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MONITORING AND TRACKING THE LONG-TERM STABILITY OF THE SUBSIDENCE CONE AT SALINA OCNA DEJ

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Abstract: *The analysis of the subsidence cone at Salina Ocna Dej involved modern measurement techniques, including drones, to evaluate terrain changes and generate a detailed 3D model. Data collection occurred in two stages, in 2021 and 2022, utilizing drones to capture a large number of high-resolution images (5472x3648 pixels) [1], resulting in a significant volume of data. These images were processed using specialized software to create a 3D model, employing advanced alignment, data fusion, and interpolation techniques. The results demonstrated that using drones offers considerable benefits over traditional methods, including increased accuracy and reduced time and resource consumption [2], with minimal errors recorded at just 0.7 mm. The project emphasized the importance of adapting initial plans to field conditions and considering weather forecasts to prevent accidents. Post-processing the data enabled clear delineation of the subsidence contour and slope angles, facilitating their integration into the analysis of other mining activities in the region. The generated 3D model serves as a reference for monitoring subsidence evolution and assessing risks to nearby residences. Continuous measurement and constant monitoring of the subsidence cone are essential to prevent potential future damage caused by slope instability and erosion.*
Keywords: *drone measurements, spatial data, pointcloud, 3D model, orthophoto, site plan, errors, precisions*

1. Introduction

The role of monitoring the subsidence cone at Salina Ocna Dej, Mina Ferdinand (23 August), is to track land movements and slope stability. On January 14, 1998, the failure of safety pillars and the rock and salt ceiling caused a significant collapse between the Csicsiri mine and Chamber III of the Ferdinand/23 August mine. Since then, the subsidence cone has continuously changed its geometry, with repeated topographic measurements indicating active movements.

Previously, measurements were conducted using traditional equipment without precise markings in the field. Therefore, it was decided to use a point cloud obtained through drone photogrammetry to fully determine the surface of the subsidence cone. This method provided a detailed geometric image and a more accurate radiography of the dynamic phenomena in the area.

Drone measurements represent an innovation for Salina Ocna Dej and other salt mines in Romania. Two drone surveys were conducted in 2021 (the first) and 2022 (the second).

2. Description of the field work method

In 2021, based on observations from online maps [3], it was decided to position a maximum of 10 ground control points, as shown in Figure 1, marked with 100x100 cm signs, for drone flights at altitudes between 50-80 meters.

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Fig. 1. Planned positioning of ground control points – year 2021

On the day of the site visit, it was necessary to reassess the placement of the control points because the terrain characteristics were not accurately reflected on the online maps, requiring repositioning due to access difficulties, as shown in Figure 2. In 2022, 13 GCP's were placed, 6 of which were in the subsidence cone area and the rest in the area of houses affected by subsidence, as shown in Figure 3. These points were marked with 100x100 cm signs for flights at altitudes between 60-90 meters.

