USE OF UAV AS A TOOL FOR DAM AUSCULTATION

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Abstract. *This study explores the application of Unmanned Aerial Vehicles (UAVs) integrated with digital aerophotogrammetry as a tool for the auscultation of earth dams, focusing on the Chasqueiro Dam, located in southern Rio Grande do Sul. Using a rotary-wing UAV equipped with a high-resolution camera, cartographic products such as orthomosaics and Digital Surface Models (DSM) were generated, enabling the identification of critical elements such as piezometers and gullies on the downstream slope that were not detected during visual inspections. The data analysis allowed for the evaluation of the variability of slope inclinations and the conditions of the dam crest, confirming that its width and elevation are adequate for structural stability. The use of techniques such as georeferencing through materialized control points and processing with specialized software demonstrated high precision and efficiency in monitoring. This method proved to be a safe, fast, and cost-effective alternative compared to conventional approaches. It is concluded that employing advanced technologies in dams can mitigate the risks of structural failures and significantly improve monitoring and maintenance practices. Continued research is recommended to integrate additional sensors to expand and refine structural and environmental analyses.*

Keywords. *Chasqueiro Dam, Digital aerophotogrammetry, Clinographic map, Orthomosaic*

1. Introduction

Dams play a crucial role in water resource management, serving as artificial structures designed to retain water or other liquids by being constructed transversely across rivers or channels. Despite their importance, structural failures still occur frequently, often resulting in severe environmental, social, and economic consequences. In Brazil, two dam failure accidents have gained prominence over the past decade: the collapse of the tailings dam at Samarco S/A in Mariana and the failure of the tailings dam at Mina Córrego do Feijão, owned by Vale S/A, in Brumadinho, both located in the state of Minas Gerais. These events highlight the importance of constant monitoring and rigorous maintenance of such structures, which are essential to prevent accidents and ensure the safety of both the population and the environment.

In this context, auscultation emerges as an indispensable tool. It consists of a set of methods, metrics, and observations applied to the behavior of engineering structures, aiming to assess their safety conditions, validate hypotheses and calculation methods employed in the design, and, when necessary, implement corrective measures [9].

Since 2022, members of the Geotechnical Group at the Federal University of Rio Grande (FURG), in partnership with other researchers, have been conducting studies exploring the use of geotechnical methods and geotechnologies for the auscultation of earth dams [3, 5, 6]. The research focuses on the Chasqueiro Dam, located in the municipality of Arroio Grande, in the far south of Rio Grande do Sul, under the administration of the Lagoa Mirim Development Agency (ALM).

This study aims to continue and deepen this line of research by integrating digital aerophotogrammetry as a tool for auscultation. By employing Unmanned Aerial Vehicles (UAVs), the technique enables the acquisition of high-resolution images and precise data that allow for the generation of detailed three-dimensional models, the mapping of deformations, and the identification of structural anomalies. The use of this approach represents a significant advancement, expanding analytical possibilities and contributing to the safe and efficient management of earth dams.

2. Material and Methods

For the execution of the photogrammetric aerial survey, a rotary-wing UAV, model *Mavic 2 Pro,* manufactures by *Dji*®, was used. This equipment was provided for this research by ALM and is illustrated in Figure 1. The UAV is a small-sized, remotely controlled device equipped with an integrated camera capable of capturing high-resolution spatial images. The UAV characteristics are described in Table 1.

Figure 1. UAV equipment

Table 1. UAV characteristics

Characteristics	Description
Weight in flight condition	907 grams
Flight autonomy	31 minutes
Maximum radio transmitter range	10 km
Battery	LIPo4s de 3850 mAH
Camera	Sensor CMOS with 20 MPi
Maximum dimensions of each photo	5472 x 3648 pi
Shutter speed	8-1/8.000 s
Camera field of view	77°
Spatial positioning	GPS + GLONASS

To ensure greater precision in the survey and control the parameters involved in image acquisition, a detailed flight plan was developed, essential for maintaining the overlap rate between images, the ideal altitude, and the appropriate speed during the flight. This flight plan, illustrated in Figure 2, was created using the free *DroneDeploy®* software, a tool widely recognized for its efficiency in aerial mapping missions. The specific characteristics of the flight plan, including altitude, lateral and frontal overlap, among other parameters, are described in Table 2.

