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Remotely piloted aircraft-based landfill monitoring

Monitoramento de um aterro sanitário com o uso de veículo aéreo não tripulado

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ABSTRACT

Solid waste causes big problems to the environment and public health when disposed of inadequately. Law 14,026/2020 updated the legal framework for sanitation and amended Federal Law 12,305/2012, which establishes the National Policy for Solid Waste, and is regulated by Federal Decree 10,936/2022, which addresses waste management. The stability of waste massifs in landfills can be compromised by vertical and horizontal displacements. To ensure landfill environments' physical and economic safety, operational measurements for monitoring such displacements are essential. Due to technological advances, new equipment and topographic survey techniques have emerged. Among them, the use of the remotely piloted aircraft (RPA) is an alternative for fast and effective monitoring, which can support strategic planning in landfills. The aim of the study was to identify displacements in waste massifs of the municipal sanitary landfill of Lages - SC using the RPA. The aerial survey was performed using the RVJET and Phantom 4 Advanced platforms with ground control points. Subsequently, orthomosaics and digital elevation models were produced. The identification of instability points in the landfill was performed. High displacement velocity was identified only at the massifs in operation. The landfill presented uniform surface settlement intensity and steady deformation velocity, not exceeding the warning level. This study calculated the displacement velocity with longer intervals between measurements than those currently used in traditional methods. Despite this, it was possible to build a database and carry out analysis by visual inspections and variations in the elevation of the massifs for preventive and corrective control of the landfill. RPA demonstrated to be adequate to monitor landfills. However, this assessment must be complemented with other instrumental analyses to understand waste massifs' behavior over time.

Keywords: aero photogrammetry; instability; landfill; solid waste; remotely piloted aircraft; settlement.

RESUMO

Os resíduos sólidos trazem grandes problemas ao meio ambiente e à saúde pública quando depositados inadequadamente. A Lei 14.026, de 15 de julho de 2020, atualizou o marco legal do saneamento e alterou a Lei Federal nº 12.305/10, a qual institui a Política Nacional dos Resíduos Sólidos (PNRS) e é regulamentada pelo Decreto Federal nº 10.936/2022. Os aterros sanitários podem sofrer com deslocamentos verticais e horizontais que podem comprometer a estabilidade dos maciços. Medições são essenciais para o monitoramento desses deslocamentos em aterros municipais por razões econômicas e de segurança. O avanço tecnológico dos últimos anos mudou as técnicas e os equipamentos utilizados nos levantamentos topográficos. A aerofotogrametria em veículos aéreos não tripulados (RPA) é uma alternativa de monitoramento rápido e eficaz para subsidiar o planejamento estratégico em aterros sanitários. Este trabalho foi realizado com o objetivo de identificar deslocamentos que evidenciem instabilidade nos maciços do Aterro Municipal de Lages (SC) usando RPA. O aerolevantamento foi feito utilizando as plataformas RVJET e Phantom 4 Advanced, com implantação de pontos de controle no solo. Com esses voos, foram produzidos ortomosaicos e modelos digitais de elevação periódicos. Com base nas séries temporais, foi realizado monitoramento para identificar pontos de instabilidade nos maciços do aterro. A alta velocidade de deslocamento ocorreu apenas nos maciços em operação. Isso era esperado em razão do constante depósito de resíduos e do baixo recalque, esperado para o período analisado. Conclui-se que o aterro sanitário continua sofrendo recalque uniforme, com deformação em velocidade estável, sem ultrapassar o nível de alerta. A análise do comportamento de recalque ao longo do tempo pode ter sido influenciada pelo excesso de vegetação existente na superfície dos maciços. Além disso, a velocidade de deslocamento foi calculada em função de leituras de cotas com tempo de espaçamento maior do que aquele correntemente utilizado nos métodos tradicionais. Apesar disso, o veículo aéreo não tripulado foi eficiente para monitorar ambientalmente o aterro sanitário. Isso possibilitou a construção de uma base de dados e a realização de análise por meio de inspeções visuais e de variação de cotas nos maciços. O RPA apresentou-se adequado para monitorar aterros sanitários. No entanto, esse monitoramento deve ser complementar a outras análises instrumentais, de maneira a contribuir para o entendimento do comportamento dos maciços ao longo dos anos.

Palavras-chave: aerofotogrametria; instabilidade; aterros sanitários; resíduos sólidos; aeronave remotamente pilotada; recalque.

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Introduction

One of the major challenges currently faced by public administrations is the inadequate disposal of solid waste. Law No. 14,026, of July 15, 2020, updated the legal framework for sanitation set out by Law No. 12,305, of August 2, 2021, which established the National Solid Waste Policy. This law is regulated by Federal Decree No. 10,936/2022, which provides for infractions and administrative sanctions for those who throw solid waste or natural waste in the open air or deposit them in inappropriate units, not licensed for the activity. The sanitary landfill is the space intended for the disposal of urban solid waste on the ground and must follow engineering standards and criteria to confine the waste to the smallest area and reduce it to the smallest possible volume, without causing damage to public health and the environment (Associação Brasileira de Normas Técnicas, 1992), being considered the most sustainable alternative for the management of urban solid waste (Lopes, 2017).

With the increase in the generation of this consequent lack of adequate place for their final disposal, public administrations have increased the physical capacity of landfills (Shimazaki, 2017). In addition, the bulks of waste from a sanitary landfill are unstable and can move over time due to the heterogeneity of the deposited materials, the densification, and the biological degradation of the moving materials (Benvenuto et al., 2019). According to Machado et al. (2010), 50% of the material deposited in sanitary landfills is of organic origin, easily degradable, being the main source of deformation (displacements) of the massifs.

Vertical displacements can be significant, between 30 to 40% in relation to the original thickness of the massif (Ling et al., 1998). The landfill is designed for an average lifespan of 20 years. In the first ten years after its closure, 90% of the expected total settlements occur (Grisolia and Napoleoni, 1996). Grisolia and Napoleoni (1995) describe the five stages of volumetric variation of sanitary landfills. Initial settlement (stage I) is related to the instantaneous mechanical compression of materials and deformable materials. The primary settlement (stage II) occurs with continuous compression and rearrangement of waste, normally after 30 days of waste deposition (Sowers, 1968). The secondary stage is associated with mechanical deformation and the initial decomposition of organic matter. On the other hand, stages IV and V occur as a result of decomposition and mechanical and biological residual deformation. Deformations in landfills tend to decrease over time (Ling et al., 1998).

