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MONITORING DEFORMATIONS IN THE E36 MINING PILLAR AT SALINA OCNA DEJ USING UAV EQUIPMENT

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Abstract: *Monitoring deformations in mining pillars in salt mines is crucial for detecting spalling, cracks, and distortions caused by internal pressures, with the aim of preventing mining accidents and maintaining structural integrity. At Salina Ocna Dej, annual measurements have not utilized drone technology, which was recently introduced in Romania. The measurements conducted with the DJI Phantom 4 Pro Plus drone in 2020 and 2024 provided essential data on changes in the mining pillar. In 2020, difficulties caused by air currents slightly affected the measurements, but by 2024, improved conditions allowed for more accurate results. The horizontal sections taken at various elevations revealed significant spalling and distortions, particularly on the eastern and western sides, with substantial rupture in the northwest corner and displacements on the northern side. Comparing the data from the two measurement sets showed a significant difference in precision, highlighting the need for regular inspections to prevent premature erosion and avoid accidents.*

Keywords: *drone measurements, point cloud, ground control points (GCP), errors, precision, pillar*

1. Introduction

Monitoring mining pillars in salt mines is crucial for detecting exfoliations, cracks, and plastic deformations caused by internal pressures [1]. This monitoring is essential to prevent mining accidents and ensure the structural stability of the entire complex. To effectively address any reductions in pillar overlap due to these issues, measurements should be performed at least semiannually or annually.

At Salina Ocna Dej, however, these measurements have traditionally been carried out only once a year or every two years. The introduction of drone technology for these measurements represents a significant advancement for this mine and is relatively new in Romania [2]. The initial use of drone technology for this purpose was conducted in 2020, followed by a subsequent measurement in 2024. This approach not only enhances the accuracy of the data collected but also improves the ability to monitor changes over time more effectively.

2. Flight plan

The DJI Phantom 4 Pro Plus drone was used, adapted for operation in underground environments where satellite systems and internet access are unavailable [3]. Due to these constraints, measurements cannot be performed as they are on the surface. Predefined flight paths could not be selected due to the small distance between mining pillars and the very low flight altitude, ranging between 4 and 7 meters. During the 2020 measurements, at altitudes between 5 and 7 meters, there was a high intensity of air currents within the mine, complicating the drone's maneuverability and requiring increased caution to avoid collisions that could

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damage the drone. Despite these challenges, there were two incidents where the drone collided with a mining pillar, resulting in damage to the propellers. Although the propellers were rendered unusable, the other components of the drone remained unaffected.

Due to the intense air currents, five batteries were fully utilized, resulting in a total flight time of approximately one and a half hours, with an actual working time underground of about three hours. In 2024, the measurements were much easier to conduct, as the air current intensity was significantly lower than in 2020. At an altitude of 6-7 meters, the drone was successfully maneuvered around the upper edges of the mining pillars without incidents similar to those in the 2020 flight.

Given the reduced air current intensity, the 2024 measurements were carried out using only two batteries, with a flight duration of approximately 35 minutes.

On-site, four square reference markers, established by the institution, were installed to obtain coordinates and altitudes. These markers, positioned over the topographical benchmarks in the mine, were visible in the drone's images and were essential for image post-processing.

Before each use, the drone underwent pre-flight checks and cleaning to ensure the proper functioning of all sensors, preventing operational errors that could endanger nearby personnel. Due to the dim lighting provided by flashlights and LED projectors, only the camera's protective filter was mounted on the drone to capture as much necessary information for subsequent processing. However, some images showed burnt areas when the drone flew toward the light source. This was unavoidable as no option has yet been developed for mounting on the drone to provide diffuse lighting with an intensity of at least 600 lumens, measured 6-8 meters from the drone, to prevent burnt areas in images and ensure proper functioning of proximity sensors.

3. Post-processing of data

The data processing was largely carried out in the same manner as the previous case study. However, the following modifications were made:

During the image alignment stage, a significantly larger number of key points and tie points were selected due to the low lighting conditions and the visible chromatic aberration in the images, as well as pixelation in certain cases (see Fig.1).