After completing the aerial survey, the captured images were transferred using the data stored on the equipment's memory card. These images were saved in JPEG format (Joint Photographic Experts Group), a widely used standard known for its efficiency and quality. Additionally, each image contained GEOTAG metadata, also known as Geomarks, which provide the spatial position of the Principal Point (PP) within a specific geodetic reference system, essential for georeferencing and accurate data processing.

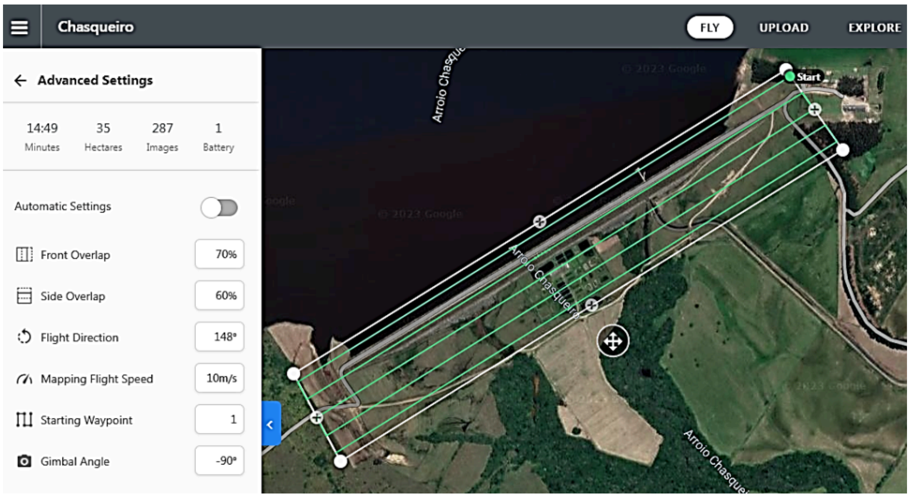


Figure 2. Flight plan

Table 2. Flight plan characteristics

Characteristics	Description
Flight altitude	100 meters
Lateral overlap of strips	60%
Frontal overlap of strips	70%
Flight azimute	148°
Camera	Sensor CMOS with 20 MPi
Maximum speed	10 m/s
Camera angle	Nadir
Spatial resolution	2,95 cm/pixel
Flight time	14'49"
Number of images	247

The processing of the images was performed using *MetaShape Professional®* software, renowned for its robustness in digital photogrammetry. The method followed is based on the approach proposed in the literature [4], which employs advanced algorithms for spatial reconstruction. This software enables the creation of high-resolution orthomosaics using techniques that identify similarities between stereoscopic images to produce seamless and detailed mosaics [2]. The result is a set of accurate, high-quality cartographic products, suitable for detailed geospatial analyses and structural assessments.

The first step in processing involved a preliminary visual evaluation of the quality of the images obtained during the survey. This procedure included a detailed analysis of the intervalometer records to identify potential inconsistencies, such as motion blur in the images caused by movement during capture or duplicate images resulting from unintentional camera triggering. Ensuring image quality at this stage is essential, as any flaws can compromise the accuracy and efficiency of subsequent processing steps.

Next, the image alignment stage was carried out, as illustrated in Figure 3. This process followed the methodology proposed in the literature [8] and implemented in the SfM (*Structure from Motion*) algorithm within the *MetaShape*® software. The algorithm uses control points identified in at least two images with a lateral or frontal overlap of at least 60% to calculate the intrinsic and extrinsic parameters of the camera, such as the PP and the image rotation orientation. Alignment is a critical step in creating a consistent foundation for generating high-quality three-dimensional models and orthomosaics.

Additionally, a detailed verification of the boundaries of the area of interest was performed. In this step, it was confirmed whether the entire region planned for the survey had been adequately imaged during the flight. This verification is crucial to ensure that there are no gaps in the collected data, guaranteeing that the complete coverage of the study area aligns with the project objectives. Thus, combining a careful analysis of image quality with precise alignment establishes a solid foundation for the subsequent stages of photogrammetric processing.

