Analysis of the evolution of a reclaimed coal mining area using historical aerial photographs

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ABSTRACT: Mining activities have a significant impact on the environment, and it is crucial for mining companies to restore the land after extraction and preserve the original landscape. Remote-sensing techniques, such as Structure-from-Motion and 3D laser scanners, have become widely used in mining for ground monitoring due to their accessibility and safety advantages. In this study, historical aerial optical imagery of a coal-mining site in León, Spain, was processed using SfM photogrammetry to analyze landscape changes from the beginning of the open-pit operation to the completion of land reclamation.

Two point clouds generated from open-access optical imagery were compared with a LiDAR point cloud from 2010. To ensure accurate georeferencing, ground control points were extracted from an additional LiDAR point cloud acquired in 2010. By comparing these reconstructions and conducting a comprehensive analysis of the site's evolution, the researchers identified a landfill and assessed the effectiveness of the mine reclamation works.

Keywords: Landslide, Coal mining, SfM, Land restoration, Aerial photographs.

1 INTRODUCTION

In recent years, remote sensing techniques have experienced a significant evolution and have become essential tools for monitoring, mapping, and understanding different environmental and man-made phenomena. These techniques enable the acquisition of information from a specific area in successive campaigns, which enables monitoring of different events and detection of movements in a study area. Among remote sensing techniques, Light Detection and Ranging (LiDAR) is the most used, providing a three-dimensional point cloud (3DPC) of the scanned surface. This geometric information can be used for characterization, evaluation, and mapping of susceptibility, as well as for monitoring and modeling of ground movements.

LiDAR system records the position, intensity, and time of the laser pulse, creating a 3D point cloud that represents the surface. This point cloud can be used to create highly accurate digital elevation models (DEM) and digital surface models (DSM) (Jaboyedoff et al., 2012).

Otherwise, Structure from Motion (SfM) technique, together with multiview-stereo (MVS) algorithms, also enables the 3D reconstruction of surfaces. This technique uses a set of overlapping images taken from different viewpoints to create a 3D model of the scene. The SfM technique uses the relative position and orientation of the camera in each image to determine the position of the 3D points. One of the main advantages of the SfM technique is that it is much more economical and manageable than LiDAR instrumentation. Additionally, SfM can be used to create 3D models of inaccessible areas or areas that are dangerous to access, making it an ideal technique for monitoring and mapping geohazards such as landslides, rockfalls, and volcanic eruptions (López-Vinielles et al., 2020; Sarro et al., 2018)

In this paper, the SfM technique has been used considering old aerial photographs in coal-mining site in León (NW Spain). Using historical aerial photographs enables for the creation of a historical record of the area, providing valuable information on changes in topography and additionally, providing insight into the evolution of landslides. It contributes to improve our understanding of these phenomena as well as our ability to predict and manage them.

2 GEOLOGICAL SETTING

The Villablino Basin, in the Laciana Valley, conforms one of the main coal basins in the province of León. Underground mining activity on "*"El Feixolín"*" began in the late 1940s, although it was notably reactivated in 1992 with the reopening of the old galleries and the drilling of new ones. This activity was primarily focused on the intermediate and lower part of "*El Feixolín*" slope. The exploitation method was the Sub-Level System, whereby the mineral was extracted through open cuts. This method divides the deposit into sections of a variable vertical height (between 50 and 100 m) in which sub-levels are prepared connected by an inclined ramp (Suárez & Rodríguez-García, 2017).

Open-pit mining on "El Feixolín" began in 1995, with significant land movements in the upper part of the slope. Both activities (underground and open-pit) coexist for more than a decade until the final closure of the exploitation in 2012. Later, the open-pit is restored by filling with a waste dumps, and replanted with native forest tree species (birches and pines). The material used for filling is heterometric and loose rock blocks and cobbles, with no cohesion. The rehabilitation and finalization finished in the spring of 2015.

Furthermore, it is important to highlight that the "*El Feixolín*" slope has a complex geomorphology characterized by the presence of a large paleolandslide controlled by several lithologies and a dip bedding slope. The result is an area with possible phenomena of slope instability, which makes it necessary to conduct studies and monitoring to prevent potential instabilities, in addition to other causes, especially after mining activities. Additionally, the site is in an environmentally protected area, which demands careful consideration and management to minimize the impact on the natural environment (Alberruche-del Campo et al., 2015). Thus, this area in the Laciana Valley is a relevant example of the consequences and challenges of coal mining activities. It highlights the importance of responsible and sustainable exploitation practices, as well as effective post-mining land management and reclaim actions.

