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Structural health monitoring and inspection of dams based on unmanned aerial vehicles photogrammetry with 3D model reconstruction

Daniel Teixeira Leite[1,2,3#], João Marcelino[1], Nuno Manuel da Costa Guerra[4], João Miguel Gomes Pires Manso[1], Nuno Miguel Cavalheiro Marques[5]

Article

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Monitoring
Safety
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Abstract

Ensuring dam safety requires continuous monitoring to detect structural anomalies such as cracks, displacements, and seepage. This study explores aerial surveys using Unmanned Aerial Vehicles combined with open-source software to enhance dam monitoring capabilities. The methodology enables efficient inspections in difficult-access areas and supports early identification of potential failure indicators. High-resolution aerial imagery was processed to generate detailed three-dimensional representations including point clouds, orthophotos, and textured models. A novel Ground Control Points Finder tool was developed to automate identification and georeferencing, significantly improving spatial accuracy and survey efficiency. The study systematically presents fourteen failure modes detectable through aerial mapping, including piping, hydraulic fracturing, foundation instability, and freeboard loss, with their characteristic surface manifestations. The approach was validated using Lapa Dam as a case study through two aerial surveys conducted ten months apart. Analysis using open-source software successfully identified surface deformations, settlements, and vegetation changes, demonstrating the methodology's effectiveness in detecting structural anomalies associated with potential failure modes. The results confirm that integrating aerial surveys with open-source processing tools offers a low-cost solution to complement dam safety assessments. The approach improves early detection of various failure modes, reduces inspector exposure to hazardous conditions, and supports informed decisions in monitoring embankment dams through accessible technology.

1. Introduction

Dam safety is a multidisciplinary field involving various areas of study. According to Portuguese legislation, dam safety encompasses structural, hydraulic, operational, and environmental aspects (Portugal, 2018). Ensuring the effectiveness of water tightness, filtering, and drainage systems is crucial for preventing percolation issues in the body of embankment dams and foundation and surrounding areas. Proper management, commitment to safety regulations, and implementation of operation and maintenance programs are essential for operational safety. Environmental considerations focus on minimizing social, economic, and environmental impacts, prioritizing protection (Quintela et al., 2001).

From a performance perspective, dam safety depends on three fundamental criteria: controlled flow, stability, and deformation compatibility (Cruz, 1996). A dam is considered hydraulically and structurally safe when percolation occurs in a controlled manner, preserving the mechanical stability of the structure under operational stresses. Figure 1 shows an embankment dam with a central core, where the core, cut-off trench, and injection curtain act as flow barriers, while filters and drainage systems regulate water movement downstream in a controlled manner. Nonetheless, inadequate flow control, instability, or excessive deformations can lead to anomalies in the body or foundation. If not detected and addressed in time, these issues can evolve into failure modes, ultimately compromising the dam's integrity. In this context,

[#]Corresponding author. E-mail address: dtleite@lnec.pt
[1]Laboratório Nacional de Engenharia Civil, Departamento de Geotecnia, Lisboa, Portugal.
[2]Universidade Nova de Lisboa, Faculdade de Ciências e Tecnologia, Lisboa, Portugal.
[3]COBA - Consultores de Engenharia e Ambiente, Lisboa, Portugal.
[4]Universidade Nova de Lisboa, Faculdade de Ciências e Tecnologia, Lisboa, Portugal.
[5]Universidade Nova de Lisboa, Departamento de Informática, Faculdade de Ciências e Tecnologia, NOVA Laboratory for Computer Science and Informatics, Lisboa, Portugal.

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visual inspections play a crucial role in identifying early-stage anomalies, such as cracks, settlements, and seepage, which might otherwise go unnoticed.

Recent technological advances have enhanced dam monitoring, particularly through Unmanned Aerial Vehicles (UAV) and laser scanning, which offer cost-effective solutions for structural assessment (Leite & Marcelino, 2020). The accuracy of UAV-collected data, however, depends on many factors, such as the quality and distribution of ground control points (GCP). These points are essential for correcting positional errors in three-dimensional models during post-processing. This paper presents an algorithm designed to improve the efficiency of GCP identification, optimizing data processing on the WebODM platform (Freire, 2022).

2. Benefits of using UAVs for visual inspection and monitoring of dams

The importance of visual inspection in the context of dam security is fundamental, and UAV can play a crucial role in developing and implementing innovative visual observation methodologies. By collecting data from UAVs, it is possible to generate a dam model from a point cloud and subsequently reconstruct its geometric representation. Point clouds result from processing georeferenced images captured during UAV flights. These three-dimensional models exhibit high geometric precision and enable comprehensive modeling of the entire structure, including typically inaccessible perspectives, such as views from above and upstream.

Beyond capturing the entire geometry during flight surveys, these models promote more thorough and phased inspections over time. The data derived from the geometric model closely resembles that obtained through instrumental monitoring, offering a numerical representation stored in a database, devoid of subjectivity. This approach is not limited to the visible spectrum; alternative systems capturing data outside this range (thermal, infrared, or ultraviolet) can also be employed. While the current study focuses on visible spectrum data, the developed technique can be applied to any sensor, if the maps obtained refer to the same positions in the image.

Although traditional visual inspections remain a fundamental tool in dam safety monitoring, they can, in some cases, involve risks and limitations due to access difficulties and potential hazards - particularly during emergency situations. An example is the Pampulha dam collapse (Brazil, 20 April 1954), where an inadequate drainage system resulted in high gradients that led to piping (Guidicini et al., 2021). As demonstrated in Figure 2, the Brazilian authorities conducted a high-risk inspection a few hours prior to the rupture, which occurred approximately 48 hours after the anomaly was first detected.