Fig. 2. Actual positioning of ground control points - 2021

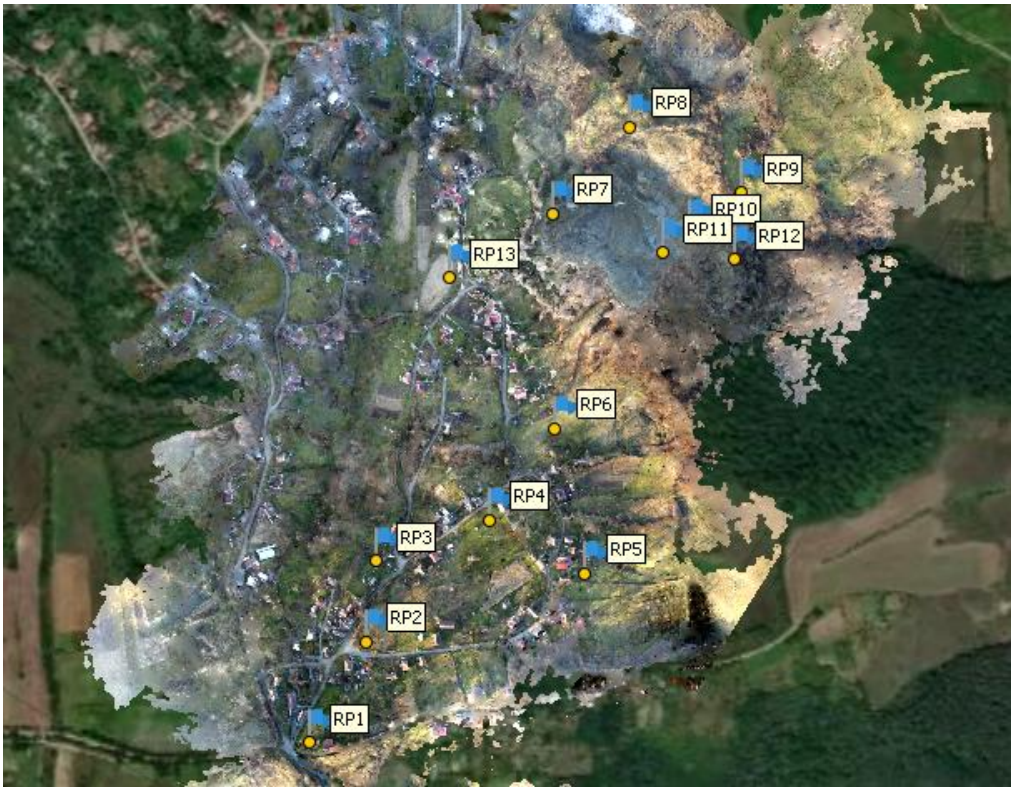

Fig. 3. Actual positioning of ground control points – 2022

The positioning of markers and measurement of control points required climbing equipment due to the crumbly terrain. The noise from the hammer caused minor soil collapses on the southern slope. During the first drone survey, 50x50 cm markers were used instead of the planned 100x100 cm due to the reduced flight altitude. These markers were square and in black-and-white for easy identification during post-processing.

Topographic measurements of the ground control points were conducted with a dual-frequency GPS station, utilizing the Rompos system and the Stereographic 70 System. The measurement conditions were excellent, although one point could not be measured due to its restricted position. In total, 8 control points were measured.

During the second measurement in 2022, topographic measurements were performed with a Trimble R6 dual-frequency GPS station under favorable atmospheric conditions, with a layer of fog at altitudes of 30-50 meters. For aerial photogrammetry, a DJI Phantom 4 Pro Plus drone was used, with a planned flight path ensuring a minimum 50% overlap. The clouds above the subsidence cone provided beneficial diffuse lighting for data capture.

The drone flight was conducted in three stages to obtain an accurate 3D model of the funnel. Batteries were changed every 20 minutes, with a total flight duration of approximately 60 minutes. The maximum altitude relative to the ground was 30 meters, with varying flight heights to capture detailed images of the target area.

3. Data post flight processing

Following the drone flight in 2021, a photographic dataset comprising 893 images was acquired, totaling 7.59 GB. The images, with a resolution of 5472x3648 pixels and good clarity, were crucial for generating the 3D model. These images, combined with ground control points whose coordinates were determined using a dual-frequency GPS station, formed the foundation of the work.

From the 2022 flight, 1587 images were collected, amounting to 12.9 GB. These images also had a resolution of 5472x3648 pixels and good clarity, significantly contributing to the creation of the 3D model of the subsidence cone.

The data processing was performed using Agisoft Metashape software, which is instrumental in creating the point cloud, 3D model, digital elevation model, and orthophoto map [4]. The images were loaded into a new workspace with an approximate location in the WGS84 coordinate system. For consistency with other measurements, the images were converted to the national Stereographic 70 coordinate system.

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Fig. 4. Image Captured by DJI Phantom 4 Pro Plus Drone – 2021

Fig. 5. Image Captured by DJI Phantom 4 Pro Plus Drone – 2022

Data alignment and fusion algorithms were crucial in this process [5], allowing for the integration and adjustment of data from multiple sources. Aligning images captured by the drone involved determining relative positions by identifying common points and calculating the necessary transformations for accurate overlay.

During the image alignment stage, various levels of precision were tested to assess their impact on the final results. It was found that a medium processing precision was sufficient, as it did not significantly affect the quality of the work but reduced the overall processing time.

Key settings such as "Key Point Limit" and "Tie Point Limit" are essential for defining the maximum number of key points and tie points considered in each processing stage. These adjustments influence the accuracy of image alignment and the time required for it. Selecting the "Adaptive Camera Model Fitting" option allows the software to detect and correct optical distortions based on the camera model information from each image's metadata, ensuring accurate interpretation of each image's geometry.

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Data alignment and fusion algorithms are fundamental for drone measurements, enabling the integration and adjustment of data to create precise and detailed 3D models. These algorithms utilize feature detection and matching, transformation estimation, weighting methods, interpolation and extrapolation, and least-squares adjustment to ensure accuracy and reliability of the collected data. The application of these techniques across various fields, from cartography to infrastructure inspections, demonstrates their versatility and importance in modern geospatial analysis [6].

In the subsequent step, the coordinates of the ground control points, determined with the dual-frequency GPS station, were imported. The automatic marker detection function was used to identify markers in images, reducing the work time and ensuring greater accuracy. Incorrectly detected markers or those with deviations from the actual ground markers were manually checked and removed. Each identified marker was associated with the corresponding coordinates, imported through the "Import Reference" function, specifying the relevant columns for name, East, North, and altitude of the ground control points.

With the 8 ground control points finalized, the entire set of images was optimized relative to these points. This process involved deselecting images and selecting ground control points to make the necessary adjustments in the software's reference panel. Additional corrections were applied, and the model was adjusted to the characteristics of the camera used for photography.

In the next step, the point cloud was generated (see Fig. 6 and Fig. 7), establishing parameters for noise filtering in the images and the targeted quality for creating the 3D model. This operation required several hours of processing due to the large volume of images and the computational resources used. To execute this step, it was essential to have at least 150 GB of free space on the computer's hard disk.