To keep operations safe and avoid risks due to the structural collapse of the massifs, it is essential that detailed and accurate monitoring of the landfill surfaces be carried out (Gasperini et al., 2014; Filkin et al., 2021). Surface measurements in sanitary landfills are usually carried out with equipment that consumes a long time and requires the displacement of operational staff, such as total receiver stations of the Global Navigation Satellite System type (GNSS) (Mello, 2017). With the unmanned aerial vehicle (Remotely Piloted Aircraft — RPA — English term adopted by the *Agência Nacional de Aviação Civil* (ANAC, 2018), less time is spent taking these landfill surface measurements, with less risk to operators (Rossi et al., 2018). With the RPA, you can obtain digitally georeferenced images with high resolution that can be converted into three-dimensional topographic models (Kullmann, 2018). Thus, the images obtained with the RPA can serve as a basis for monitoring and controlling these landfills (Chaidas et al., 2018).

The settlement monitoring aims to verify that the displacement is in the acceptable range, and can be carried out by inspection (and/or instrumentation), such as topographic data, piezometry, and field inspections (Benvenuto et al., 2019). Field inspections make it possible to observe the occurrence of erosion and cracking on the slopes, the drainage condition, the adequacy of material disposal, the presence of animals, among other incidents (Andrades, 2018). With these inspections, it is possible to assess the pattern of occurrences and whether there is any instability in the massifs. According to Filkin et al. (2021), through a simple visual analysis it is possible to determine the landfill configuration, assess the gradient (and, consequently, the stability) of the slopes, check the physical components and identify signs of violation of the mass integrity (cracks, subsidence, etc.).

Reference values based on the degree of risk of vertical displacements of slopes and sanitary massifs can vary from 2 to 4 cm day^{-1} (attention state), 4 to 10 cm day^{-1} (alert state), and greater than 10 cm day^{-1} (intervention state) (Kaimoto, 2009), due to the heterogeneity of the materials.

The RPA is a piece of equipment with a simple operation that allows the mapping of large areas and/or inaccessible by land, with reduced operating time in the field (Droneng, 2018). In addition, they can fly at low altitudes and slowly, with the ability to acquire high resolution spatial and temporal data, representing important advantages over conventional platforms that have been widely used over the years (Pajares, 2015).

Tucci et al. (2019) tested the feasibility of using photogrammetry for frequent volume monitoring of stockpiles of materials. He concluded that the results detected with the RPA reached adequate precision for the practical requirements of the case study. The products generated using the RPA make it possible to measure the volume already used or to be filled in a sanitary landfill, according to Chaidas et al. (2018). Baiocchini et al. (2019) studied the use of the RPA for monitoring in sanitary landfills, and concluded that the precision and accuracy of the data obtained were very close to traditional methods, such as total stations. In this way, the RPA can be used as a low-cost tool for detecting variation in massif quotas, assisting in planning and decision-making in landfills (Incekara et al., 2019).

This research aimed to identify vertical displacement (settlement) and evaluate the relevance of using remotely piloted aircrafts to replace the traditional methods of monitoring the massifs of a sanitary landfill located in Lages (SC).

Material and Methods

The research was carried out between May 2018 and February 2019 at the municipal sanitary landfill of Lages, state of Santa Catarina, located approximately 20 km from the city center on an unpaved road accessed by BR-282 km 204, in a total area of 39.88 ha.

The landfill receives about 140 tons per day (Class II Waste A) from 12 municipalities in the region. The residues are compacted daily by the crawler tractor, and later the residues are spread in the cell and covered by layers of dirt. The gravimetric analysis carried out by the municipal sanitary landfill in Lages showed that 36% of the total waste received is organic. The landfill has currently 40% of its entirety available. Table 1 shows general information about the sanitary landfill in the city of Lages, according to data collected in *Panorama de Resíduos Sólidos do Estado de Santa Catarina* (Panorama of Solid Waste in the State of Santa Catarina) (Santa Catarina, 2017).

This research was proposed to monitor changes over time and identify places that show possible instabilities in the landfill massifs, with a view to increasing the safety of the landfill. The flowchart of the proposed methodology is shown in Figure 1.

Stage 1: Planning

In the planning stage, the number and location of the control points to be installed on the landfill, the aircraft's path, the height of the flight, the area to be covered by the flight, the number of photos, the lateral and longitudinal overlaps of the photos and the desired Ground Sample Distance (GSD) were determined. Literally translated, GSD stands for "Distância de amostra do solo", in Portuguese. The lower the GSD, the greater the level of detail and the better the definition of objects (Droneng, 2018).

Stage 2: data collection

The topographic data collection was performed based on 14 control points distributed in the study area (Figure 2). These points were identified using quicklime so that they became visible and identifiable in aerial images. Zekkos et al. (2018) highlighted the importance of ground control points for making reliable aerophotogrammetric products.

The terrestrial coordinates of these points were raised by signal receivers from the *Global Navigation Satellite System* (GNSS) of two frequencies (L1 and L2), model Sokkia GRX1, through the *Real Time Kinematic* (RTK) method. A reference vertex, named BASE, was implanted, and its coordinate was processed by using the Precise Point Positioning (PPP) method. The GNSS data was used as a control and check point in the processing of RPA data.

Three flights were carried out for survey and data collection. The first and second flights occurred, respectively, on May 5 and September 9, 2018, and the third, on February 13, 2019. On the first flight, the images were captured with a fixed-wing RPA model called RVJET, own manufacture, with a polyethylene (styrofoam) structure and an embedded 24-megapixel RGB digital camera. The RPA flight autonomy is 90 minutes and the area cover is up to 1,000 hectares per flight.