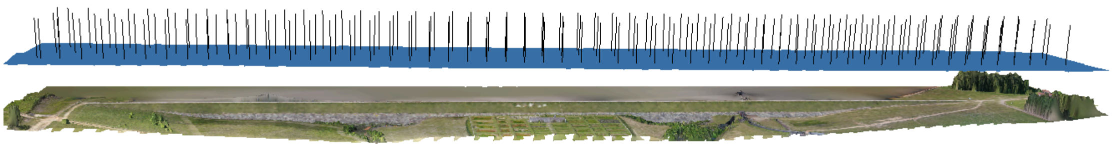


Figure 3. Image processing with strip alignment

Although the images already contained geodetic coordinates of the PP, these were corrected through georeferencing using eight control points materialized in the field along the crest of the dam. This process was performed to enhance the horizontal and vertical accuracy of the results. For this purpose, a pair of GNSS receivers capable of receiving real-time corrections (Real-Time Kinematic – RTK) was utilized. The receivers, provided for this research by ALM, were *Emlid*® Reach RS2 models, featuring L1 and L2 bands and multi-constellation compatibility (GPS, GLONASS, BeiDou, and Galileo).

Initially, the base receiver was installed on a Forced Centering Mark (FCM), which was implemented by ALM and integrated into the Brazilian Geodetic System (SGB). The three-dimensional position was transmitted via the internal UHF (Ultra High Frequency) LORA (Long Range) radio. Using the mobile receiver, known as the Rover, the control points used in photogrammetric processing were recorded.

In this process, the static method was employed, resolving ambiguities and obtaining a fixed solution with horizontal precision of 7 mm + 1 ppm and vertical precision of 14 mm + 1 ppm. After the field survey, the files containing the control points were exported in CSV (Comma Separated Values) format for subsequent import into the photogrammetric processing workflow.

Table 3 presents the location of the control points, using coordinates projected in the UTM system, defined at the central meridian 51ºW, corresponding to zone 22, with orthometric altitudes. Figure 4 shows a map of the locations of these control points. The insertion of control points was carried out by identifying the targets in the images and manually translating the point onto the marked position.

The subsequent steps involved generating the homologous point cloud and constructing the Digital Surface Model (DSM). Additionally, an orthomosaic was created to provide a comprehensive understanding of the area. For the generation of these products, the multiview technology of the *Metashape*® software was utilized. This technology allowed the processing of arbitrary images with varying overlap, as long as homologous points existed in distinct images. Finally, both the orthomosaic and the DSM were exported in Tagged Image File Format (TIFF) with a spatial resolution of 3 cm.

Table 3. Control points location

Control point	X Coord.	Y Coord.	Z Coord.
1	310653.128	6439823.847	45.752
2	310619.178	6439788.061	43.494
3	309626.599	6439178.616	45.760
4	309644.99	6439176.882	43.605
5	309814.916	6439297.537	45.972
6	310125.099	6439486.448	46.993
7	310354.918	6439635.546	45.991