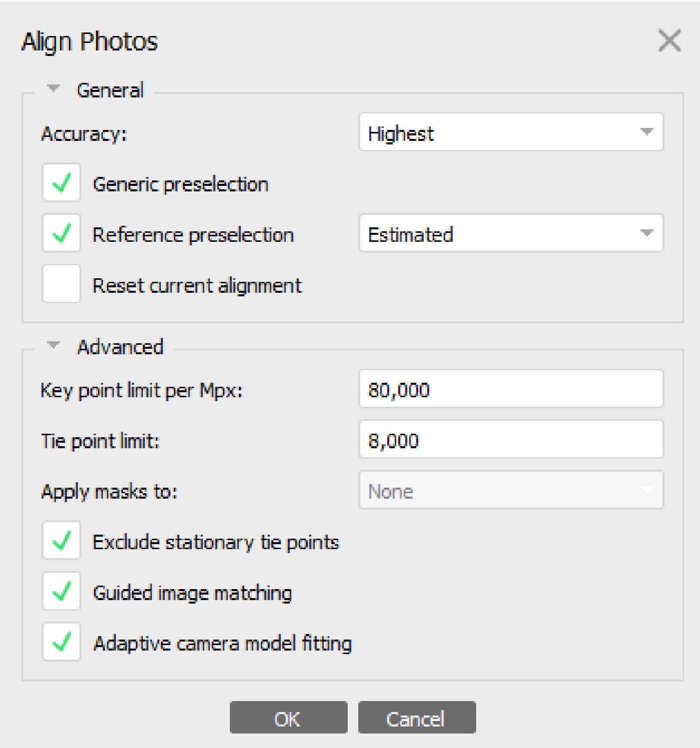

Fig. 1. Image Alignment Settings

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To ensure the accuracy of the 3D model, an error minimization technique using bundle adjustment was employed [4]. This method involves minimizing the differences between observed points and projected points, thereby enhancing the precision of the reconstructed model.

$$E = \sum_{i=1}^{N}[(x_i - \hat{x_i})^2 + (y_i - \hat{y_i})^2] \quad (1)$$

where:

E - is the total error function

(xi,yi) are the observed point coordinates

((x_i)̂, (y_i)̂) are the projected point coordinates

This is done using optimization algorithms, such as the Least Squares Method, to adjust projection and rotation parameters. Altitude adjustment was not performed in the altitude adjustment program because, underground, the drone does not have access to satellite systems and, therefore, the program installed on the control remote cannot detect the flying altitude. At best, the altitude in the EXIF data of the captured images only reflects the last known altitude of the drone.

After each adjustment of the GCP positions in the images, image alignment optimization was repeated. This process allowed for the reduction of errors associated with the GCPs and the entire point cloud. Although this process is very detailed, if the project does not require millimeter precision, repeated adjustments are not justified; that is, it is not necessary to adjust each GCP in the relevant images pixel by pixel.

The point cloud was generated through the 3D reconstruction of points from the aligned images. This forms the basis for the 3D model of the studied surface.

$$P = K \cdot R \cdot (X - C) \quad (2)$$

where:

P - represents the set of projected points.

X - represents the set of points in the real-world coordinate system.

C - represents the set of camera coordinates.

At first glance, the generated point clouds contain between 49 and 149 million points, which is enormous, as shown in Figure 2.