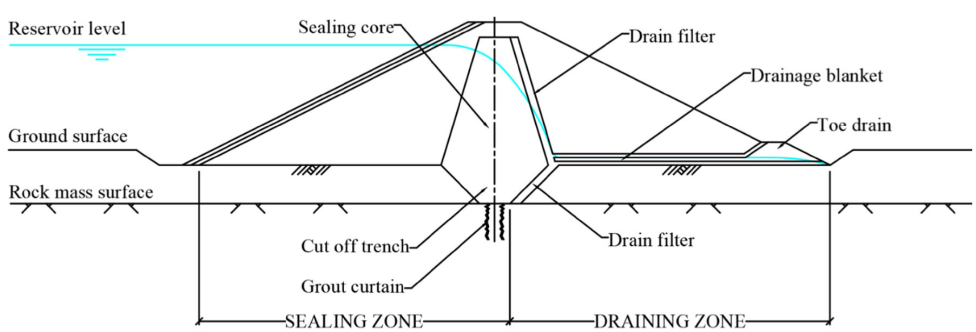

Figure 1. Representation of adequate internal flow in an embankment dam with a central core.

a) b)

Figure 2. High-risk inspection conducted at the Pampulha Dam, Belo Horizonte (CMBH, 1954): (a) expert group; (b) rupture of the dam.

In this context, UAVs offer significant benefits. The ability of UAVs to reach hard-to-access areas efficiently and safely is well-documented, leading to a significant reduction in the exposure of workers to potential hazards. UAVs can capture detailed and precise images of the structures, allowing for the early identification of potential issues.

Figure 3 shows an example of a slope about 40 m high, where cracks and slips have been identified. This image was taken from a 3D model obtained from a point cloud generated by processing images taken by a drone. It was possible to identify and map the anomalies in approximately 40 minutes, without putting the inspectors at risk, with the advantage of obtaining an accurate description of the geometry and characteristics of the anomalies. UAVs can be equipped with high-resolution cameras and advanced sensors, including multispectral cameras, radar, LiDAR, infrared, and magnetic sensors. This enables comprehensive data collection across various spectrums, enhancing the detection of anomalies, such as deformations, settlements, cracks, seepages, and wet zones.

When aerial photogrammetry processes are conducted, UAVs produce orthophotos and spatial models, providing valuable information on the dam's current condition and allowing precise comparisons of anomaly evolution over time. Aerial photogrammetry is a well-established technique traditionally carried out using manned aircraft, where a sequence of overlapping images is captured along a predefined flight path. This methodology has been successfully adapted for use with UAVs, enabling greater flexibility and reducing operational costs, while maintaining the core photogrammetric principles. Images captured by digital cameras or even mobile phones can also be employed in the photogrammetric process to enhance the resolution of orthophotos in areas affected by anomalies, especially in localized or hard-to-access zones. However, the accuracy and resolution of the final products depend strongly on several parameters, including the camera sensor specifications, flight altitude, and image overlap. Lower altitudes allow finer Ground Sampling Distance (GSD), meaning that each pixel represents a smaller area on the ground. This approach enhances the efficiency of traditional visual inspections, allowing for a more comprehensive and precise analysis of the structural condition.

To establish a potential failure mode, it is essential to conduct a comprehensive analysis of the anomalies, emphasizing their correlation with monitoring, whenever such a link can be established. Integrating UAV-based techniques with traditional visual inspections is crucial for identifying the failure mode most consistent with the observed anomalies. Creating accurate three-dimensional models of the dam, and associated structures, provides numerous visualization and analysis possibilities, that would otherwise not be achievable.

3. Main failure modes mappable with UAVs

Most anomalies in embankment dams typically appear on the surface, abutments, and adjacent areas, and they may be linked to potential failure modes. Accurately identifying the developing failure mode in an embankment dam is crucial, as early detection allows for effective mitigation measures to address the issue and prevent severe consequences. To categorize anomalies into a potential failure mode, they should be analyzed collectively and, whenever possible, associated with monitoring devices. Combining these findings with visual inspections is important to identify the failure mode most consistent with the observed anomalies.

Figures 4 to 17 schematically present anomalies related to fourteen failure modes manifesting on the surface, in the foundations, and/or in the dam abutments, which can be mapped using UAVs. These anomalies include cracks, slumping, seepage, settlements, uplifts, deformations, sinkholes, heaving, muddy water, wet zones, and others. It is essential to examine these together, to correctly assess the failure mode developing in the embankment dam.

Figure 3. Visual inspection of a high-risk area using a drone (image extracted from a textured 3D model generated from drone-captured images).

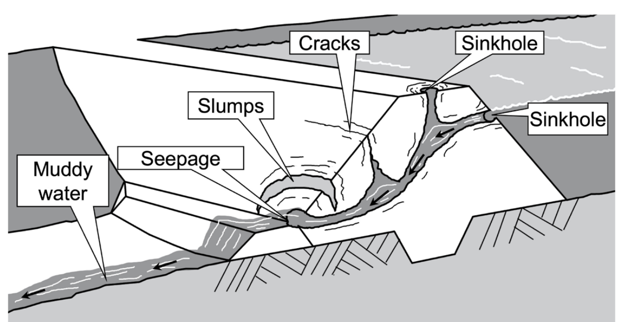

Figure 4. Piping in embankments. This can be identified through seepages with muddy water, slumps, and arch cracks, as well as the presence of sinkholes (Guidicini et al., 2021; USBR, 2019; GBC, 2020).