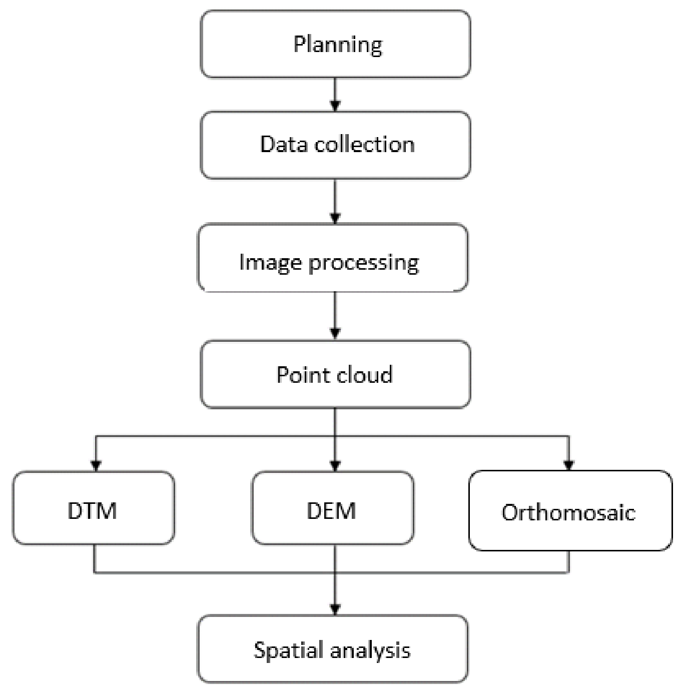

Figure 1 – Landfill monitoring methodology flowchart with the RPA.
Source: Cunha (2020).

Table 1 – General information about the Lages sanitary landfill.

Owner	Municipality of Lages
Operator	Serrana Engenharia Ltda
Integrated region of RS	Region of Lages
Service life capacity	560,939.81 tons
Recyclables sorting facility	No
Installation of composting unit	No
Municipalities that deposit in the landfill	Bom Retiro, Correia Pinto, Lages, Urupema, Urubici, São Joaquim, Capão Alto, Painel, Rio Rufino, Bom Jardim da Serra, São José do Cerrito and Ituporanga

Source: adapted from *Panorama de Resíduos Sólidos de Santa Catarina* (Santa Catarina, 2017).

In the other analyses, a Phantom 4 Advanced device was used, with an autonomy of 30 minutes, containing a camera with a CMOS sensor, with 20 megapixels of resolution. Both pieces of equipment contain a GNSS system for coordinates management. The characteristics of each flight are shown in Table 2.

Stage 3: image processing

Image processing was performed with software specialized in digital image processing and photogrammetry. The scale accuracy of the mapping was based on the values validated by Droneng (2018), where the maximum expected error in planimetry (X and Y) is 1 to 1.5 times, and in altimetry (Z) it is 2 to 3 times, both relating to the GSD. The products generated in the surveys had an average GSD of 3.4 cm pixel-1. The generated data contain a high density of 3D points that allow the punctual analysis of the terrain relief. The DSM (Digital Surface Model) and orthomosaic were created from the original point cloud, while the DTM (Digital Terrain Model) was performed by classifying the manual point cloud, removing objects that could interfere with the analyses.

Stage 4: data monitoring

The data were analyzed and compared to each other to detect areas affected by instability processes, which were evaluated according to the criteria of visual interpretation in the field, analysis, and registration of the landfill components, determination of slope, places of occurrence of settlement, and associated speed. Nineteen classes of land use and occupation were established through photo interpretation performed in SIG, and an overview map of the landfill was created on the last flight. The classes were named landfill area, available area, weighing scale, water tank, passage box, water course, rainwater drainage, vertical drain, treatment station, roads, infrastructure, massif in operation, finished massif, monitoring station well, light pole, gas station, exposed waste, piping, and vegetation.

The analysis of an orthomosaic makes it possible to evaluate the incidences that can aggravate the degree of displacement of the massif, cause or potentiate some type of risk to health and the environment.

Table 2 – Characteristics of the three flights carried out for data collection at the Lages sanitary landfill (SC).

Characteristics	Flight 1	Flight 2	Flight 3
Flight date	05/05/2018	09/05/2018	02/13/2019
Camera Model	ILC-6000	FC-6310	FC-6310
Camera resolution	6,000 × 4,000	4,864 × 3,648	4,864 × 3,648
Camera focal length	16 mm	8.8 mm	8.8 mm
Number of images	468	1,027	1.106
Flight height	158 m	122 m	125 m
Longitudinal overlap	80%	80%	80%
Side overlap	70%	70%	70%
Ground Sample Distance (GSD)	3.48 cm pixel^{-1}	3.42 cm pixel^{-1}	3.46 cm pixel^{-1}

ILC: interchangeable lens camera; FC: filter cartridge.
Source: Cunha (2020).

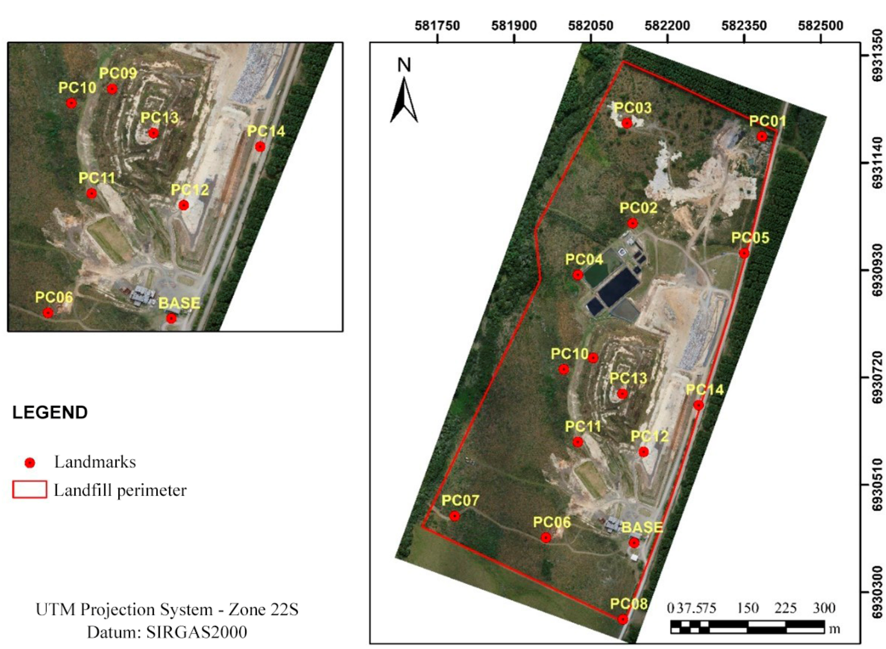

Figure 2 – Distribution of reference marks on the landfill.
Source: Cunha (2020).