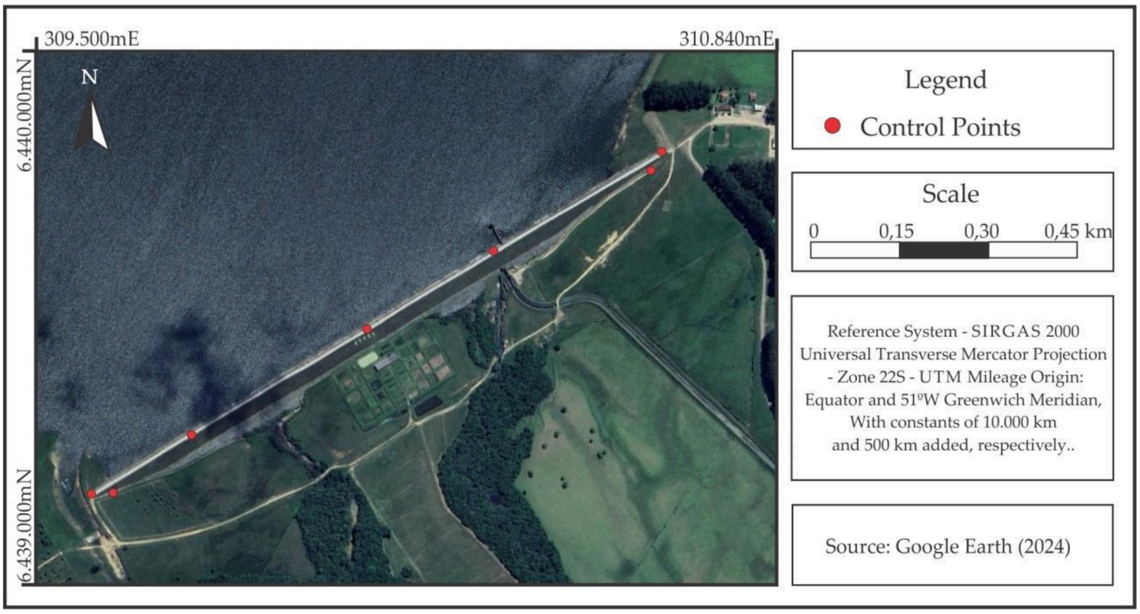


Figure 4. Map of control points location

3. Results

Using the orthomosaic, six piezometers with steel caps measuring 40 x 40 cm were mapped. Additionally, three gullies were identified on the downstream slope, which had not been detected through visual inspection. The lengths of these gullies range from 20.09 to 25.71 meters, as measured directly from the orthomosaic, which is presented in

Figure 5. Table 4 provides the UTM coordinates of the piezometer locations, while Table 5 details the UTM coordinates and lengths of the three gullies identified on the downstream slope.