3 DATA AND METOHODOLOGY

The methodology applied is based on the use of historical aerial photographs to reconstruct the topography, and thus be able to monitor its evolution through the generated Digital Elevation Models (DEMs) (Riquelme et al., 2019). The Feixolín mining exploitation has been studied using three different sources of information: two sets of color photogrammetry frames (2001 and 2011), and an airborne laser scanning (ALS) point cloud. Consequently, the situation of the slope in the study area, corresponding to the years 2001 (stage 1), 2011 (stage 2) and 2014 (stage 3) has been rebuild.

Models provide useful digital information, allowing for the analysis of the morphological characteristics of the topography in the past stages. The topography generated in the different stages has been compared to each other, taking the ALS-derived point cloud as a benchmark. Thanks to this comparison, the "active areas" (areas prone to instability) were analyzed to verify their relationship with the landslide movements detected and monitored with other techniques (GPS, UAV, INSAR, etc.). Thus, the applied methodology has allowed for the identification and quantification of changes in the topography, focusing on: (1) stable areas, evaluating how similar the generated model is to the reference model, and (2) active areas (cuts, waste dumps, etc.).

3.1 Data

To rebuild the stage 1, which reflects the topography of the open-pit mining during its exploitation, digital color aerial photographs captured in 2001 were used, provided by the "*Quiquenal*" project. This national scope photogrammetric flight was performed on behalf of the National Geographical Institute, and thanks to it, color photogrammetry frames were got at an approximate scale of 1:40,000 and a pixel size (GSD) between 56 cm and 1 m, depending on the areas (Instituto Geográfico Nacional, 2021).

The stage 2 represents the topography once the reclaim after the mining exploitation was carried out. To get this information, an ALS point cloud was used, acquired in 2011 by the National Geographical Institute. The ALS point cloud has a point density of approximately 5 points per square meter and a vertical accuracy of about 15 cm.

Stage 3 has been got from color digital aerial photographs captured in 2014, provided by the "National Aerial Orthophoto Project"(Instituto Geográfico Nacional, 2016).

3.2 Methodology

The workflow involved the following steps: (1) aligning the photographs, (2) inserting additional control points derived from the 3D georeferenced point cloud captured with ALS, (3) optimizing the camera parameters, (4) reconstructing the surface with a tiled model from the depth maps, and (5) sampling the mesh at points. The result was a georeferenced 3D point cloud, registered with the ALS-obtained point cloud.

Photogrammetric restitution was conducted using the SfM-MSV technique and AgiSoft PhotoScan Professional software (Agisoft LLC, 2016). The images were cropped to preserve the central pixel that coincided with the optical axis and the surface, and to mask the fiducial markers for processing. All the cropped images had the same pixel size, so that the software would process them with the same parameters.

The alignment process estimated the parameters of the internal and external camera orientation in the local coordinate system and correlated the images with each other. During this process, the model underwent linear transformation, including translation, rotation, and scaling. The SfM-MVS method was used to align the images, providing a scattered point cloud along with the relative position and orientation of the aerial photos.

To establish the Ground Control Points (GCPs), the point cloud derived from ALS generated in the PNOA project (Instituto Geográfico Nacional, 2021) was used. This 3DPC has an elevation accuracy of 20 cm and a point density of approximately 0.4 pts m^{-2}. However, because of the wide temporal interval between stage 1 (2001) and stage 3 (2014), some reference elements could only be identified approximately (e.g. crossroads, rocks, or building roofs), making the work difficult.

Control points (GCPs) were inserted in stage 1, which was, by far, the most challenging stage in terms of feature identification because of pixel size, topographical changes, and colors. Subsequently, all existing GCPs in stage 1 were attempted to be identified in the other stages. Although some of these points were successfully identified, changes in the terrain shape (vegetation, mining activity, etc.) prevented the identification of many GCPs, and therefore additional GCPs had to be inserted to improve the reconstruction process in the other stages. After the addition of GCPs, the camera parameters were optimized, and the error of each GCP was automatically calculated in meters and pixels. Points with unacceptable errors (e.g., 10 m) were reviewed and corrected.