Interpolation and extrapolation are fundamental mathematical techniques in processing and analyzing geospatial data obtained from drone measurements [7]. These techniques enable the generation of estimates for unknown points based on a set of known points, enhancing the accuracy and completeness of digital models.

Interpolation is the process of estimating values for unknown points situated between known points. This method provides detailed information about areas that have been surveyed, filling gaps within the existing data set.

Extrapolation is used to extend geospatial models beyond the range of the collected data. For instance, if a drone captures elevation data for a portion of a terrain, extrapolation can estimate elevations for adjacent, unknown areas, thereby aiding in the overall planning and analysis of the terrain.

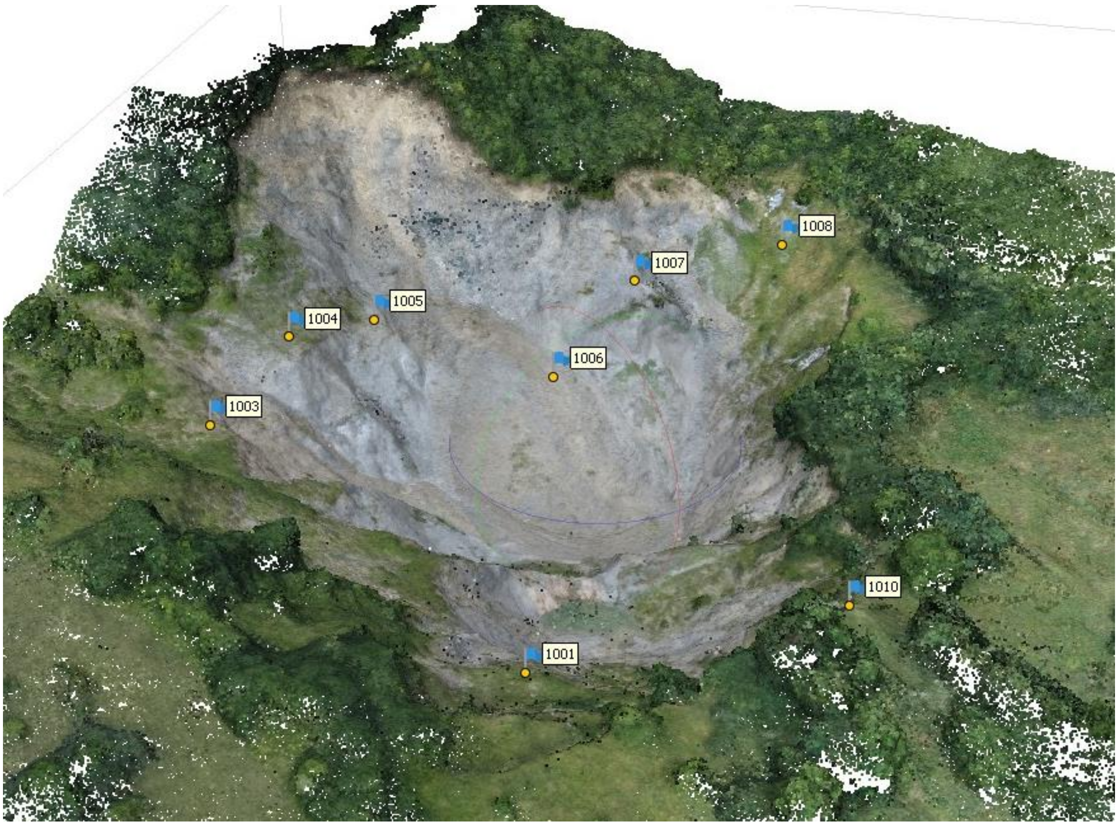

Fig. 6. Point Cloud and Ground Control Points – 2021

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Fig. 7. Point Cloud and Ground Control Points – 2022

After generating the point clouds, Digital Elevation Models (DEMs) of the terrain were created to accurately depict level differences and determine the depth of the subsidence cone (see Fig. 8 and Fig. 9). These models provide a detailed view of the terrain changes and help in understanding the subsidence phenomenon.