As shown in the previous figures, different failure modes can present signs of anomalies both on the surface of the structures, as well as in adjacent areas. These anomalies can be detected through conventional visual inspections and/or using UAVs for aerial dam mapping (Leite & Marcelino, 2020). The use of UAVs allows for monitoring the entire dam and adjacent areas from perspectives not possible with traditional inspections and recording images with dimensional accuracy. By combining the expertise of dam inspectors with sophisticated monitoring technologies, it is possible to identify anomalies associated with the failure modes at an early stage, enabling the implementation of preventive measures to guarantee dam security.

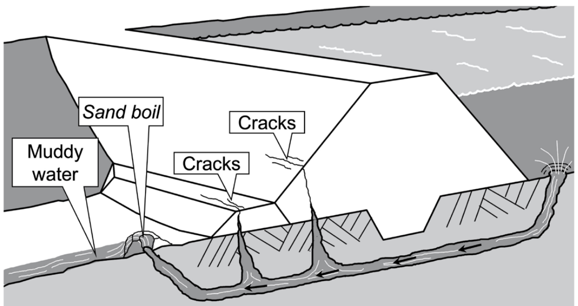

Figure 5. Piping in foundations. In foundations, the piping can manifest itself through downstream seepages with the presence of turbid water or the dragging of fines from the foundation, sand boils, and cracks on the embankment (FEMA, 2023).

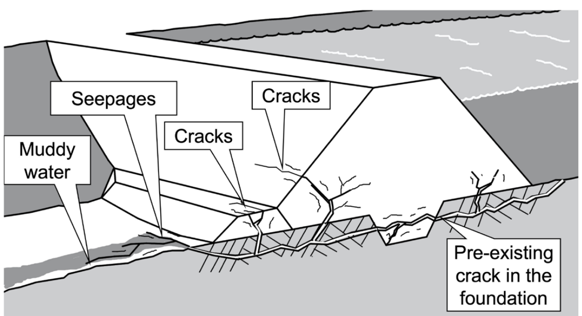

Figure 6. Piping into pre-existing fractures. Pre-existing fractures in the foundations can facilitate the occurrence of piping, which is initially manifested by cracks, seepages with muddy water, and/or fines from the foundation (Mejia, 2013).

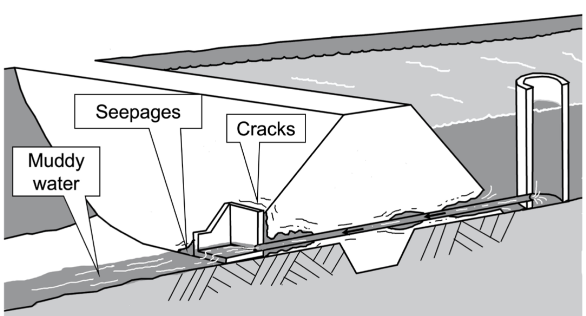

Figure 7. Piping on contact between soil and structure. Piping can occur at the interface between the soil and the structure, initially manifesting itself through cracks, seepages of muddy water, and with the presence of fines from the foundation in the zone downstream of the dam (Silveira, 2019).

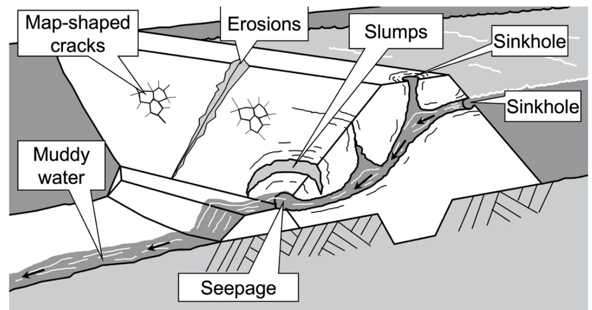

Figure 8. Piping in dispersive soils. Dispersive soils are susceptible to piping, which can be manifested by map-shaped cracks, erosions, as well as seepages, slides, sinkholes, and the presence of muddy water (USDA, 2006; Tosun & Kılbıyık, 2006; Hardie et al., 2009; Cruz, 2008).

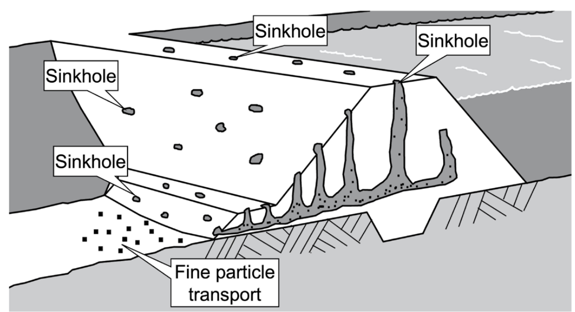

Figure 9. Piping by suffusion. Poorly graded soils, which allow for the migration of fines, can result in the suffusion process, which is typically evidenced by the formation of numerous sinkholes and the presence of fines in the downstream slope (Richards et al., 2015; USACE, 2022).