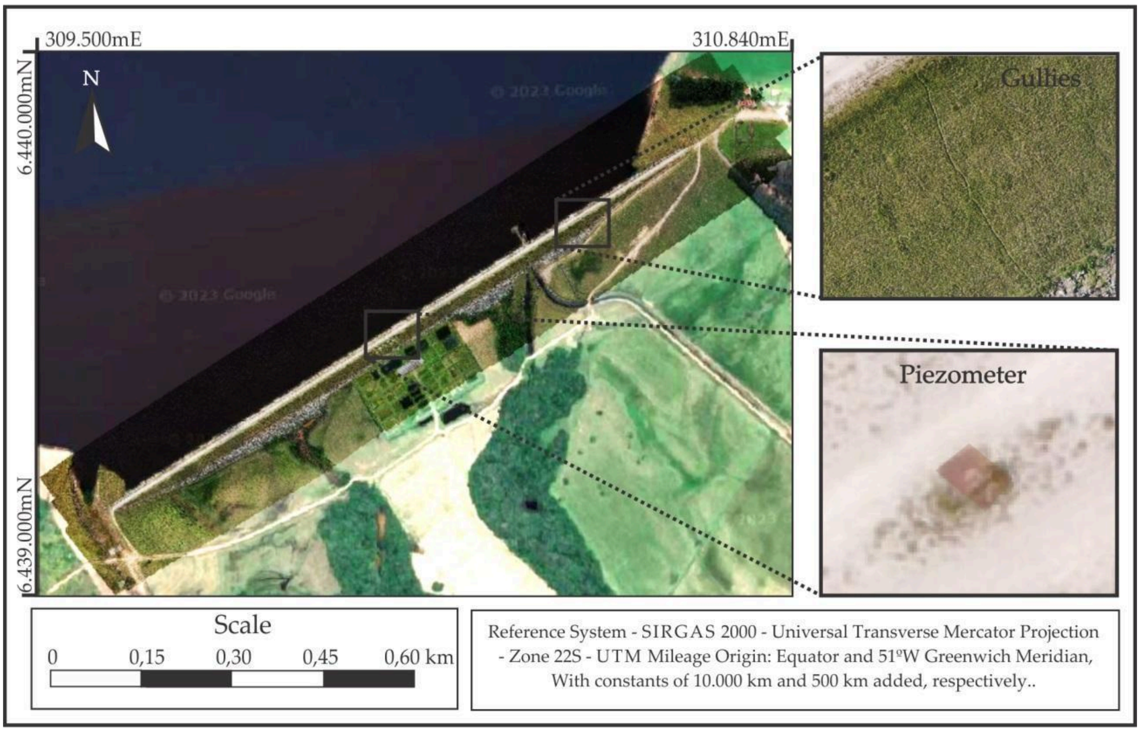


Figure 5. Chasqueiro dam orthomosaic

Table 4. UTM coordinates of piezometers identified using the orthomosaic

Piezometer	X Coord.	Y Coord.	Z Coord.
1	310.288,73	6.439.591,68	45,88
2	310.119,19	6.439.485,58	46,26
3	310.034,44	6.439.432,56	46,11
4	309.949,58	6.439.432,49	45,91
5	309.864,85	6.439.326,50	45,65
6	309.703,77	6.439.225,73	45,25

Table 5. UTM coordinates from the closest position to the crest and length of gullies on the downstream slope

Piezometer	X Coord.	Y Coord.	Z Coord.	Length (m)
1	309.975,23	6.439.390,71	45,91	20,09
2	310.292.31	6.439.588,57	45,93	22,20
3	310.376,11	6.439.641,41	45,97	25,71

In the DSM (Digital Surface Model), a clinographic evaluation of the upstream and downstream slopes was conducted to analyze the variability in their inclinations. For this purpose, the DSM was converted into a slope matrix, divided into seven slope intervals, capturing the existing topographic variations (Figure 6). It was observed that inclinations of 20% to 30% predominate on both slopes. Near the crest of the dam, smaller areas with inclinations close to 32% were identified. Despite this variability, it is concluded that the slopes' inclinations do not present significant issues.