Thus, these evidences were observed in the orthomosaic and validated in the field. The slope gradient of the waste piles can influence the stability of the massifs. The evaluation of the terrain declivity was carried out by interpolation in a SIG environment, using the "slope" tool, based on a DTM of one-meter resolution. Four slope classes were adopted, that is, 0-15º, 15-25º, 25-45º and greater than 45°. The limit slope gradient established by the municipal landfill of Lages is 45°, a value that refers to the declivity of the slopes of the massifs.

To compare the vertical displacements (settlements) in a distributed and egalitarian way for the entire landfill, a grid of 10x10m points was built throughout the massif area. The values of the quotas were extracted from the DTM with a spatial GSD resolution of 1m collected between one analysis and another. The difference between the two aerial surveys is given by the Equation 1:

$$\Delta h = h_n - h_{n-1} \quad (1)$$

In which:
Δh: quota difference between two aerial surveys (m);
h: quota value (m);
n: last aerial survey carried out (number);
n-1: aerial survey prior to the last survey carried out (number).

In addition, to evaluate changes in terrain quotas between two surveys, DTMs were used with quotas rounded to whole numbers. Thus, only quota differences greater than 1 m were classified.

Stage 5: spatial analysis of parameters

To quantify the degree of criticality in which the displacements occurred, that is, to classify the potential risk, an analysis of the daily speed was carried out according to the general criteria of action for sanitary landfills proposed by Kaimoto (2009). The difference values between two quotas (Δh) were divided by the number of days between one aerial survey and another. The value ± 2 cm day^{-1} was considered the variation limit, as they were classified as being at high risk and requiring, at least, attention, according to the ABNT (the Brazilian Association of Technical Standards) classification (Associação Brasileira de Normas Técnicas, 1992).

Results Presentation

Stage 2 and 3: data collection and image processing

The approximation of the objects made it possible to identify the components of the landfill in 18 classes for monitoring and accompanying the development of works. In the 1:500 scale it is possible to easily identify the exposed residues, the compactor vehicle, roads, PEAD geomembranes, and other details of the terrain surface (Figure 3). In the 1:50 scale, it is possible to clearly visualize one of the gas pipelines that make up the massif.

The planialtimetric map of the survey carried out on 02/13/2019 shows the distribution of the 18 identified classes, highlighting the area of the massifs already completed and the massif in operation (Figure 4). 58 vertical gas drains, 4 monitoring stations, 892 m^2 of a drainage system, 9,925 m^2 of an effluent treatment station (ETS), 3,470 m of road, and 997 m^2 of infrastructure, among others, are distributed throughout the 83,609 m^2 of waste mass area.

Through the images obtained by the RPA, it was possible to detect and monitor the main incidents that occurred in the studied period and the potential risks associated with the activity (Figure 5).

The erosion points highlighted on the map are located outside the massif and refer to the land's rainwater drainage (Figure 5). The lack of vegetation was observed only in the recently completed massif, and there is no evidence of erosion at the site. The exposed waste area refers to recent material deposits, which will be covered by a layer of earth after the operation. The apparent geomembranes are located in the cell in operation and do not pose any problem to the landfill. This was verified in the on-site inspection.

The survey on 05/05/2018 showed the existence of four points with a slope above 45° (red color) in the already deactivated massif and in the disposal area (Figure 6). Through visual inspection, it was found that the red dots under the old massif are due to excess vegetation.

In the analysis of 02/13/2019, in addition to the points found outside the massif area, there was an occurrence of slope above the allowed limit at the site of expansion of the new cell, and at a point in the waste layer in the cell in operation, which would probably be corrected during the completion of the work (Figure 7). Through the evaluation of the volumetric reduction, one can analyze the behavior of the waste cells. With the difference in the values of the altimetric quotas (axis Z) obtained between two surveys, it was possible to analyze the vertical movement of the land surface. The range of variation of the grid of quotas on the ground was stratified into 10 classes in the range of - 1 m to + 1 m.

Stage 4 e 5: spatial analysis and monitoring

Is possible to see that the points represented in shades of red (reduction in the quota value between the two surveys) are predominantly located in areas of already completed massifs (Figure 8). The points with dark blue color represent an increase in the value of the quotas greater than 1 m (> 1), and are located in the area of the disposal of materials in the massif still in operation.

The changes in the quotas of the massifs, which ranged from -3 to 7 meters high, can be observed in Figure 9. In 66% of the sampled area, no difference in quota was diagnosed between the first and second surveys, assuming the minimum interval equal to 1 m.

The analysis of the difference in quotas between the surveys on 09/05/2018 and 02/13/2019 (Figure 10) shows numerous points with a bluish color on the deactivated massif. The remaining points above 1 m are located in the waste landfill area in the cell in operation.