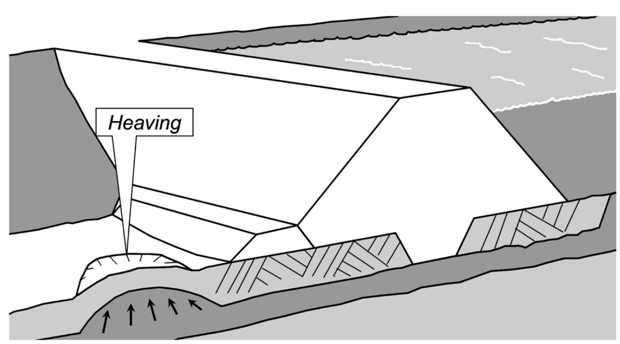

Figure 10. Heaving and Hydraulic lifting. The aerophotogrammetry process allows the comparative analysis of point clouds, facilitating the identification of anomalies, such as heaving, caused by excessive underpressure (Robbins et al., 2015; Bandeira et al., 2018).

4. Open-source software for processing and analyzing 3D models

Aerial surveys have become increasingly efficient and cost-effective with the use of UAVs. By applying aerophotogrammetry techniques, which utilize images captured by UAVs, various spatial models can be generated, including Digital Surface Models (DSM), Digital Terrain Models (DTM), orthophotos, elevation maps, and contour lines. These models are valuable in the context of dam safety, as they enhance structural monitoring and anomaly detection.

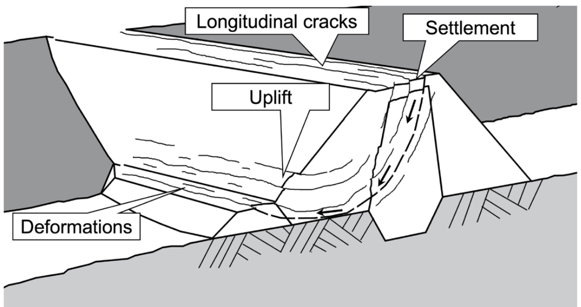

Figure 11. Excess pore pressure. When the loads applied to soils increase rapidly and the pore water pressures are not allowed to dissipate, a loss of shear strength may occur, thereby facilitating the occurrence of longitudinal cracking and settlement (Souza, 2017; Mello, 1982).

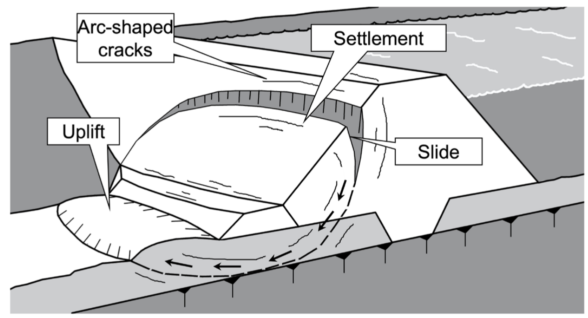

Figure 14. Foundation shear instability. In the presence of soft soils in the foundation with insufficient load-bearing capacity, there is a greater propensity for sliding, settlement, uplift, and arch cracks (Vu et al., 2023).

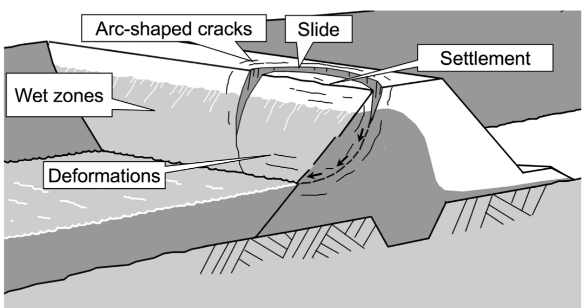

Figure 12. Rapid drawdown failure. The rapid drawdown of the reservoir can cause instability in the upstream slopes, increasing the probability of slides, settlements, and arch cracks (Narita, 2000; FERC, 1978).

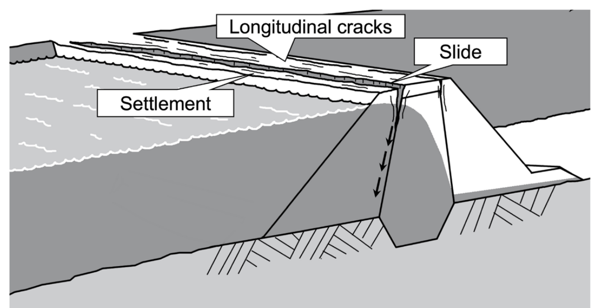

Figure 15. Freeboard loss failure. Rockfill dams or dams with collapsible material can experience excessive settlement due to wetting, especially during the first filling of the reservoir, resulting in longitudinal cracks, sliding, and deformations (Marcelino, 1996).

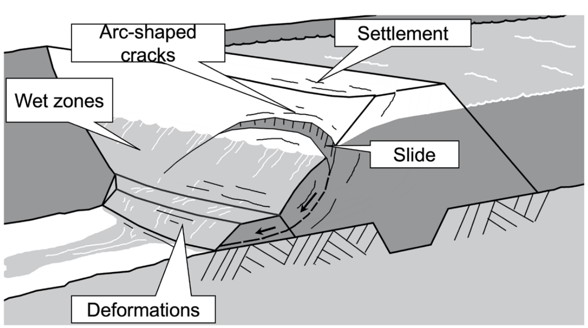

Figure 13. Faulty drainage system. Deficiencies in the internal drainage system have the potential to elevate the water level within the embankment, favouring the formation of wet zones, settlements, cracks in the arches, deformations, and slides (Mello, 1997).