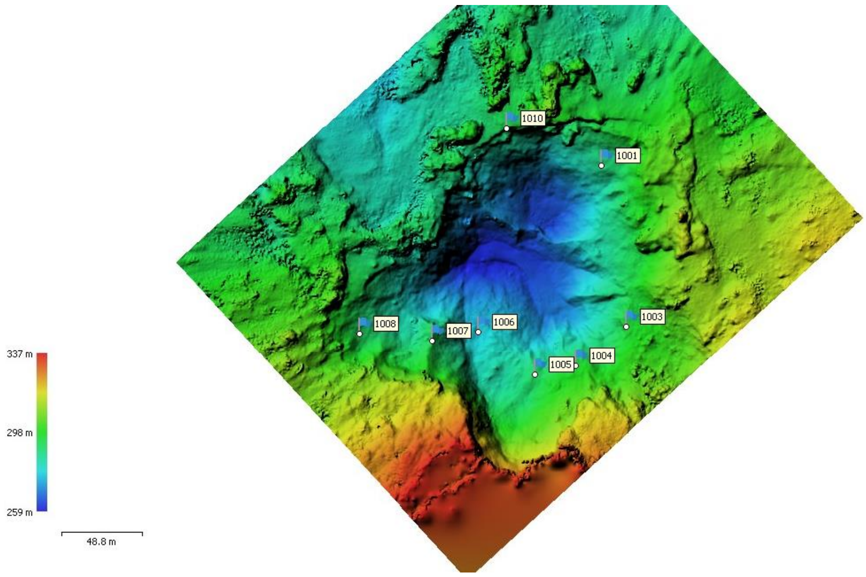

Fig. 8. DEM – 2021

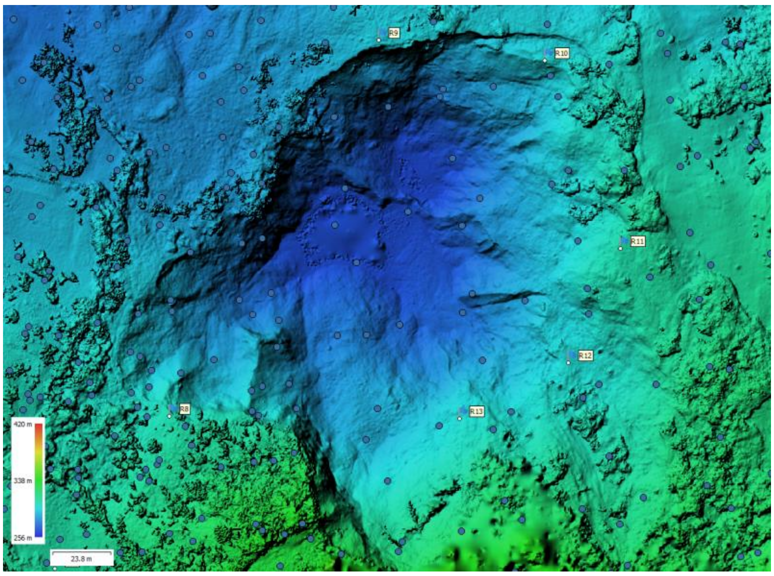

Fig. 9. DEM – 2022

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The next step was to generate the 3D model of the subsidence. It was decided to filter out vegetation to obtain a clearer view of the shape of the subsidence.

The final step involved generating orthophotos in the Stereo70 reference system. This was done to ensure compatibility with the point clouds and to allow their use in other processing programs for further verification of the subsidence area. The orthophotos will facilitate future comparisons with subsequent measurements (see Fig. 10 and Fig. 11).

Fig. 10. The central area shows the orthophoto overlaid with the map provided by the software – year 2021

Fig. 11. The sinkhole section of the orthophoto – year 2022

Data processing in AutoCAD was conducted in stages to examine various aspects of the sinkhole [8].

Initially, the data exported in .LAZ format were converted in ReCap Pro, transforming them into .RCS files recognized by AutoCAD. This step was essential to prevent AutoCAD from freezing, as it cannot handle millions of points without performance issues.

The newly created files were imported onto the coordinates given in the Stereo70 reference system on separate layers using the POINCLOUDATTACH function. To create longitudinal sections in the North-South and East-West directions (Fig. 12 and Fig. 13), the latest orthophoto was imported using the MAPIINSERT function. This allowed the orthophoto to be attached in AutoCAD and overlaid with the point clouds.