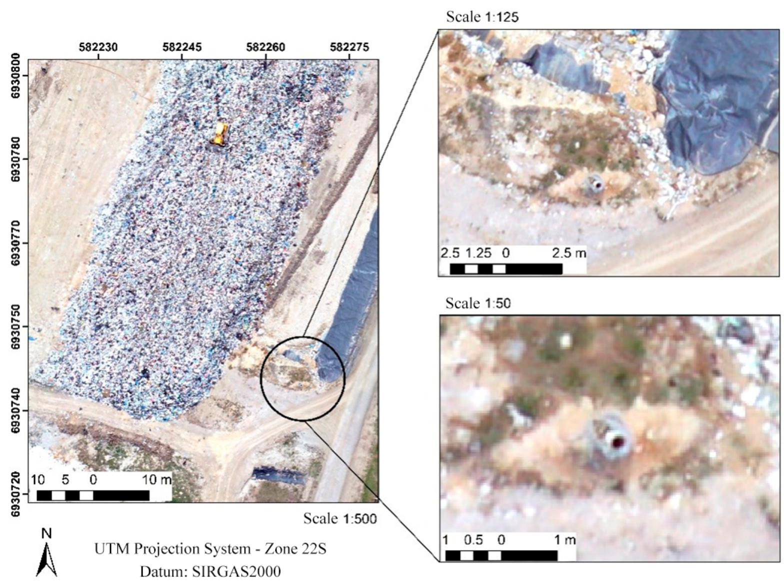

Figure 3 – Analysis of components at different scales of proximity.
Source: Cunha (2020).

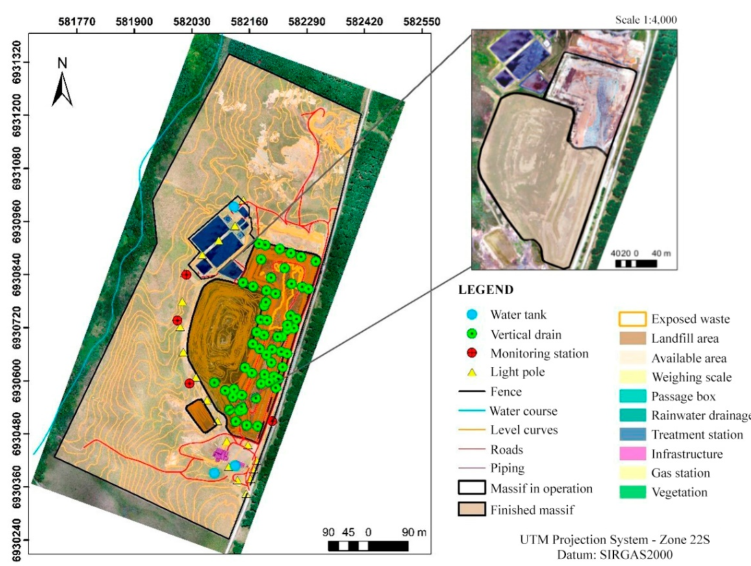

Figure 4 – Planialtimetric map of the survey on 02/13/2019.
Source: Cunha (2020).

It can be seen that 423 points (50.71%) suffered a positive vertical displacement, in which the quota value increased from the first to the second survey (Figure 10). Of these points, 300 (35.9%) are within an interval of 0 to 1 m, and are mainly related to the existence of vegetation on the massif. Of the total points, 14.7% had a quota variation greater than 1 m, and are related to the process of grounding solid waste destined for the landfill, the construction of new structures and the excessive growth of vegetation in the already completed cell of the sanitary landfill. The negative vertical displacement was observed in 411 points (49.29%) considering the surveys of 09/05/2018 and 02/13/2018, and occurred due to the recess of the massif, the existence of vegetation on the massifs and operational processes in the landfill. Of these points, 405 (48.56% of the total) fall within the range from 0 to -1 m.

Figure 11 demonstrates in general the places where the quota variation occurred, with an amplitude from -5 to 7 meters high.

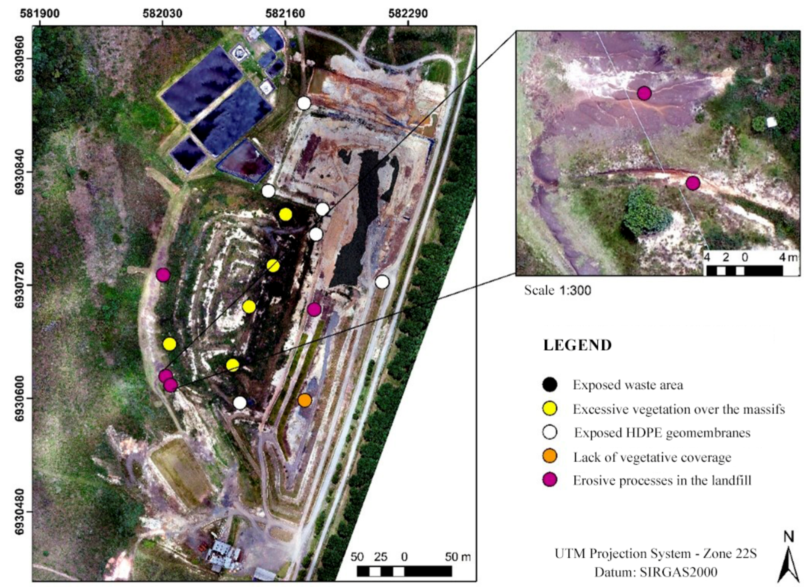

Figure 5 – Incidences observed in the survey on 02/13/2019.
Source: Cunha (2020).

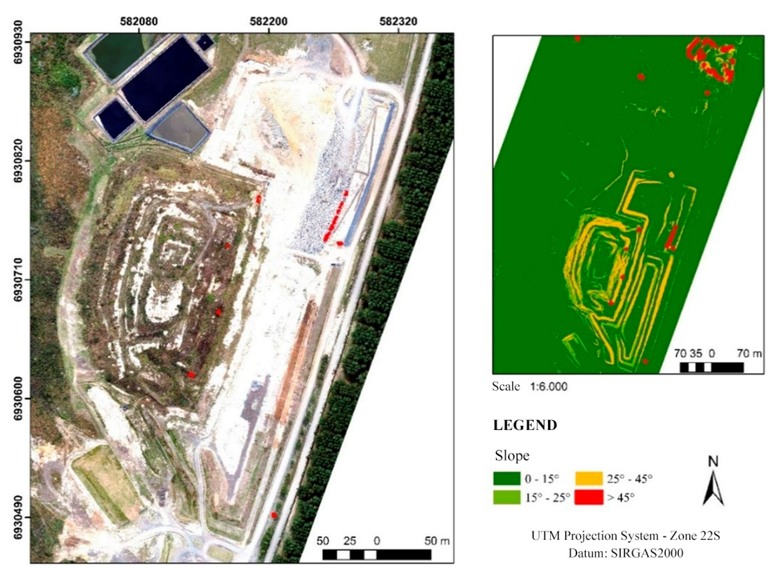

Figure 6 – Terrain declivity in the survey on 05/05/2018.
Source: Cunha (2020).