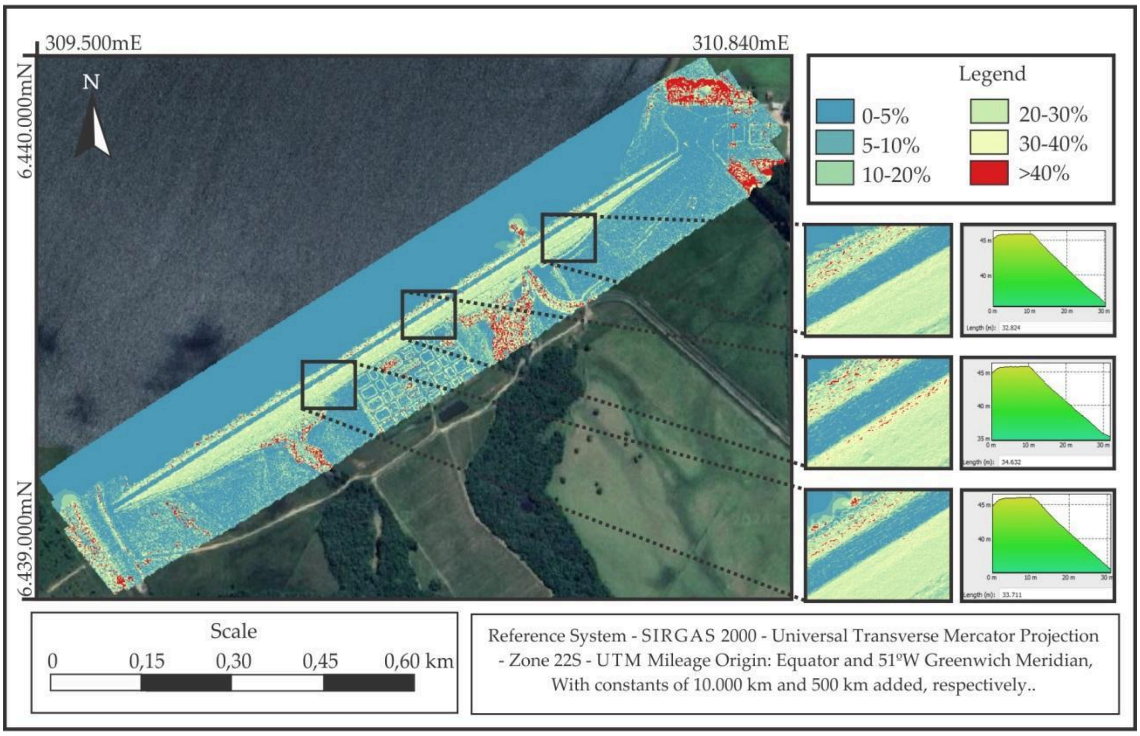


Figure 6. Chasqueiro dam clinographic map

An important observation derived from the DSM data relates to the width of the crest. While the basic design specified a width of 6 meters, a width of 9 meters was observed in the field. It is understood that this increase in the dam's width likely contributed to the absence of an apparent toe filter in any of the evaluated profiles, as originally planned for altitudes between 26 and 32 meters (Figure 7).

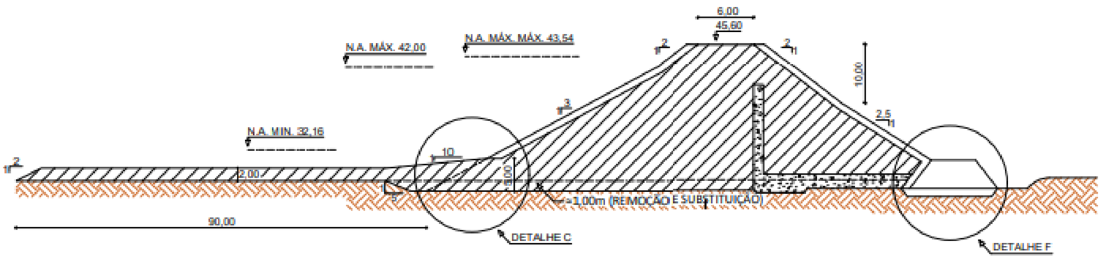
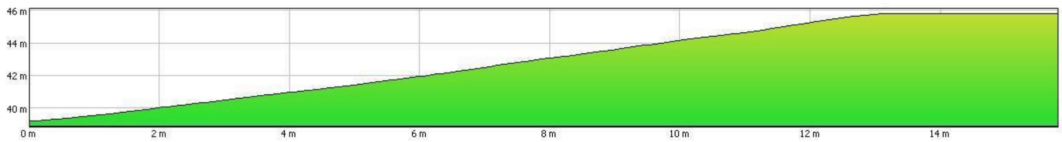
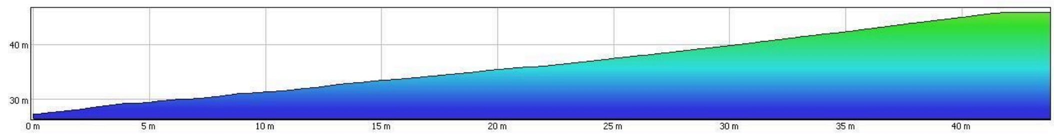


Figure 7. Typical cross-section between elevations 26 and 32 m [1, 7]

Figure 8 presents longitudinal profiles of the dam's downstream slopes. While Figure 8a represents a section entirely above 32 meters in elevation, Figure 8b corresponds to a section with lower altitudes. Since these profiles are directly generated by the *Metashape Professional*® software, it is not possible to edit the figure to accurately measure the slopes' inclinations.



(a)



(b)

Figure 8. Longitudinal profile of the downstream slope obtained through DSM: (a) in a typical section fully above 32 m elevation; and (b) in a typical section with lower elevations

To address this limitation, the images were digitized using the Digitize function of the *Grapher*® software, which allowed for the creation of Figures 9 and 10. These figures display the linear adjustments used to calculate the slope inclinations, where Alt. represents the altitude and Dist. represents the distance. For accurate calculation, the graphs were truncated at the boundary between the slopes and the crest.