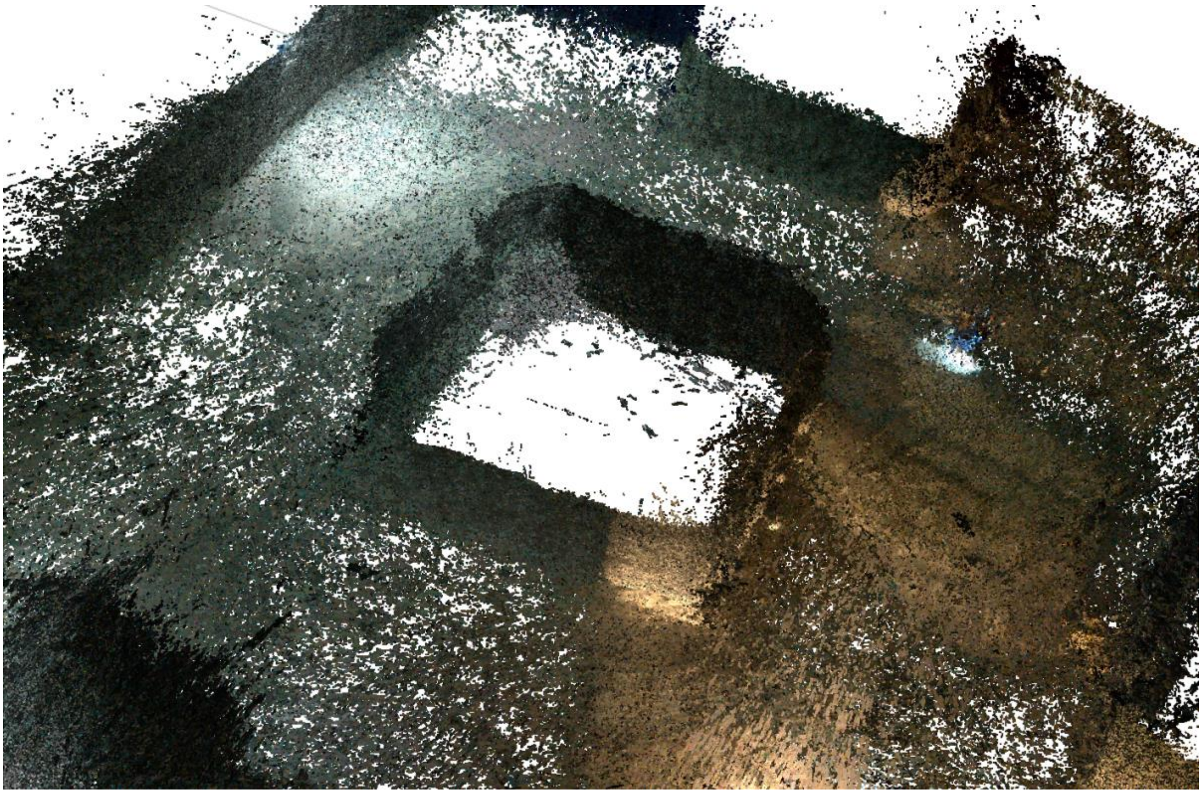

Fig.2. Pointcloud

Surface modeling and interpolation are performed to create a continuous representation of the studied surface. Interpolation algorithms, such as linear interpolation or kriging, are used to estimate unknown values between the measured points [5].

$$Z(x,y) = \sum_{i=1}^{N} \lambda_i \cdot Z_i \quad (3)$$

where:
Z(x,y) is the interpolated value at the point (x,y)
λi are the interpolation coefficient
Zi are the measured values of the points

During data processing, there were situations where the thickness of the contour of the mining pillar was excessive in some cases. Subsequent analysis revealed that some images had incorrectly placed GCPs (Ground Control Points) on the specified markers, leading to a phenomenon known as "lamination" or "exfoliation" of the point cloud. This phenomenon occurs when the quality of the photos used to generate the point cloud varies significantly. In areas where high-quality images were used, the point cloud was precise and well-defined. Conversely, images that were not correctly aligned for various reasons led to a decrease in the overall accuracy of the point cloud. This caused misalignments, aberrations, and dislocations of points relative to their correct positions in the final point cloud, as the post-processing software failed to correctly identify their positions. These issues required careful review and additional adjustments to ensure optimal accuracy in the final data obtained. (Fig. 3)