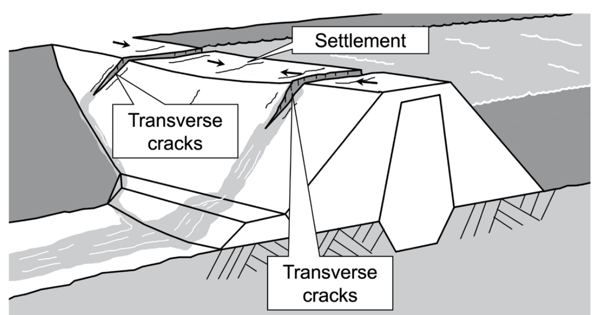

Figure 16. Freeboard loss due to cracks. Differential settlements in the foundation and embankment can cause transverse cracks, resulting in a loss of clearance and favouring the opening of a breach in the dam (He et al., 2021; Fell, 2015).

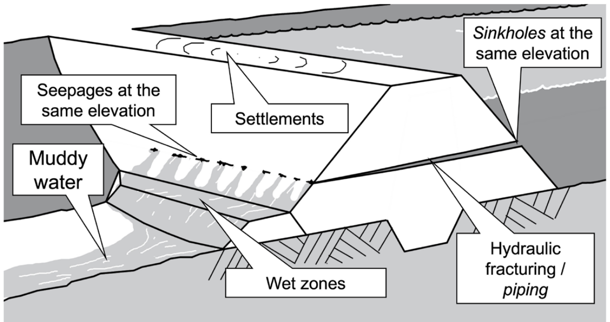

Figure 17. Hydraulic fracturing. Construction problems between joints or layers in embankments, as well as differential settlements, can lead to hydraulic fracturing and seepage at the same level, as well as sinkholes, and settlements (Sherard, 1986).

While UAV's acquisition costs are relatively low, commercial software for image processing can require significant investment. Open-source software (OSS) provides a viable alternative, offering high-quality results at a lower cost. Additionally, OSS fosters flexibility, independence from specific suppliers, and the potential for further application development.

Ensuring high geometric accuracy is essential to improve model quality and efficiency. Ground Control Points (GCPs) with known coordinates may be used during data collection to enhance spatial accuracy. These points, visible in multiple images, provide pixel-based coordinate references that align photographs with real-world coordinates. This process significantly improves the precision of object reconstruction algorithms by correcting image geometry.

In this study, UAV technologies were applied in dam observation using Open Drone Map (ODM) in its web interface version, WebODM (OpenDroneMap, 2025). This tool serves as a graphical user interface (GUI) for ODM, a collection of open-source tools that convert aerial images into georeferenced outputs, such as maps, point clouds, digital elevation models, and 3D textured models. The image processing workflow in ODM consists of six key operations: 1. Structure from motion (SfM); 2. Multi-view stereo (point cloud densification); 3. Meshing; 4. Texturing; 5. Georeferencing; and 6. Orthophoto generation.

By leveraging WebODM, this approach optimizes financial resources while maintaining full control over data analysis processes. Although OSS may lack some of the user-friendly interfaces of commercial software, it offers greater flexibility and facilitates result dissemination (Leite et al., 2024, 2025; Marcelino et al., 2024). The prioritization of OSS in aerial data processing provides an accessible and adaptable solution for UAV-based dam monitoring. Furthermore, it allows the sharing of data and developments without the constraints of licensing systems. It also helps to maintain data in the future due to open standards used in data files.

In addition, within the domain of point cloud comparison, the CloudCompare program emerges as an essential tool, assisting in the identification of surface changes across different surveys. Developed as an open-source project, CloudCompare is designed for visualizing, editing, and processing 3D data, with a focus on point cloud and mesh analysis. Its latest version, 2.14. alpha, Kharkiv, released on September 29, 2024, is governed by the GNU General Public License (GPL), allowing its use for various purposes, including commercial and educational applications (CloudCompare, 2024). CloudCompare supports several features, such as change detection, and can compare two different point clouds, proving useful in detecting settlements, heaving, and other deformations related to mass movements in dams and adjacent areas.

5. GCP finder tool

To enhance the precision and accuracy of aerial mapping conducted with UAVs, the use of Ground Control Points (GCPs) is essential. These points serve to correct errors and distortions that may arise during image processing and play a crucial role in verifying topographical accuracy. Additionally, they enable the assessment of the quality of the generated models.

Despite their importance, manually identifying and assigning reference coordinates to GCPs in hundreds of UAV-captured images is a labour-intensive and error-prone process. To address this challenge, LNEC, in collaboration with Nova University Lisbon, developed the GCP Finder tool (Freire, 2022). This software automates the detection and georeferencing of GCPs, significantly improving efficiency in aerial surveys.

Even when images are georeferenced, various factors – such as image resolution, pixel size, optical quality, and minor UAV flight variations – can introduce substantial errors in determining camera positions. GCPs help mitigate these errors by providing high-precision reference points.

An effective GCP should be easily identifiable from high altitudes, feature distinct shapes or colours that contrast with the surrounding environment, and include a well-defined reference point for GPS placement. Regardless of their format, GCPs should have a matte finish to prevent reflections that could interfere with automatic detection in the images (Kuze, 2015). Figure 18 shows an example of GCPs locatable with the GCP Finder software.

The process of manually compiling a list of GCP coordinates for each photograph is feasible for a small dataset, though it becomes highly inefficient for large-scale surveys. The GCP Finder tool automates this process, enabling the accurate and efficient extraction of GCP coordinates across extensive datasets. The software is freely available on GitHub (2025a) (console version) and GitHub (2025b) https://github.com/octaviojardim/Web-Interface-GCP-Finder (web interface version for server installations). These repositories include the source code, installation instructions, and practical application examples.