The software then estimated the camera positions and calculated the depth information for each camera, generating a dense point cloud of the terrain surface with the MVS algorithm. After generating the point cloud, the reconstruction was visually inspected for significant errors.

Once the georeferenced point clouds were got, comparison, volume detection, and quantification were performed using the Difference of Dems (DoD) technique. The procedure involved the following steps: (1) exactly equal rectangular crop in the area of interest of the clouds to compare, (2) rasterization with a 1m point separation, (3) elevation difference of the rasterized points. Volume calculation was determined as the summation of the changes per cell surface, all being equal as they were rasterized.

4 RESULTS

Figure 1 shows the changes detected between the two stages, showing how there has been a decrease in altitude shown in blue in the quarry and a significant increase shown in red in the surroundings, corresponding to the waste dump or fill.

Figure 1, in which it is observed that the mode is close to 0.1 m, which is an indicator that the reconstruction has been successfully carried out given the error of the technique and data.

As seen in the volume calculations, the 3 areas in which there have been earthworks stand out again, which have already been addressed in the Methodology section. In addition, a new calculation has been made, in which the mobilized material in zone 3, corresponding to areas where instabilities are identified, has been studied. Comparing the models generated between 2001 and 2014, it has been determined that the thicknesses in that area reach almost 50 meters in the southern part of zone 3, and are between 15 and 20 meters in the northern part. Figure 2 shows the distribution of thicknesses throughout all of zone 3. A series of profiles of the obtained thicknesses have also been extracted, through three sections drawn in zone 3.

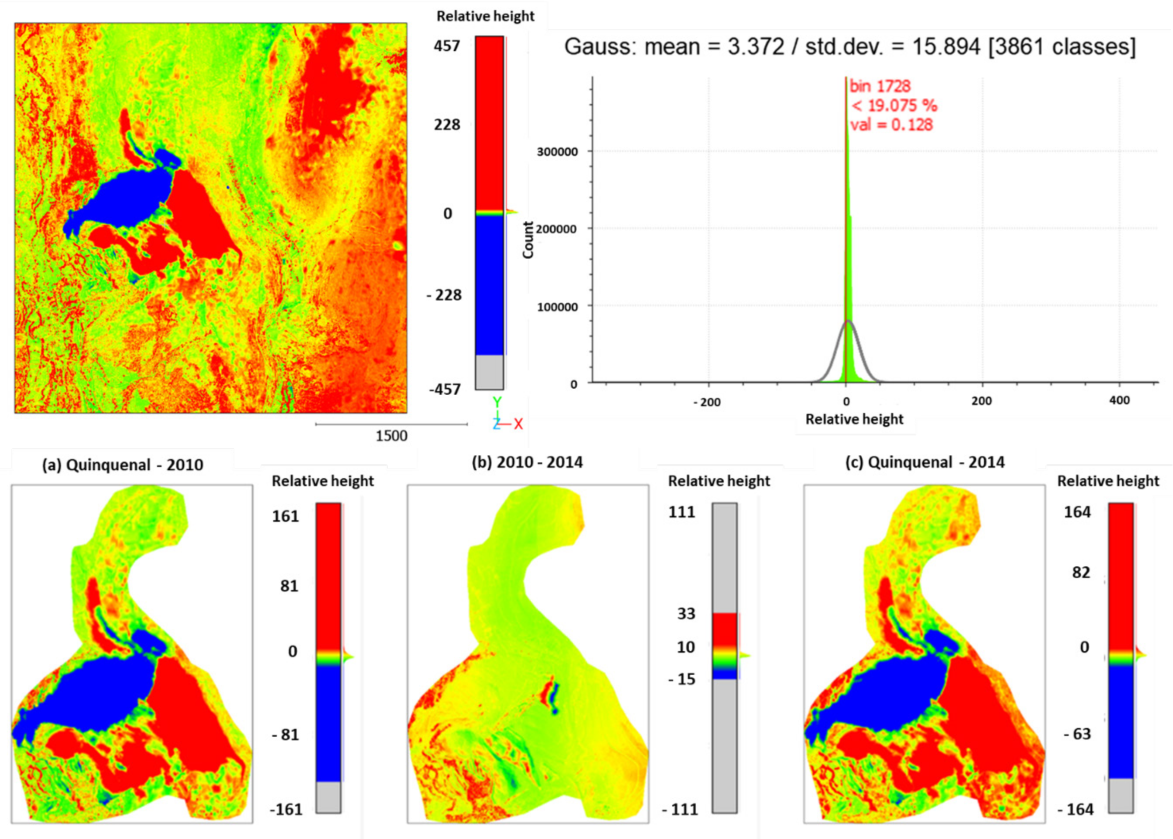

Figure 1. DoD of the Five-Year Flight and the 2010 LiDAR Flight. View of the changes detected in the selected region between each stage. Blue color represents extraction or decline in elevation, while red color represents accumulation of material or vegetation growth.