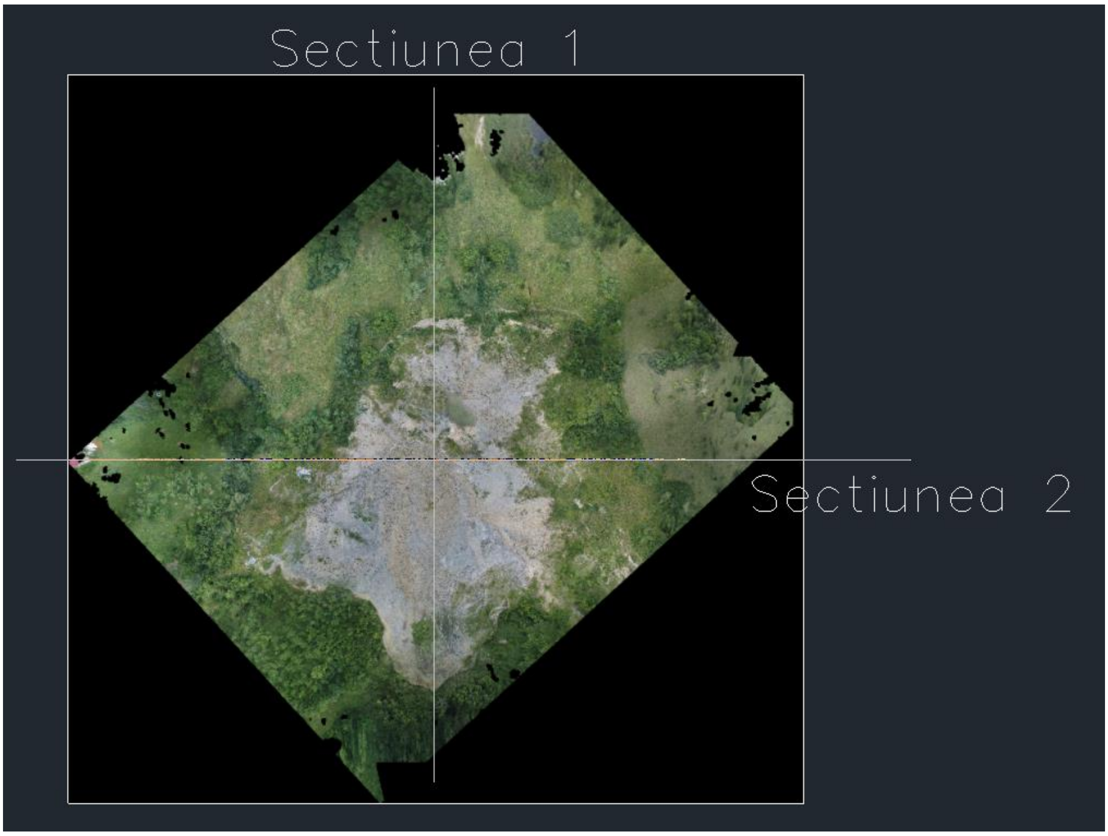

Fig. 12. Sections in the sinkhole area – ortho2021 – year 2021

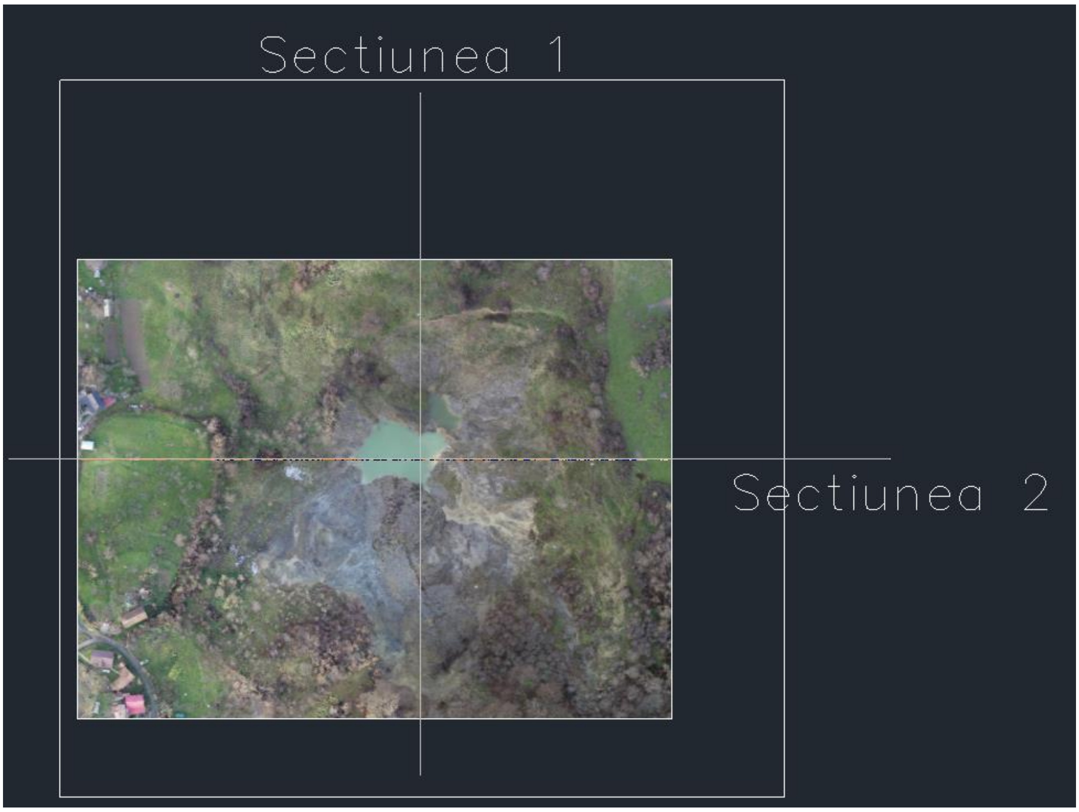

Fig. 13. Longitudinal Sections in the Sinkhole Area – Ortho2022 – Year 2022

The next step was generating the two longitudinal sections. By adjusting the North and East coordinates for these sections, areas with frequent sinkhole occurrences were observed and identified.

Based on the point clouds, areas that had undergone the most deformation were identified. This was due to the fact that during this time period, tens of cubic meters of soil had detached from the slope as a result of precipitation and the very steep embankments.