6. Case study

To illustrate the benefits of using UAVs in dam inspection, a case study is presented, based on surveys conducted as part of safety inspections by LNEC at the Lapa Dam. Lapa is an earthfill dam with a maximum height of 24 m and a crest elevation of 174.0 m (Figure 19). The normal water level (NWL) is 170.0 m, the maximum water level (MWL) is 171.92 m, and the minimum operating level (MOL) is 162.2 m. The reservoir at MWL has a relatively small volume (0.64 hm^3), with a flooded area of 9.5 ha. The upstream and downstream slopes have inclinations of 1:3.25 (V:H) and 1:2.5 (V:H), respectively. The downstream face features a berm, 2.5 m wide, located at 164.0 m elevation. To ensure high-resolution imaging in this study, aerial surveys were carried out using a DJI Phantom 4 Pro drone equipped with a 20 MP camera. The precision of UAV-based photogrammetry is influenced by several factors, including the sensor specifications, flight altitude, and the distribution of ground control points (GCPs). Specifically, lower flight altitudes enable the generation of finer GSD, which represents the real-world size of one pixel in the image. For this case, flights were conducted at a height of approximately 15 meters, resulting in a GSD of about 0.4 cm/pixel at the dam crest. While this resolution ensures detailed surface modelling, the incorporation of GCPs remains essential to improve georeferencing accuracy and minimize distortions during the reconstruction of 3D models. These surveys were conducted on two separate occasions, on 07/20/2021 and 05/19//2022, aiming to identify possible settlements and other anomalies.

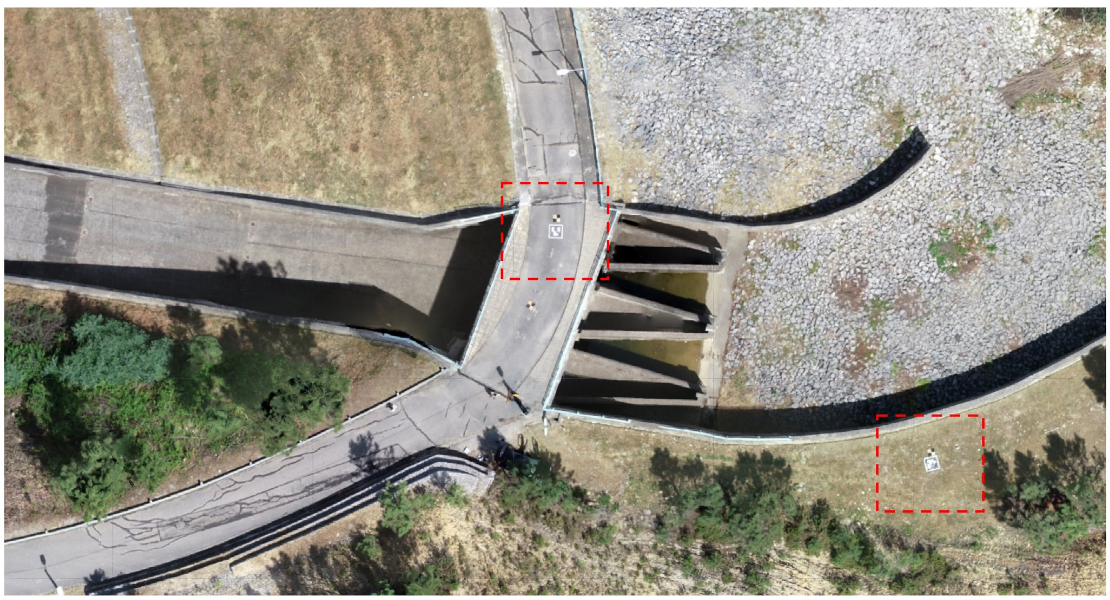

Figure 18. Example of ground control points identifiable with the GCP Finder.

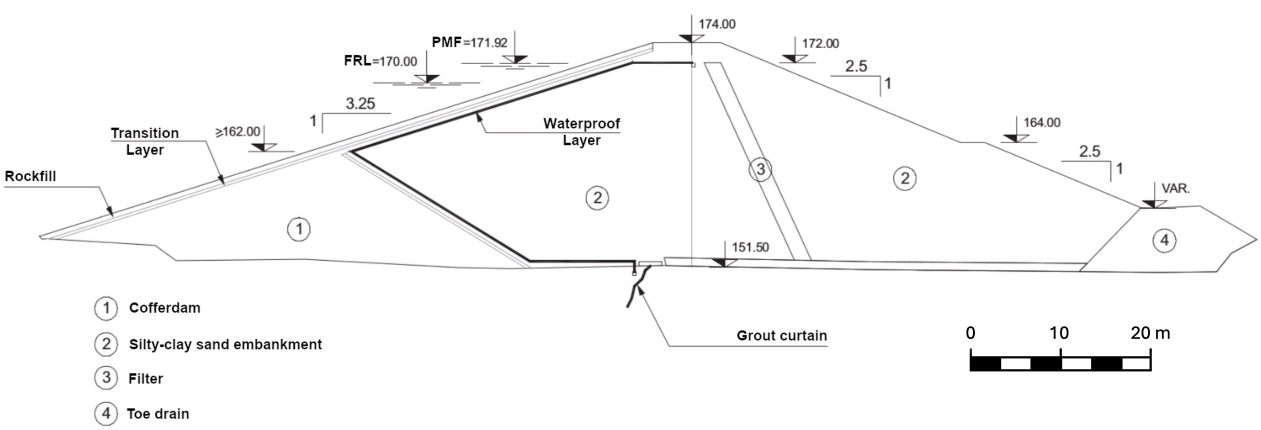

Figure 19. Cross-sectional profile of the Lapa Dam.