The construction of the DSM also allowed for the evaluation of altitude along the entire length of the crest, as shown in Figure 11. On average, the dam was constructed at an elevation of approximately 45.90 meters, compared to the 45.60 meters specified in the basic design [7]. It is noteworthy that, at no point, is the field-measured altitude lower than the design specification. It should be emphasized that these data were derived from a Digital Surface Model, meaning that all terrain irregularities (such as grass and pebbles) influence the detected altitudes. This highlights the importance of considering such factors when interpreting the elevation data.

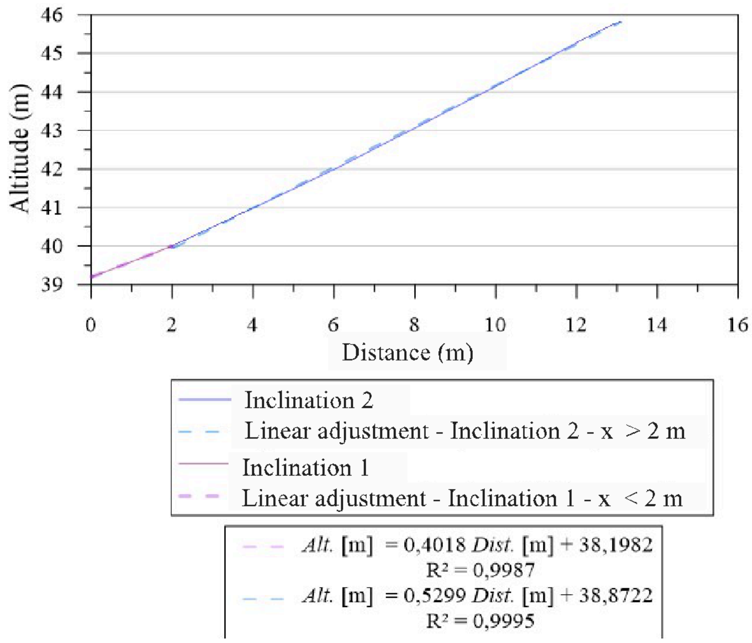


Figure 9. Inclination of the downstream slope in a typical section fully above 32 m elevation

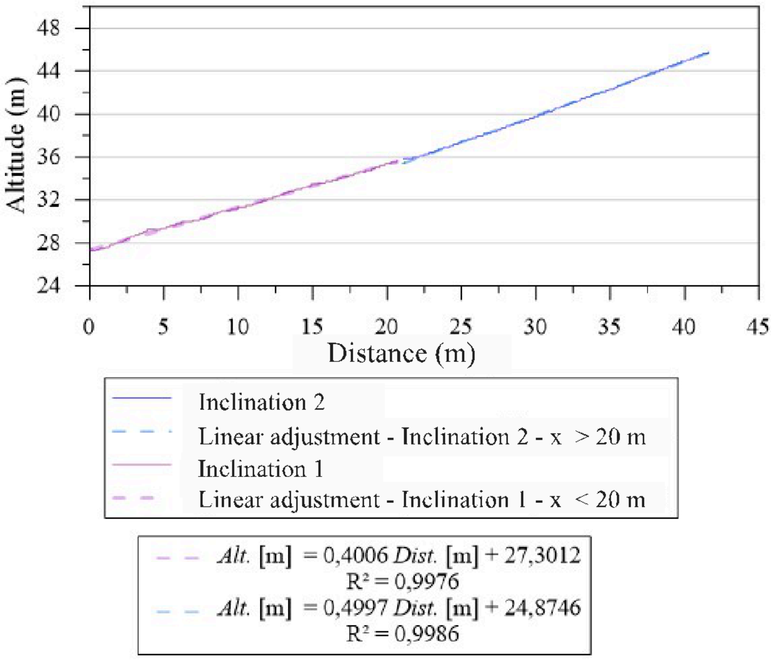


Figure 10. Inclination of the downstream slope in a typical section with elevations bellow 32 m

Figure 12 presents the statistical analysis of this data, based on 1,915 sampled points. It is observed that the median value is 45.91 meters, with the lower quartile at 45.84 meters and the upper quartile at 45.99 meters. Since no outliers were detected in the presented graph, it is understood that all portions of the dam's crest have altitudes greater than those specified in the basic design.