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4. Results obtained

The position of the contour line from 2011 was determined based on the placement of a benchmark at the edge of the sinkhole during the measurements. The broader limits from 2011 may be attributed to the benchmark not being placed exactly at the break line, possibly for safety reasons. The contour from 2021 was determined directly from the 3D model created by Agisoft Metashape, thus eliminating the positioning error from 2011. However, the 2021 processing might have errors due to the lack of visibility of the break line, obscured by vegetation on the edge of the sinkhole. These issues were largely resolved using Civil 3D software by rotating the point cloud and delineating the contour accordingly.

Overlaying the sections on the orthophotoplans from 2021 and 2022 shows that rainfall no longer infiltrated the ground as it did in previous years. Instead, a second lake formed over approximately one year. This larger water accumulation, verified through point clouds and contour lines in that area, demonstrated that its depth ranges from 4 to 7 meters. The following describes the results based on a longitudinal profile created through this area to track the behavior of the slopes.

In 2022, real-time field measurements revealed the subsidence of a portion of the slope, considering that shortly before this phenomenon, a GCP marker had been placed in that area.

Finally, the two point clouds will be compared based on the two longitudinal profiles created for the years 2021 and 2022 (Fig. 14, Fig. 15, and Fig. 16). The magenta line represents the profile based on measurements from 2021, while the white line represents the profile based on measurements from 2022.

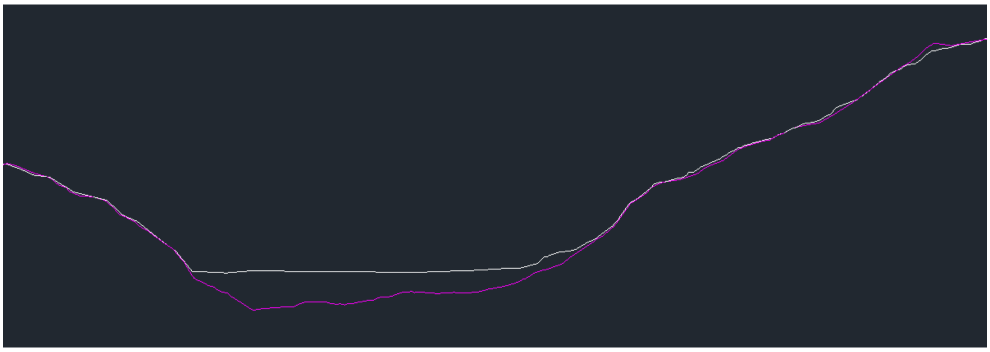

Fig. 14. Section 2 in the subsidence cone area – year 2022

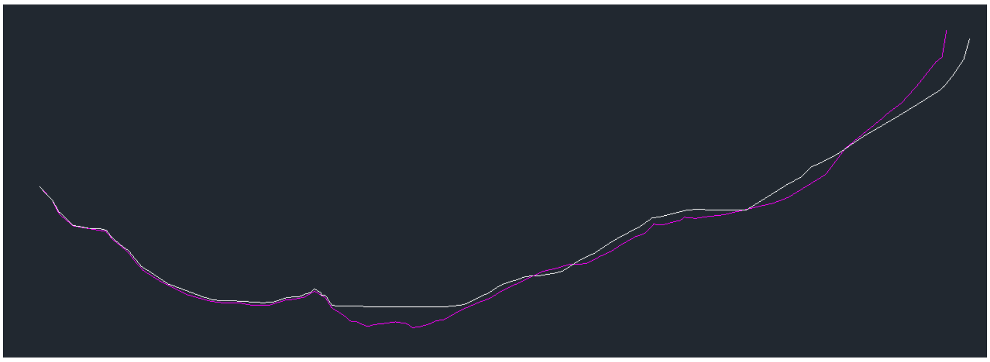

Fig. 15. Section 1 in the subsidence cone area – year 2022

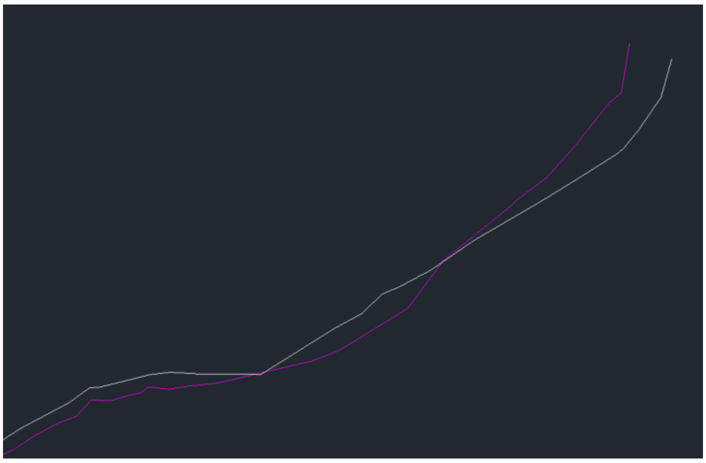

Fig. 16. Section 1 in the subsidence cone area, Southern part – 2021-2022

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Based on multiple profiles, it can be observed that over the course of a year, rocks with inclinations of at least 39 degrees, and in some areas even 50 degrees, have detached from the southern slope. Due to precipitation, these rocks have eroded, and along with the vegetation covering them, they have caused collapses, leading to changes in the geometry of the entire subsidence cone (Fig. 17).