However, in 84.7% of the sampled area, no difference in quota was diagnosed, assuming the minimum interval equal to 1 m.

Following the values adopted by Kaimoto (2009) and by the Brazilian standard NBR-11682, Stability of Slopes (Associação Brasileira de Normas Técnicas, 1992), the limits for speeds with values of ± 2 cm/day were determined in this study. The settlement rate between the two surveys (between 05/05/2018 and 09/05/2018) was calculated for 123 days, and the highest value found was 4.92 cm/day, in places of deposition of new residues (Figure 12). In general, it can be observed that the values are below the established limit (± 2 cm/day).

Locations with speeds between 2 cm/day and 4 cm/day (yellow) need attention and values above 4 cm/day (red) represent alert, according to the criterion established by Kaimoto (2009). it can be noted that these points continue to refer to the service fronts, not showing large settlements in the massifs (Figure 13). The sites that presented displacements with speeds greater than ± 2 cm/day are located in the massif in operation. In Figure 13, the locations with a displacement speed between the surveys on 09/05/2018 and 02/13/2019 (161 days between one survey and another) are represented. The maximum displacement speed value reached was 4.17 cm/day.

Discussion of Results

The monitoring of the construction design and geometry of the landfill is a way to ensure safety and maximize the volume of waste that the massif can receive. Also, monitoring makes it possible to follow the evolution of slopes and identify possible problems. The analysis of the mosaic of orthophotos enabled the identification and quantification of the landfill components with a high degree of visibility and, with this, to carry out direct measurements of distance and area, according to Santos et al. (2019).

With the database, it was possible to create a history of monitoring the progress of the work, qualitatively and quantitatively, such as the area occupied by the massif and the number of instruments and components installed in the project.

The analysis of incidences makes it possible to identify the places where potential environmental problems may occur. The analyses were easy to identify in the generated orthomosaics and were able to assist in immediate decision-making. Attention should be paid to the incidents that have been observed. In these cases, in places with excessive vegetation, there may be a decrease in the veracity of the data collected. In addition, erosion sites, also identifiable, may show displacements in the massifs. Furthermore, places with no or little vegetation are more susceptible to erosion than places where the soil contains vegetation cover (Costa and Rodrigues, 2015). It was found that there were no erosion points in the massif area, related to rainwater drainage.

Locations with greater declivity are more prone to erosion than flat areas, as steeper slopes favor the concentration and increase the velocity of surface runoff (Costa and Rodrigues, 2015; Oliveira et al., 2018). In general, the slopes observed presented gradients within the pre-established pattern by the managers of the municipal landfill of Lages, with an inclination of up to 45º. It was found that the slopes spotted above 45º are related to the excess of vegetation at the site. This may cause a reading error in periodic surveys, and interfere with the results of the surface analysis. In the massif in operation, three points were found above the limit referring to exposed residues that were still being handled. The other points were outside the massif area, and were related to the terrain relief itself or the removal of material to cover the landfill (disposal area). According to Brito et al. (2016), sites with slopes above the established figure (45º) are more predisposed to erosion and landslides, as they have high surface potential energy.

In the analysis of quota variation, the results obtained by the three analyses indicated that there were no significant settlements in the massifs. The alterations that occurred in the analyzed time interval were mainly related to the coverage and movement of solid waste, and the excessive growth of vegetation in the old massif. From the first to the second survey, land cleaning was carried out to avoid processing errors that may have caused this reduction in the value of the quotas on the massif. It was possible to observe that the DTM generated through the manual classification of the point cloud was unable to exclude vegetation in some points. In this way, for the monitoring of the massifs using the RPA, it is recommended to clean the land for better visualization and validation of the collected data. This is necessary because the vegetation interferes in the delimitation of the values of the quotas.

Figure 7 – Terrain declivity in the survey on 02/13/2019.
Source: Cunha (2020).

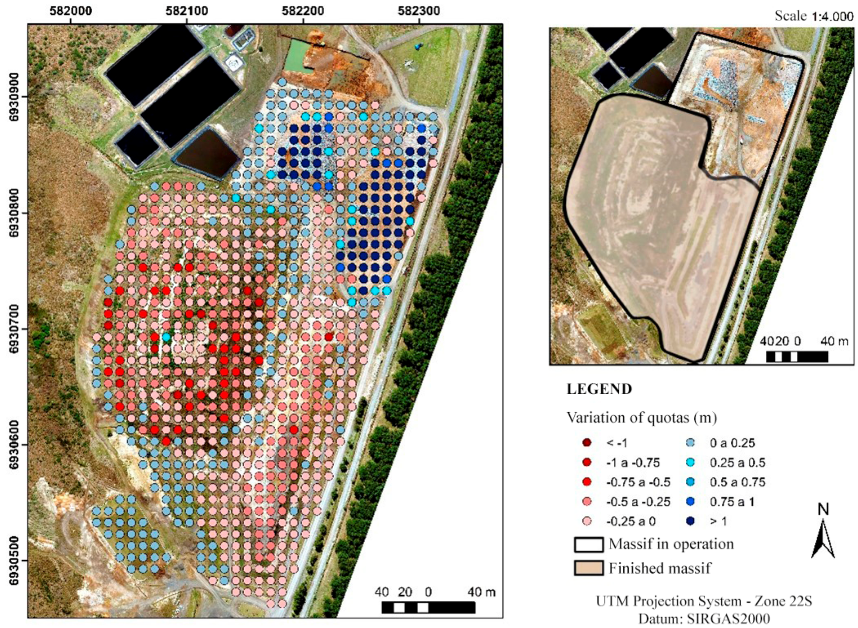

Figure 8 – Monitoring of settlement between the surveys on 05/05/2018 and 09/05/2018.
Source: Cunha (2020).