5 CONCLUSIONS

Using old aerial photographs has enabled the reconstruction of two Digital Elevation Models (DEMs) for three stages of Feixolín exploitation, using data collected and downloaded from public and freely accessible repositories, using a commercial software SfM-MVS. The obtained DEMs allowed a retrospective analysis of Feixolín exploitation in the long term, and thus to detect changes in its topography; to estimate the volumes extracted; to know the arrangement of man-made fills; etc. However, disclaimers were also identified in using this technique with historical images: (i) inability to choose the time interval, as it is conditioned by the availability of information; (ii) difficulties in reconstructing specific areas because of shadows and/or vegetation; (iii) medium-high errors in photogrammetric restitution, compared to those performed with photographs taken with other techniques (drones); and (iv) uncertainty in the quantification of volume (variations from 4% to 20%, for large and small scales, respectively).

The available historical data sets used to reconstruct the DEMs have contributed to the study of past processes, demonstrating that places that have aerial photographic archives can investigate the topography evolution or dynamics. The proposed methodology is an improvement of the use of traditional stereoscopes. The comparison of each DEM regarding a reference point allowed the detection of changes due to open-pit mining activities and the estimation of the extracted volumes. Thus, the results show that throughout the Feixolín exploitation (zones 1, 2, and 3), an estimated increase in volume of 10,829 m3 has occurred. This volume increase is mainly due to three factors: (1) mobilized material; (2) inherent errors in the technique; (3) vegetation growth; and (4) the degree of material compaction. In zone 3, where a landslide is located, the estimation of filler thicknesses reaches approximately 50 meters in the south (profile 3) and between 15 and 20 meters in the north (profile 1) (see Figure 2).

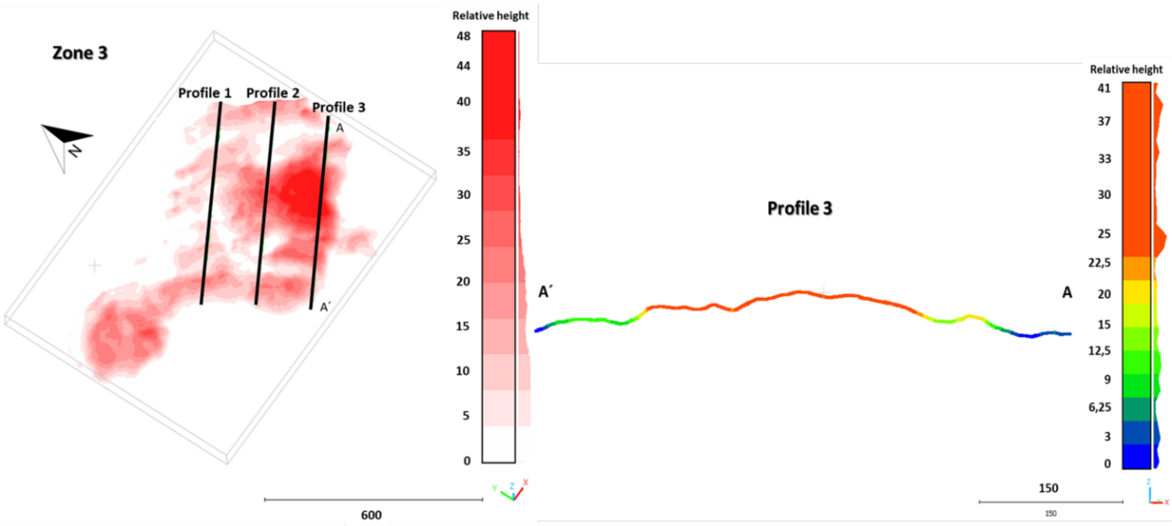

Figure 2. View of changes in zone 3 and tracing of profiles.

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