2 - Classification of Horizontal Displacement Risk Levels

Author	Acceptable	Attention	Caution	Intervention
[6]	-	$v \leq 25$ mm/day	$25 < v \leq 100$ mm/day	$v > 100$ mm/day
[7]	< 2,5 mm/day	$2{,}5 < v \leq 10$ mm/day	$10 < v \leq 40$	> 40 mm/day
[8]	-	$v \leq 10$ mm/day	$10 < v \leq 25$ mm/day	$v > 25$ mm/day

In general, it can be observed that the speeds of horizontal displacements are approximately 2 mm/day or less, which is considered acceptable according to Table 2.

The smallest actual horizontal displacements (Figure 7) were recorded in the regions of markers D01, D02, D03, D24, D25, E04, and E39. Conversely, the largest actual horizontal displacements (Figure 7) were observed in the regions of markers D19, D34, D35, E38, E39, E43, and E45.

4.2. Displacement distribution maps with geostatistics

The regions displaying the highest historically accumulated displacements are found in the intermediate and lower layers of the landfill, attributed to the stresses from the upper layers and the extended period of landfilling (Figure 8).

Upon reviewing Figure 9, it is evident that the regions with the highest average horizontal displacement speeds remain consistent, as do those with the lowest speeds. Thus, it is accurate to assert that, for the studied period and this landfill site, the areas experiencing more and less rigorous horizontal displacement are stable. Therefore, the SLCG exhibits a consistent trend in displacement speed. This phenomenon is attributed to the advanced degradation stage of waste in the monitored region, which significantly reduces displacement speeds.

Following an analysis of the actual displacements in comparison with the cumulative horizontal displacements and the incorporation of data regarding the average speed of horizontal displacements, it can be inferred that the vertical movement speed exceeds the horizontal speed. This phenomenon suggests that the dynamics of vertical and horizontal movements operate independently, reflecting a distinction in the rate of displacement and in the forces that influence the occurrence of displacements, and consequently, the stability of the slope [9], [10].

The evaluation of areas with the greatest actual displacements was conducted through the analysis of the heat map presented in Figure 10. The zone exhibiting the highest actual displacement coincides with areas of higher landfill elevation, rendering them more prone to mass movements.

When analyzing the surface markers distributed in the SLCG cell, it was found that areas with more recent waste exhibited a greater horizontal displacement, indicating increased instability of the waste cell. In contrast, regions with older waste demonstrate smaller displacements. It is noteworthy that similar behavior was documented in a prior study [11] which investigated the horizontal displacements of the Metropolitan Center Landfill in Bahia, Brazil.

Geoenvironmental monitoring in landfills, particularly through the analysis of horizontal displacements, represents a crucial practice that enhances safety and operational efficiency in managing these sites. The implementation of conventional instrumentation techniques, such as surface markers and topography, plays a pivotal role in ensuring environmental stability, safety, and mitigating potential risks associated with landfill operations. Incorporating geostatistical methods enables the modeling and interpretation of spatial patterns in horizontal displacements, revealing trends and insights that may not be discernible from raw data analysis alone.

V. CONCLUSIONS

Spatialization techniques employing heat maps have demonstrated efficacy in facilitating precise and simplified visualization and analysis of spatial patterns indicative of movements within landfills (including accumulated horizontal displacements, actual displacements, and average horizontal displacement speeds). These methodologies enable the identification of areas characterized by high concentrations and distributions of movements within landfill sites. Consequently, they provide valuable insights that can inform decision-making processes related to the operation, monitoring, and design of these projects, enhancing the ability to pinpoint critical regions with greater accuracy.

Monitoring landfills is critical due to their potential to cause substantial environmental and community-related accidents. Furthermore, landfill operations are dynamic and intricate, posing challenges in effective monitoring, as demonstrated in this study by the loss of instruments dedicated to monitoring horizontal displacements. This highlights the demand for continuous surveillance of instrumentation and timely maintenance as necessary.

The findings from this study indicate low values of accumulated horizontal displacements, actual displacements, and maximum average horizontal displacement speeds, suggesting a low operational risk. However, the parameter values utilized in this study are derived from other landfill contexts. Each landfill possesses unique characteristics and specificities, rendering generalizations impractical. Therefore, these values should serve simply as guidance for the implementation and management of such projects.

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