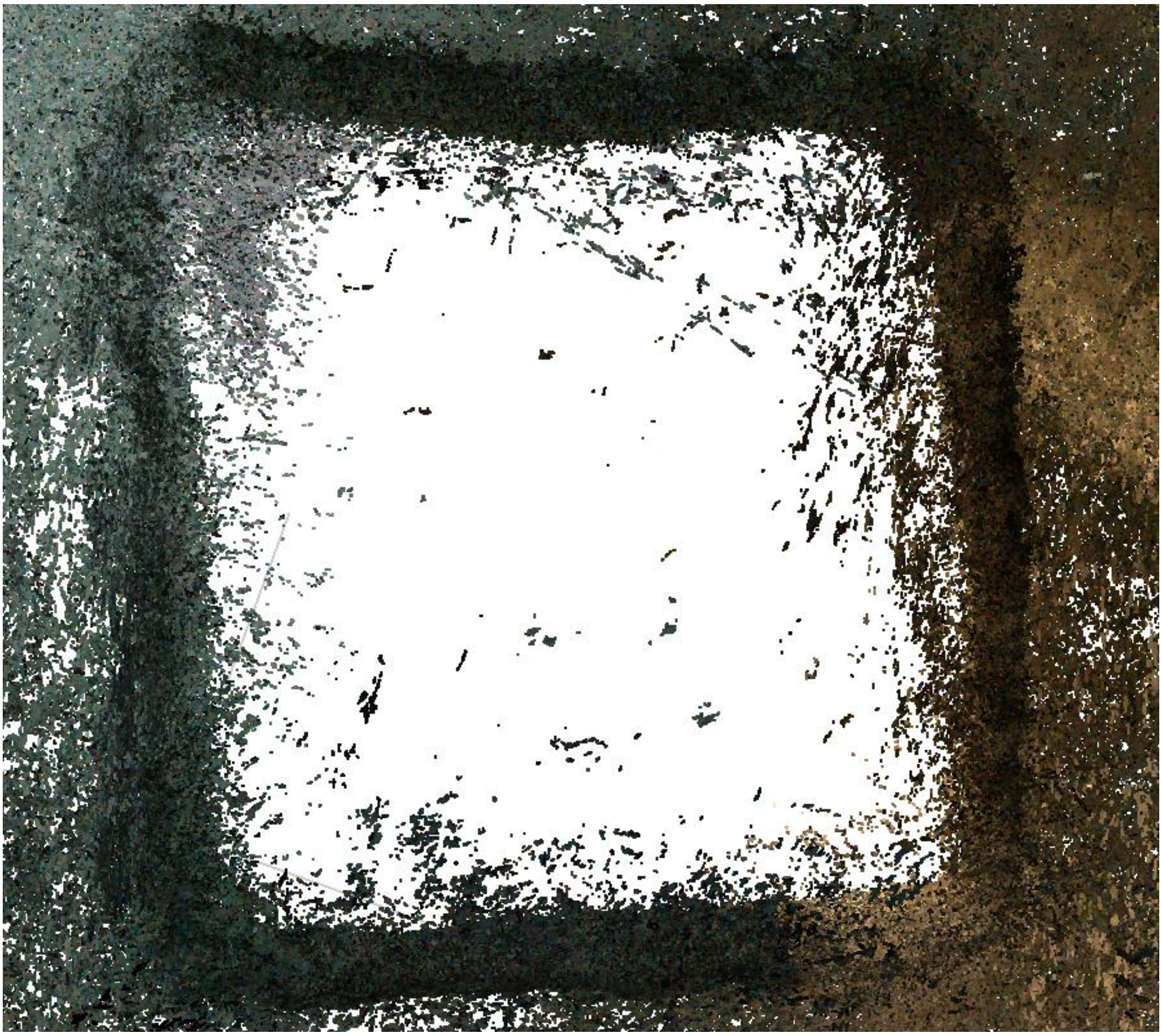

Fig. 3. Exfoliation of points in the unfiltered point cloud

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All irrelevant areas were removed, and the point cloud was cleaned using the filtering function available in the processing software. After applying these filters, the volume of the point cloud decreased significantly, reaching approximately 1.9 to 3.6 million points, with a "thickness" of the mining pillar contour of 5 to 10 mm. The elevation module was activated on the point cloud to verify the height of the mining pillar. Compared to 2020, in 2024, the generated point cloud extends up to the gallery ceiling, due to the reduced fluctuation and intensity of the airflow, which facilitated easier drone flight. (Fig. 4 and Fig. 5)