It was also noted that the slopes are beginning to stabilize at an angle of approximately 32 degrees. The magenta line represents the profile section based on measurements from 2021, while the white line represents the profile section based on measurements from 2022.

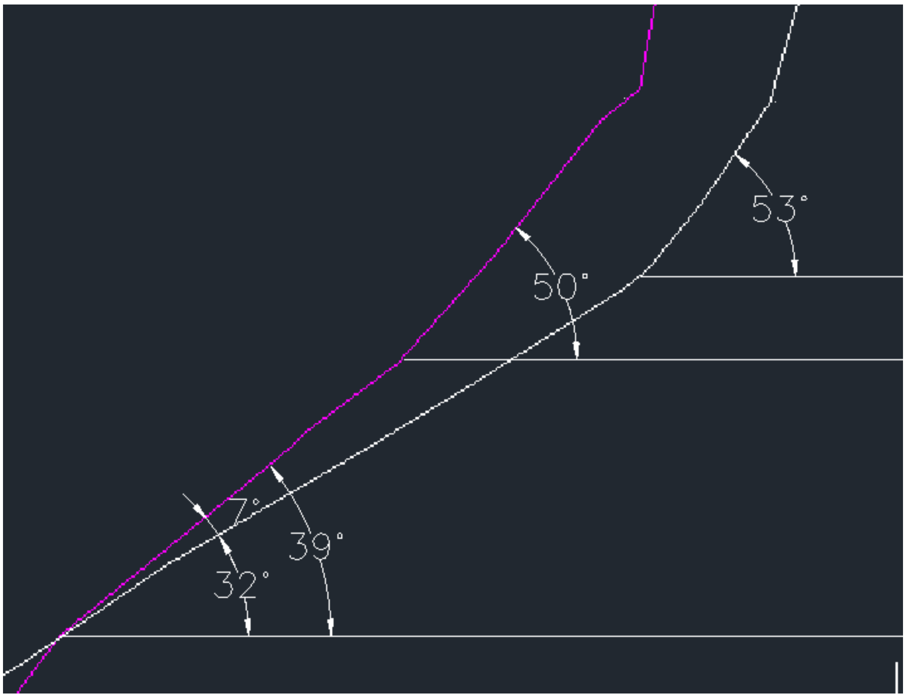

Fig. 17. Section 1 Southern Part – Slope Inclination – 2021-2022

The next step performed on this dataset was the verification of the sinkhole perimeter by overlaying the two contour outlines based on the two datasets. (Fig. 18.)

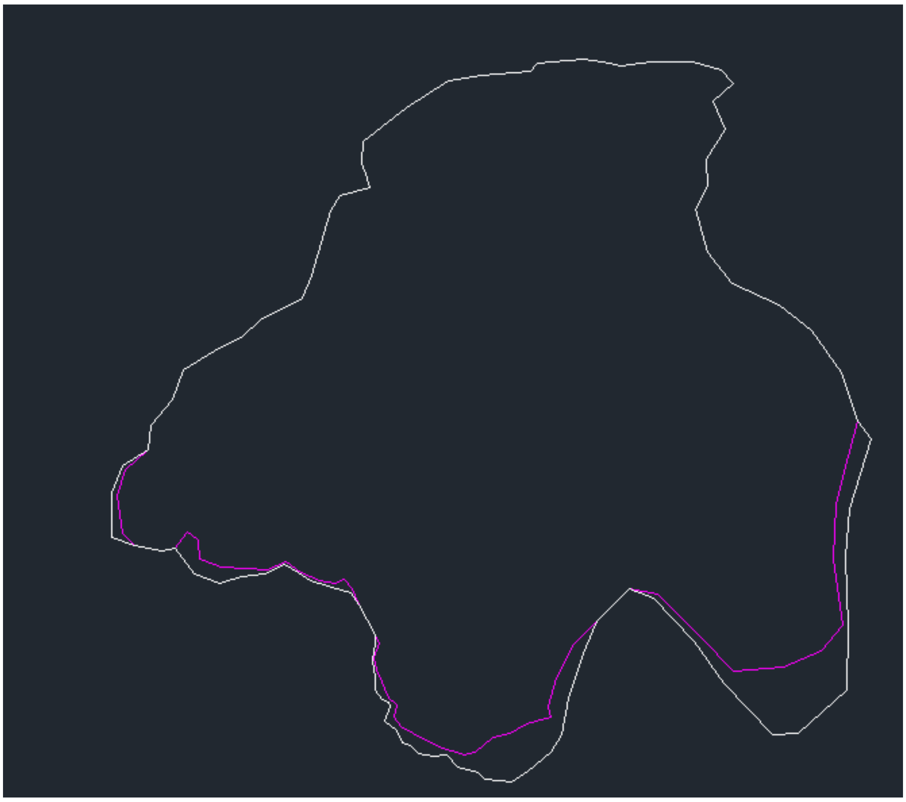
Fig. 18. Sinkhole Contour – 2021-2022

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The contours were created for the sinkhole perimeter areas in such a way that they represent the boundary of the subsidence zone across the entire surface of the sinkhole.