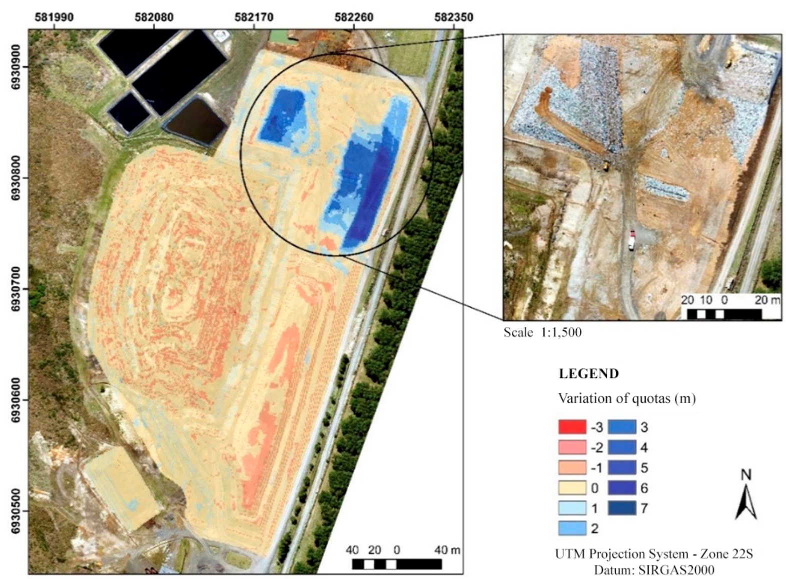

Figure 9 – Changes in the quotas of the massifs between 05/05/2018 and 09/05/2018.
Source: Cunha (2020).

The results of the settlement speed of this study show that in both analyses the values above the limit are justified by the daily deposition of residues in the area and by the excavation for implantation of the new cell.

Although it is preliminary work, it can be seen that there were no significant displacements in the completed massif that could cause risks to the workers at the site. However, conclusions regarding instabilities are not possible exclusively through the analysis of topographic data. For this reason, it is worth noting that the displacement data generated by the RPA are complementary to the data generated by other analysis instruments, such as the piezometer, which show the real behavior of the waste masses.

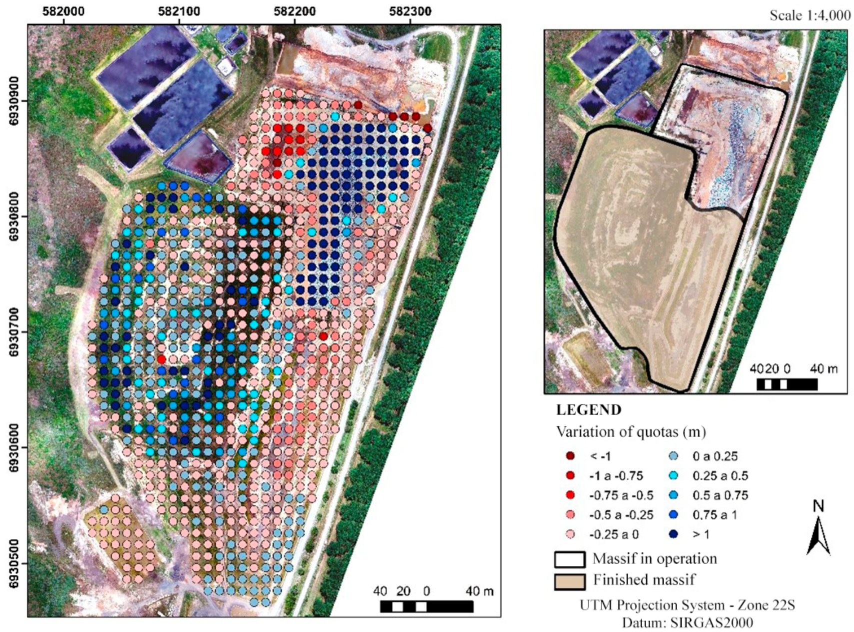

Figure 10 – Monitoring of settlement between the surveys on 09/05/2018 and 02/13/2018.
Source: Cunha (2020).

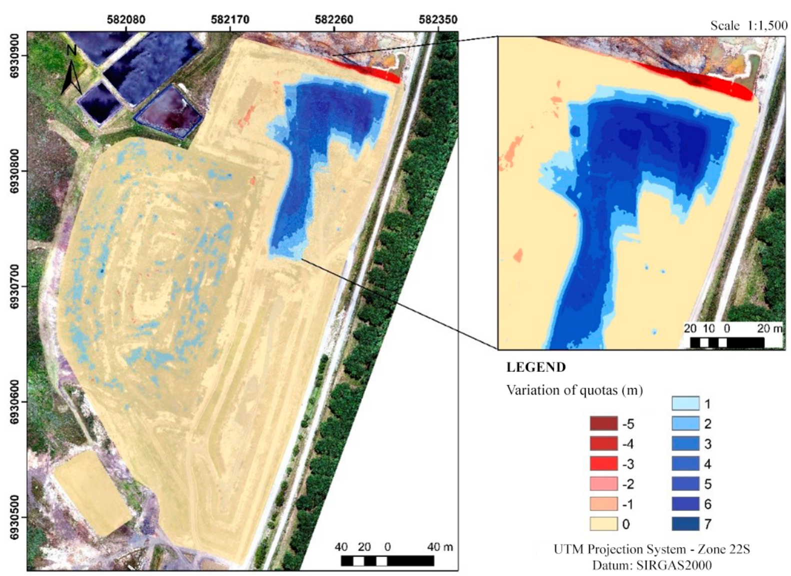

Figure 11 – Changes in the quotas of the massifs between the second and third surveys.
Source: Cunha (2020).

Furthermore, according to Mello et al. (2022), monitoring routines, when performed periodically, provide a robust database with a high level of operational performance, providing effective information in monitoring for the prevention and correction of landfill projects. The quota reading must be performed at average intervals of 30 days, as recommended for traditional analysis.