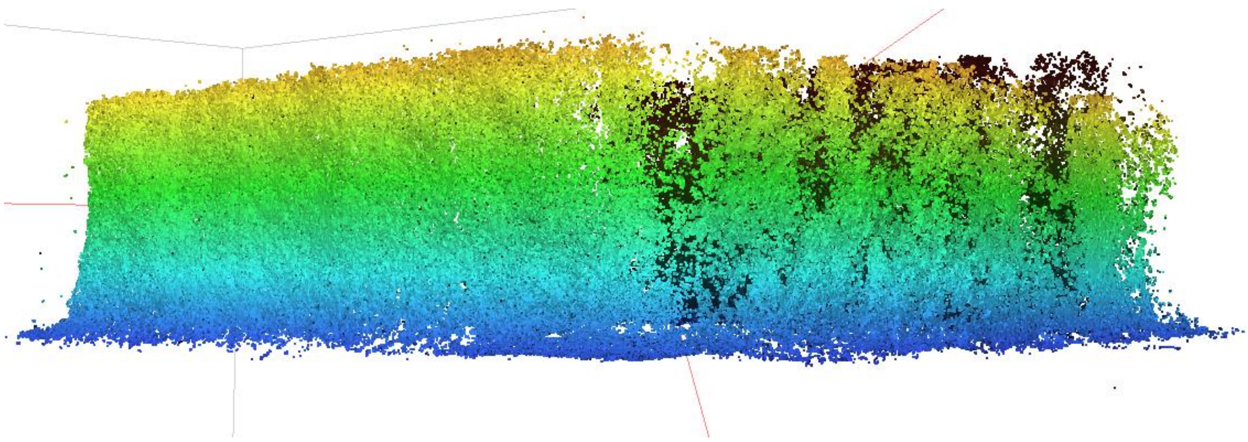

Fig. 4. Filtered point cloud 2020 (S-E corner view)

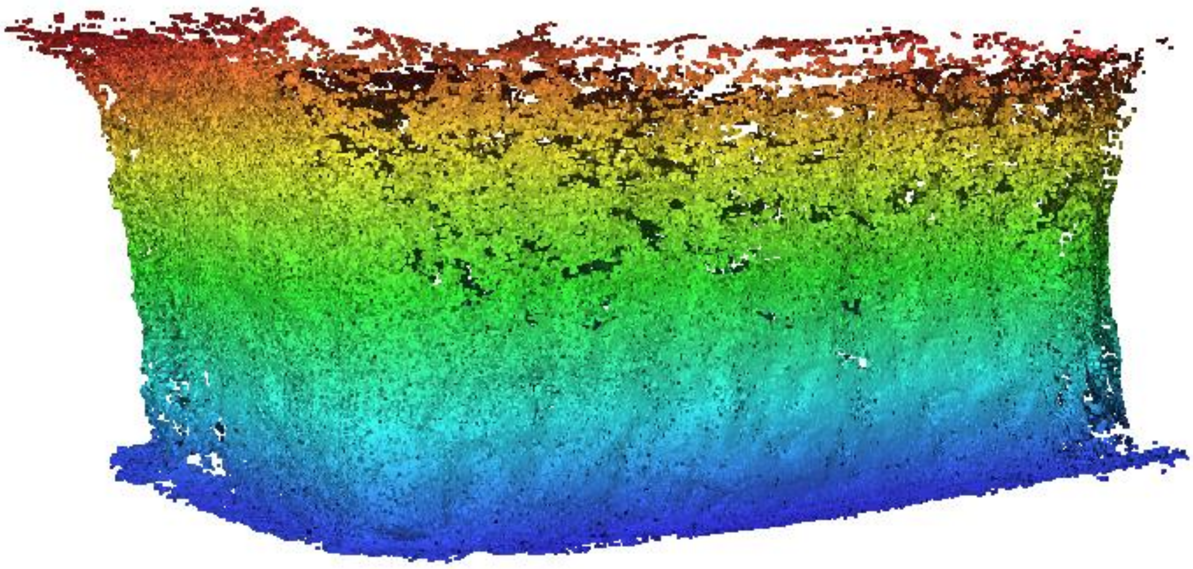

Fig. 5. Filtered point cloud 2024 (S-E corner view)

To verify the conformity and accuracy of the data in Metashape, processing verification reports were generated. These reports contain relevant information such as the camera position on the drone during aerial photography, the required overlap of images for correct point cloud generation, and the evaluation of GCP errors after updating the data according to imposed constraints. In our case, the camera rotation was not a relevant variable since the camera was fixed in a single position.

Based on the camera locations, the propagated errors are zero in both cases, as shown in Figure 6. The image overlap for proper alignment and compliance with the requirements was excellent. The propagated errors on the point cloud and 3D model show a slight difference: the point cloud from 2020 has an error of -2 mm on the top left to bottom right diagonal and +2 mm on the top right to bottom left diagonal (Fig. 7). In 2024, the propagated errors on the point cloud and 3D model are +4.8 µm on the top left to bottom right diagonal and -4.8 µm on the top right to bottom left diagonal (Fig. 8).