Figure 20. Textured model of the Lapa Dam (WebODM).

As shown in Figure 20, processing the images using WebODM software allows the generation of textured 3D models. It also enables the creation of DTM and DSM, such as the one illustrated in Figure 21, and contour lines associated with orthophotos (Figure 22). This results in a set of accurate data on the geometry and condition of the structure, highly useful for dam safety. These models faithfully represent the condition of all areas of the dam and surrounding regions.

As illustrated in Figure 22, this survey enabled the detection of an area of old settlement in the central region of the dam, indicating a loss of freeboard, mass movement, landslides, and cracks in the embankment and/or foundation. In detail, Figure 23 shows the cracks in the area where the settlements occurred.

Figures 24 and 25 show a comparison between two orthophotos generated in WebODM, from surveys performed over a period of approximately 10 months, whose differences in vegetation can be easily observed.

For a comparative analysis of deformations over a specific period, the use of CloudCompare software is recommended. This program allows for examining discrepancies between point clouds generated from images captured by UAVs, as shown in Figure 26. The areas highlighted in red represent differences greater than 1 m, indicating the removal of shrub vegetation during dam maintenance. The green and yellow areas denote changes of about 0.5 m, associated with the removal of ground vegetation. By analysing the colour patches and comparing them with the orthophotos (Figures 24 and 25), it is possible to distinguish between the deformations in vegetation and minor deformations in areas of interest, such as the crest and upstream rock protection. However, no significant deformations were observed in the body of the dam (blue patch), indicating that no substantial deformations occurred between the two surveys, as expected.

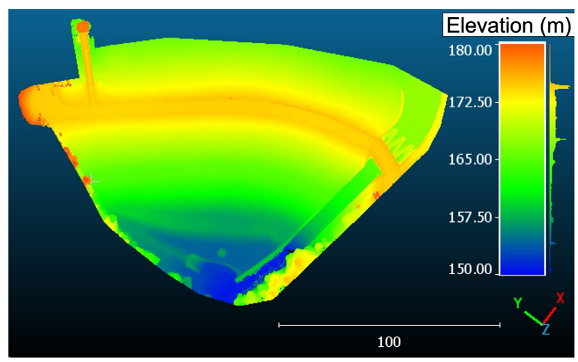

Figure 21. Digital Surface Model.

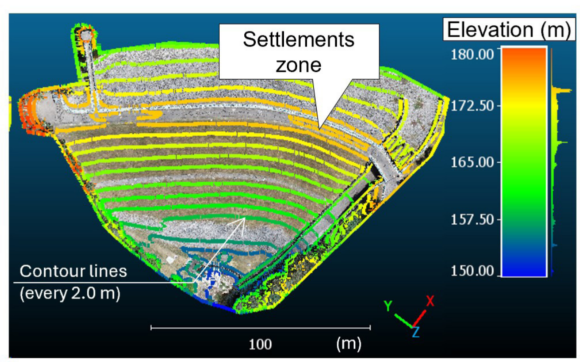

Figure 22. Contour lines (every 2.0 m).

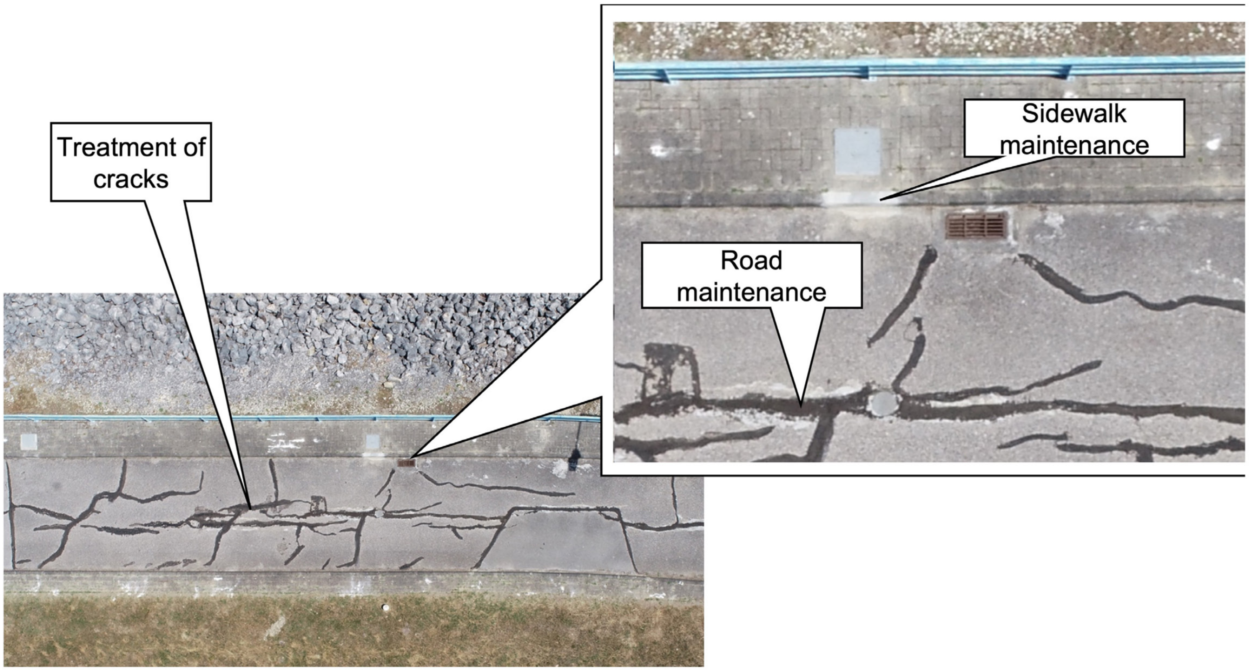

Figure 23. Treatment of cracks in the area where settlement has occurred.