It was observed that the most significant issues are in the southern part of the sinkhole, where the instability of the terrain has caused an increase in the boundary of the sinkhole due to displacement from the slope. This has resulted in a 6% expansion of the sinkhole perimeter over the course of one year. While this could potentially be a mere coincidence due to unfavorable weather during this period, it is clear that ongoing monitoring is necessary to facilitate stabilization efforts and ensure the safety of the local residents.

Based on the analysis of the two overlaid contours with the point clouds and orthophotoplan, it was observed that the distance between the edge of the contour and the nearest building to the sinkhole is 58.7 meters, approximately 1 meter closer than in 2021.

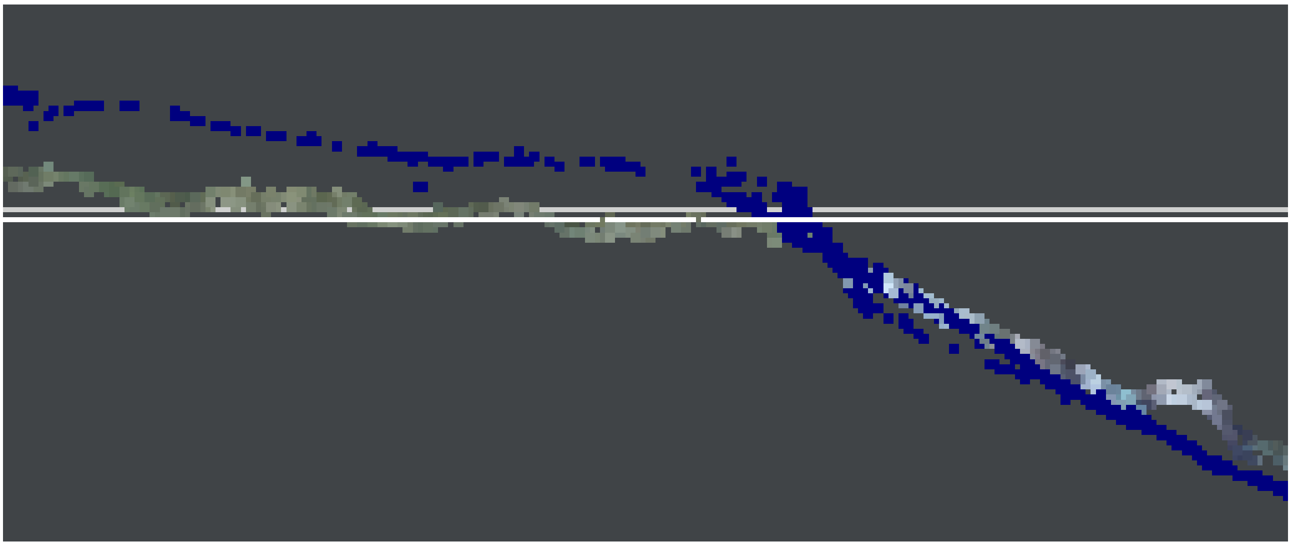

Fig. 19. Western Slope – 2021-2022

5. Conclusions

Based on the measurements taken, several important conclusions can be drawn: it is essential to have detailed knowledge of the work objective, including its limitations and strengths, to achieve the proposed goals. It is necessary to adapt the plans developed in the office to the conditions on the ground.

Using drones for measurements provides significant benefits compared to traditional methods, offering a larger and more accurate dataset with reduced time and labor costs and increased precision. The errors recorded in this work were only 0.7 mm.

Weather forecasts must always be considered, avoiding flights in strong winds or precipitation to prevent material damage and potential injuries to people or animals.

Data post-processing allowed for the clear delineation of the subsidence contour and slope inclinations, providing a 3d model of the objective. This model can be integrated with other works in the area of Salina Ocna Dej, offering a detailed perspective on all mining activities in the region.

The data was exported in various formats (dxf, csv, txt, tiff, jpeg) compatible with other cad programs, facilitating further analyses and checks of the area's condition.

The resulting 3d model serves as a reference for future observations of subsidence evolution, including monitoring the widening of edges and their advancement towards nearby residences, with the closest being 58.7 meters away.

Continuation of measurements is necessary, considering that subsidence may become more frequent due to erosion caused by precipitation and slope instability, exacerbated by strong vibrations contributing to the displacement of unsupported terrain. In 2022, it was observed that slopes frequently stabilized at an inclination of approximately 30-32 degrees. The most significant displacements occurred on the southern slope, which is continuously degrading.

It is essential to monitor this subsidence cone to intervene in a timely manner if the slopes do not stabilize in the coming years to avoid endangering human lives and property [9].

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