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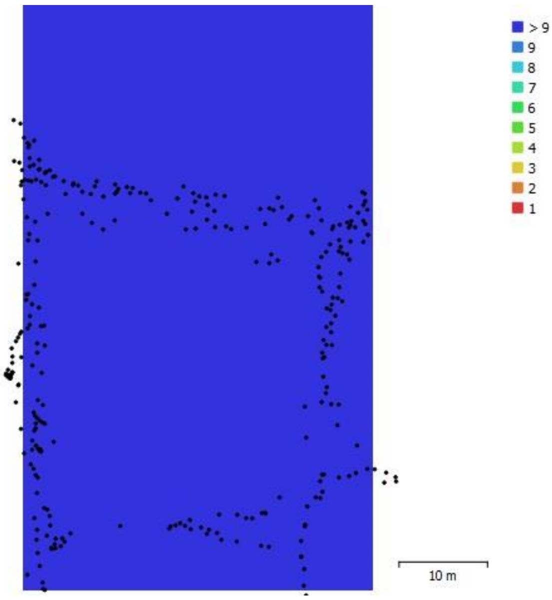

Fig.6. Report with Image Location and Overlap 2024

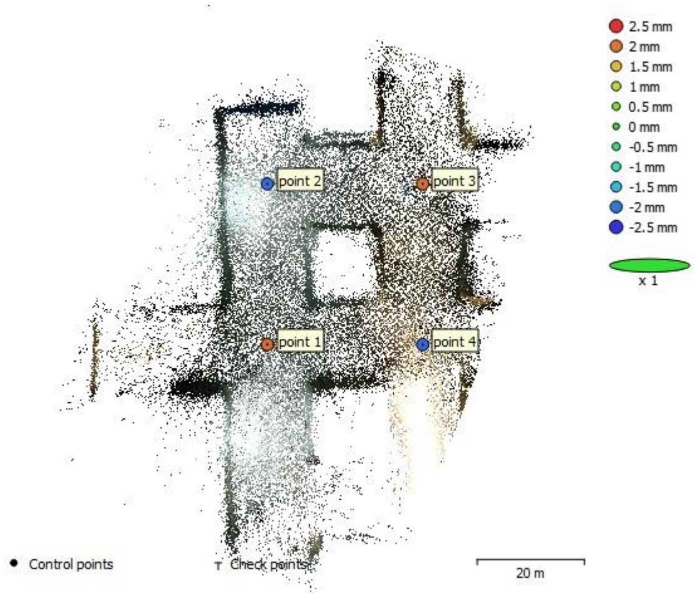

Fig.7. Propagated Errors on the Point Cloud with GCPs 2020

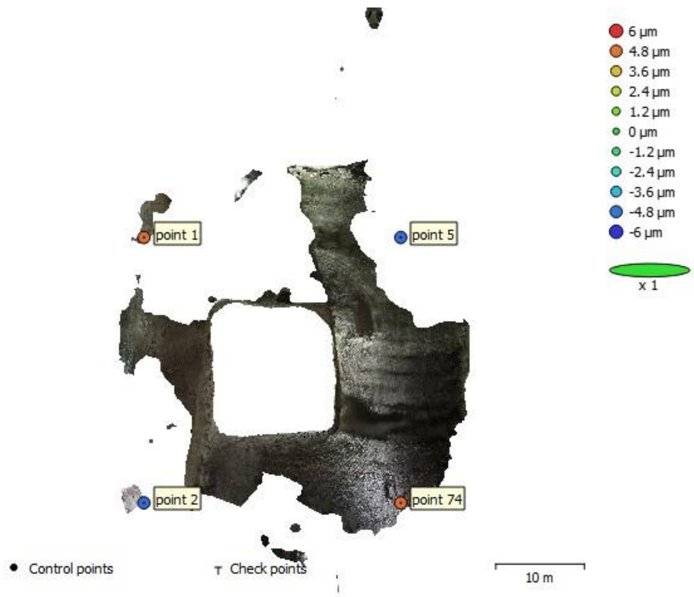

Fig.8. Propagated Errors on the Point Cloud with GCPs 2024

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The data generated based on the reports provide an initial confirmation of the correctness of the process and procedures, and implicitly the results obtained. The difference in precision between the two point clouds, namely ±2 mm in the initial measurements and ±4.8 µm in the 2024 measurements, is significant and cannot be overlooked under these conditions.

After generating and filtering the point clouds, they were exported in the Cloud Optimized LAZ format (.copc.laz) to be uploaded into Autodesk Recap Pro. Within this program, the point clouds were converted from the .copc.laz format to the .rcs format, which is recognized by AutoCAD. This allowed for the effective verification of changes over time to the mining pillar by comparing the data obtained from the two measurement sets.