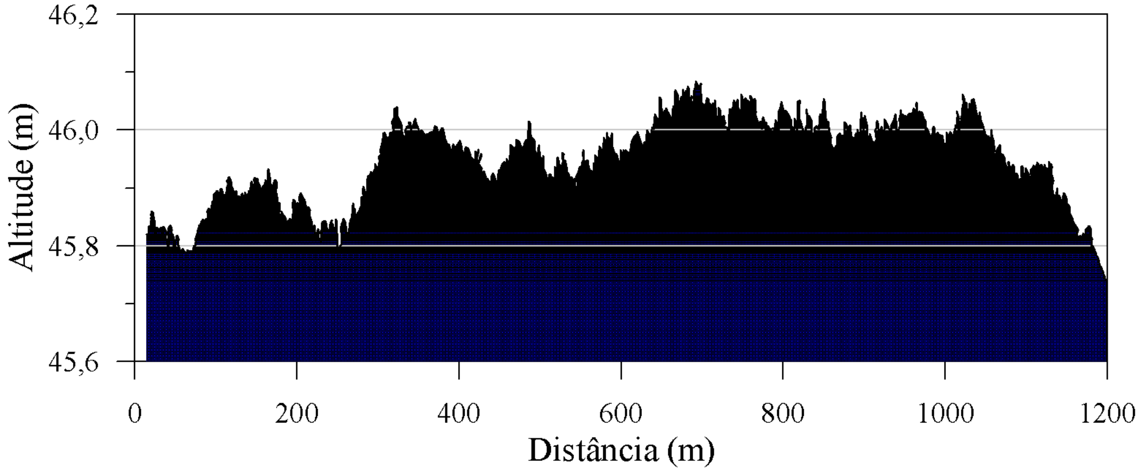


Figure 11. Altitude along the crest length

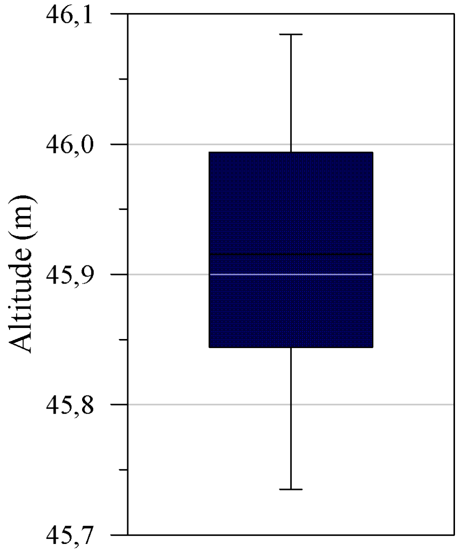


Figure 12. Altitude distribution

6. Conslusions

Based on the results obtained in this study, it is possible to conclude that the use of Unmanned Aerial Vehicles (UAVs) combined with digital aerophotogrammetry proved to be an effective tool for the auscultation of earth dams. The application of this technology allowed the identification of key features at the Chasqueiro Dam, such as the precise location of piezometers and the detection of gullies on the downstream slope that had not been observed during visual inspections. Additionally, the detailed analysis of the generated data, such as the Digital Surface Model (DSM) and the orthomosaic, enabled the evaluation of slope inclination variability and the conditions of the dam crest, indicating that its width and elevation are adequate to ensure the structure's stability.

The use of techniques such as georeferencing with materialized control points and photogrammetric processing in specialized software ensured high precision in the results obtained. This approach not only enhanced monitoring capabilities but also proved to be a safe, fast, and cost-effective alternative compared to conventional methods.

This study reinforces the importance of integrating advanced technologies into the management of critical structures such as dams, promoting greater operational safety and mitigating risks of structural failures. It is recommended to continue research to refine the application of these tools, including the incorporation of new techniques and sensors, which can complement structural and environmental analysis. Thus, the presented approach significantly contributes to the evolution of monitoring and maintenance methods for earth dams within the context of geotechnical engineering.

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