Conclusions

The incidence analysis made it possible to identify places with excess vegetation and the absence of vegetation and erosion points on the landfill site. Excess vegetation can interfere with the quality of data collected with the RPA, while the absence thereof can weaken the soil in terms of its resistance to erosion. The results showed that the Lages

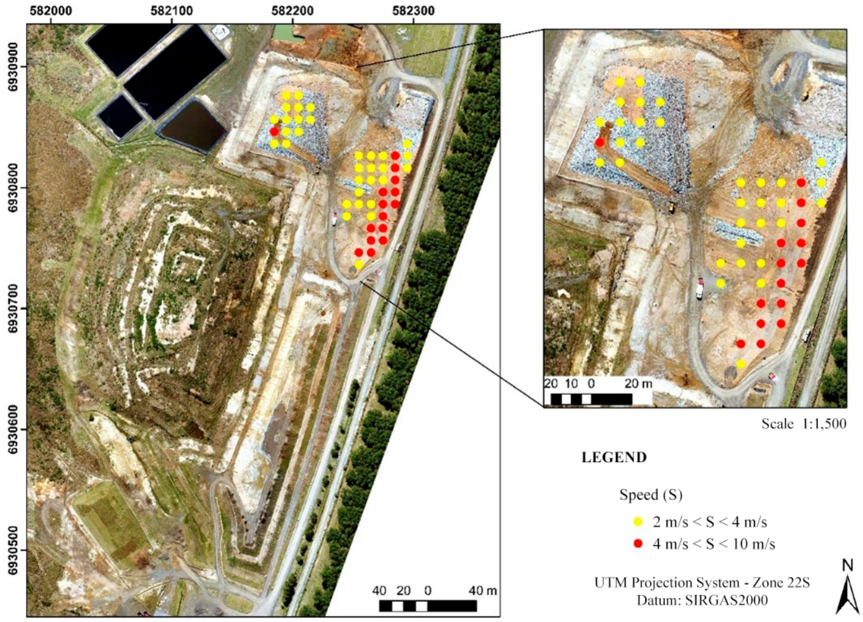

Figure 12 – Distribution of settlement speeds between 05/05/2018 and 09/05/2018.
Source: Cunha (2020).

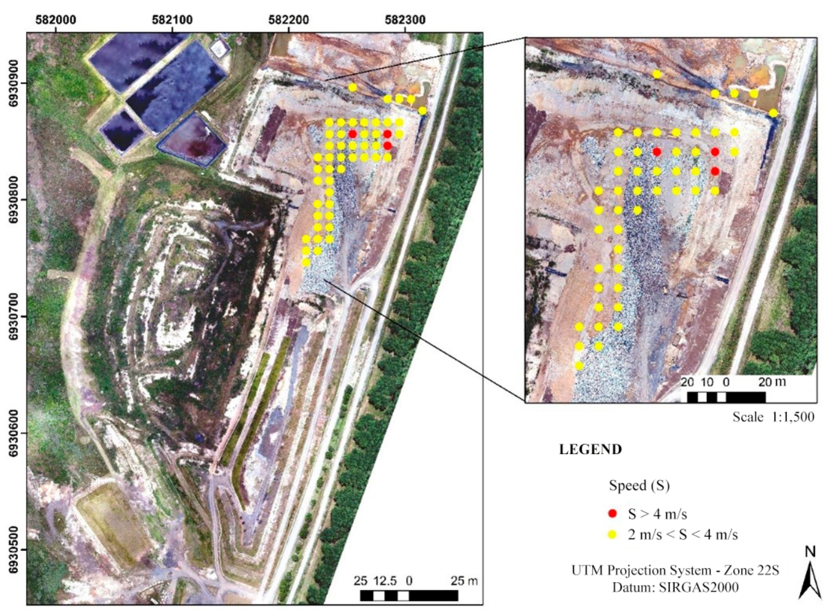

Figure 13 – Distribution of the settlement speeds between 09/05/2018 and 02/13/2019.
Source: Cunha (2020).

landfill presented a settlement speed within the limits established in the study. There were high values of settlement only in the places of temporary deposition of waste, not exceeding the safety levels suggested by the legislation. As a result, it is not necessary to intervene in the landfill activities, even though the Lages landfill needs a history of data on displacements.

Although the RPA has a high potential for application, it was not possible to monitor the internal conditions of the massif, such as pore pressure. Pore pressure is quantified by a piezometer and is essential for the analysis of landfill stability. The RPA also did not detect the existence of horizontal displacements. Thus, this technique must be used in conjunction with other geotechnical analysis methodologies to achieve the purpose of making the work safer and more predictable. In places with dense vegetation, it is recommended that the land be cleaned to obtain data closer to the real thing.

The RPA serves as a support for the monitoring of sanitary landfills, and can be used as a complement to analyzes by managers in order to contribute to planning and decision making. The study and application of these aircrafts in the monitoring of sanitary landfills should develop in the coming years, improving the techniques for analyzing the behavior of massifs. It is recommended that the minimum quota difference be less than 1m so that the analysis is more sensitive. However, in this study, the quotas used are justified because it is an exploratory study of a new monitoring technique. In addition, it is recommended that readings should be performed at smaller intervals, according to the practice already used in traditional methods (topographic readings with average intervals of 30 days). This fact is of paramount importance because it is a sanitary landfill with peculiar behavior in terms of speed, direction, and direction of displacement. In the present work, this was not possible due to the limitation of the equipment used in the analyses, such as RPA.

The analysis of the historical data of the RPA, if validated, can allow the prediction of the occurrence of disasters in landfills. Continuing to monitor the Lages landfill will enable definitive conclusions on the long-term behavior of the massifs.

Contribution of authors:

CUNHA, M. B.: Search; Investigation; Writing — First Draft; Image processing; Spatial analysis; Validation. BERTOL, I.: Orientation; Planning; Writing — Review and Edition; Validation; Resources. BUCK, A. L. B.: Co-orientation; Methodology; Equipment; Data Curation.

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