4. Generating Sections and Data Verification

The point clouds were imported into AutoCAD Civil 3D using the POINTCLOUDATTACH command, with each dataset placed on separate layers [6]. These point clouds were aligned according to the fixed local coordinates specified in the .rcs files.

The process began by creating a horizontal section of the mining pillar using the SECTIONPLANE command. The elevations at which the horizontal section was to be made were established, and the desired section thickness was specified. (Fig.9. and Fig.10.)

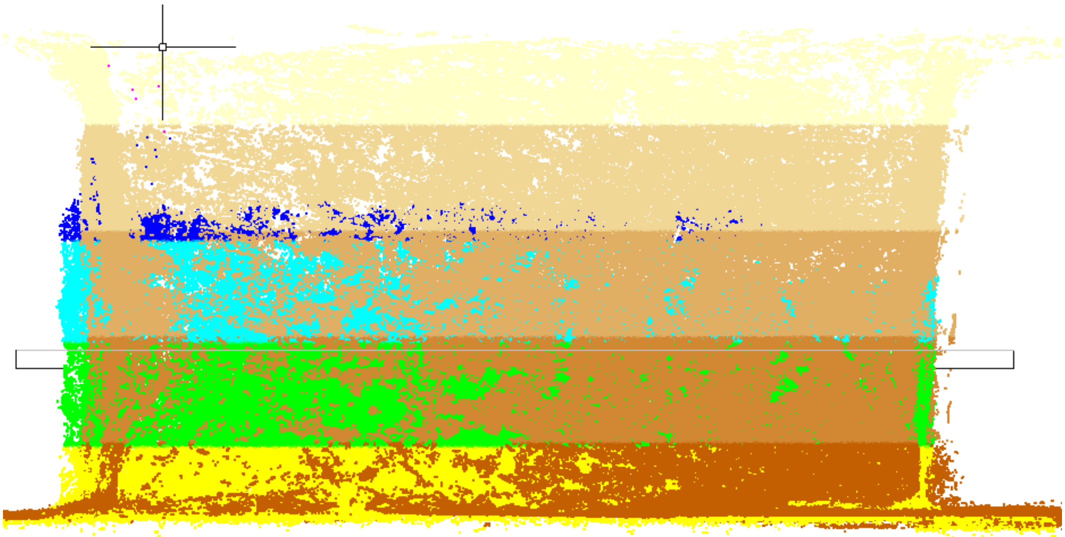

Fig.9. Side View - Point Clouds Where the Section is Made

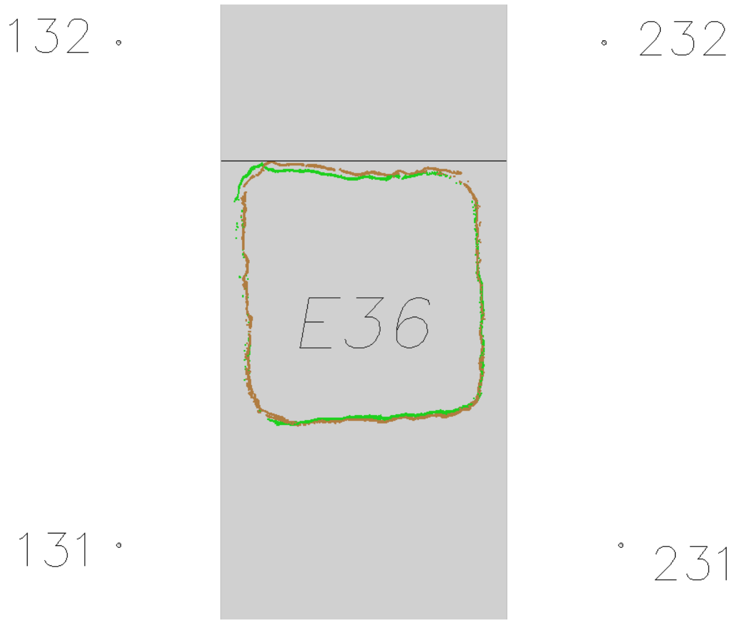

Fig.10. Cross-Section of Point Clouds from 2020 and 2024

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Horizontal sections were created at various elevations: 158m, 159m, 160m, 161m, and 161.5m. Sections above these elevations were not performed because, at two of the sides, the 2020 measurements did not provide sufficient information to generate a complete point cloud up to the gallery ceiling, as mentioned in the introduction of this case study.