Figure 24. Survey performed 07/20/21.

Figure 25. Survey performed on 05/19/22.

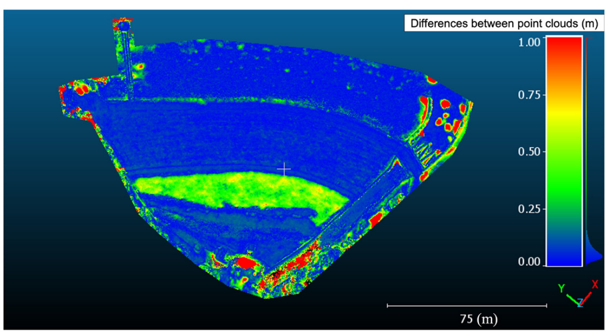

Figure 26. Point cloud comparison (CloudCompare).

7. Conclusions

The integration of UAV technology and open-source software has significantly enhanced dam monitoring, offering a cost-effective, precise, and comprehensive approach to anomaly detection. This study demonstrates how UAVs equipped with high-resolution sensors, coupled with advanced photogrammetric processing techniques, can improve structural assessments by generating detailed 3D models, orthophotos, and point clouds. The proposed GCP Finder tool further optimizes this process by automating the identification and georeferencing of Ground Control Points, improving accuracy and efficiency in data processing.

However, despite the clear advantages of using UAV photogrammetry for dam monitoring and safety, several limitations must be recognised. Firstly, weather conditions such as strong winds, rain and poor visibility can make drone operation difficult and reduce image quality. Secondly, dense vegetation or steep, inaccessible terrain can obstruct the line of sight of images and jeopardise the generation of complete point clouds. Thirdly, although low-altitude flights and multiple GCPs allow for high-resolution surveys, these factors increase operational complexity and require a good command of operating this equipment. In addition, reliance on GCPs implies additional fieldwork, time and logistical planning.

A case study of the Lapa Dam highlights the effectiveness of UAV-based monitoring in identifying settlements, cracks, and vegetation changes over time. By utilizing Open Drone Map (ODM) and CloudCompare software, structural deformations and surface alterations were systematically analysed, reinforcing the value of UAV applications in dam safety assessments. This approach not only enhances the ability to detect potential failure modes at an early stage, though it also reduces human exposure to hazardous environments, thereby improving overall safety. Moreover, UAVs facilitate periodic inspections from multiple perspectives, ensuring a more thorough and reliable assessment compared to traditional methods. The integration of UAV-based techniques with conventional visual inspections enables a more data-driven and proactive approach to dam safety management. By leveraging open-source tools like WebODM, this methodology is accessible, scalable, and adaptable to various dam monitoring applications worldwide.

Ultimately, the findings of this study underscore the transformative potential of UAV technology in dam monitoring. The combination of high-resolution imaging, automated georeferencing, and robust data analysis tools provides engineers and decision-makers with valuable insights, promoting early anomaly detection and ensuring the structural integrity of embankment dams. Future advancements in UAV capabilities and artificial intelligence-driven data processing are expected to further refine and expand the applications of this technology, making dam safety assessments more efficient, reliable, and sustainable.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have reviewed and approved the contents of the paper, and there are no financial interests that could have appeared to influence the work reported in this study.

Authors' contributions

Daniel Teixeira Leite: conceptualization, data curation, visualization, writing – original draft. João Marcelino: supervision, validation – original draft. Nuno Manuel da Costa Guerra: supervision, validation – review & editing. João Miguel Gomes Pires Manso: supervision, writing – review & editing. Nuno Miguel Cavalheiro Marques: supervision, validation – review & editing.

Data availability

The datasets generated analysed in the course of the current study are available from the corresponding author upon request.

Declaration of use of generative artificial intelligence

This work was prepared with the assistance of generative artificial intelligence (GenAI) tools, specifically OpenAI ChatGPT, only with the aim of improving the clarity and flow of the English language in the manuscript, assisting in the refinement of figure captions, and suggesting concise phrasing for technical sections while ensuring consistency with journal style. The entire process of using this tool was supervised, reviewed and when necessary edited by the authors. The authors assume full responsibility for the content of the publication that involved the aid of GenAI.

List of symbols and abbreviations

DSM	Digital Surface Models
DTM	Digital Terrain Models
GCP	Ground Control Point
GNU	GNU's Not Unix
GPL	General Public License
GUI	Graphical User Interface
LiDAR	Light Detection and Ranging
MOL	Minimum Operating Level
MWL	Maximum Water Level
NWL	Normal Water Level
ODM	Open Drone Map
OSS	Open-source Software
SfM	Structure from Motion
UAV	Unmanned Aerial Vehicle

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