Based on the horizontal sections, with a thickness varying between 0.10 and 0.50m, a contour was created using a polyline. This allowed for precise identification of changes over time to the mining pillar.

5. Data interpretation

The sections previously created provided the basis for outlining the interior contours, which allowed for precise visualization of the changes over time [7]. The blue line represents the interior contour of the pillar from the 2020 point cloud, while the red line represents the interior contour of the mining pillar from the 2024 point cloud, as shown in Figure 11.

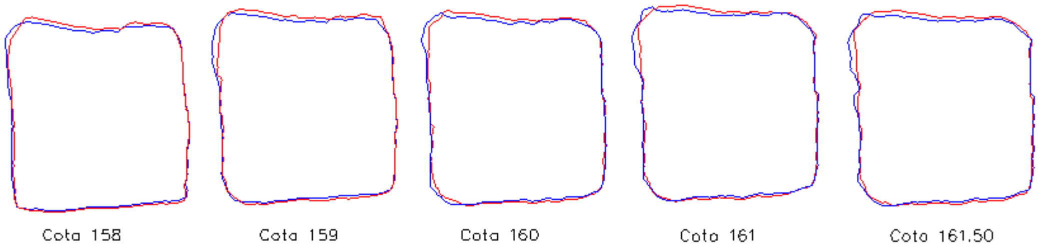

Fig.11. Overlay of Horizontal Section Contours 2020-2024

To verify the pillar's contour and section against the database held by the salt mine, the three contours were overlaid at the 158m elevation: the contour from the mine, obtained using a total station or theodolite, and the two contours derived from drone measurements processed into point clouds.

It is observed that the position of the mining pillar is generally consistent with that in the mine's archive, but there are differences in its shape, reflecting deformations that have occurred over the past four years. The brown line represents the E36 pillar contour according to the coordinates specified by Salina Ocna Dej. This is overlaid on the other two sections based on the 2020 and 2024 measurements, as shown in Figure 12.

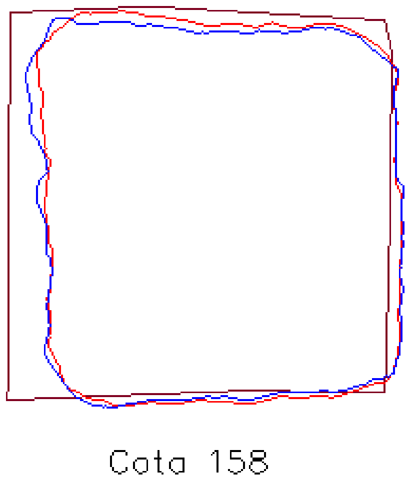

Fig.12. Overlay of Horizontal Section Contours 2020-2024 vs. Mine Archive

6. Conclusions

Based on the above points, the following conclusions can be drawn:

- Enhanced Detail with Drone Measurements: Traditional measurement equipment cannot match the level of detail provided by drone-based measurements and the generated point cloud. The advanced technology of drones offers a more comprehensive and precise depiction of mining pillars.

- Efficient and Precise Surface Analysis: Differences in the surface area of the mining pillar, as illustrated in tabular form, are detected more quickly, easily, and accurately using drone measurements compared to alternative methods. (See Table 1.)

Table 1. Overlap of Horizontal Section Contours: 2020-2024 vs. Historical Archive

The elevation at which the section was made (m)	**Year of UAV measurements**	
	2020	**2024**
	Measured area per section (m^2)	
158.00	199.088	200.872
159.00	198.180	201.454
160.00	198.564	199.796
161.00	201.593	202.754
161.50	200.940	202.330

- Significant Deformations Observed: The measurements indicate substantial exfoliation and degradation on the eastern and western sides of the mining pillar. This highlights the effectiveness of drone technology in detecting such structural changes.
- Notable Damage in the Northwest Corner: A more pronounced rupture was observed in the northwest corner of the pillar, emphasizing the importance of detailed analysis in identifying critical areas of damage.
- Displacement on the Northern Side: The northern side of the pillar shows notable displacement due to cracks that have developed over time, leading to plastic deformation of the structure.
- Need for Regular Inspections: Observations, measurements, and checks underscore the necessity for increased vigilance. Regular inspections, at least annually, are crucial for addressing premature erosion and preventing potential mining accidents [8]. Ensuring ongoing monitoring and maintenance will help maintain the structural integrity of the mining pillars.

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