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Terrestrial laser scanning in the construction of a numerical model geometry related to underground post-mining facility

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Abstract: The procedure of building a quasi-3D geometry of a numerical model of an underground post-mining facility is presented in the article. For this purpose, measurements were made, based on the terrestrial laser scanning (TLS) technology, of a fragment of St. John adit, which is part of the underground tourist route "Geopark" St. Johannes Mine in Krobica in Lower Silesia in Poland, in the neighborhood of Krobica, Gierczyn and Przecznica – the places located in the vicinity of the well-known health resort Świeradów Zdrój. TLS, as one of the most advanced mining surveying technologies, enables accurate mapping of even the most complex geometries of underground mining facilities. This opens wide possibilities in the construction of more accurate numerical models of the behavior of the rock mass around such underground objects. As a result, more reliable calculation results are obtained, which are the basis for designing mining support protection, for example, with rock bolting. This translates into an improvement in the safety of underground excavations, in the conditions of exploitation in mining as well as in historical post-mining excavations made available to tourists.

In the construction of the geometry of numerical model, software such as Trimble RealWorks was used to orientate individual "point clouds" from measurement stations. CloudCompare software was also used to generate cross sections to the adit axis, and AutoCad software was used for processing and spatial orientation of a selected characteristic cross section. Using the latest version of the FLAC 3D v.9.0 software, the excavation cross-section geometry obtained from measurements was mapped to and discretized (i.e., meshed), giving it a third dimension at the same time.

Keywords: Terrestrial laser scanning; numerical modeling; mine survey.

1 Introduction

The method of securing the underground mining excavation is indirectly dependent on its shape, which in turn is adopted in relation to the geotechnical and technological conditions as well as the state of stresses in the rock mass. These aspects determine the adoption of a circular, horseshoe or quadrangular shape. Excavations with a circular cross section are optimal for rock mass of poor quality (ground mass, post-glacial deposits, heavily weathered rock). Horseshoe-shaped excavations with various proportions (height, width, and elevation of the vault) are suitable for use in a good-quality rock mass and in high-pressure conditions, they are often closed with a floor vault. However, quadrangular excavations are made in rock mass of good quality and with clear geological divisions. The shape of mining excavations should be adapted to the shape of the relaxed rock mass zone, which is formed after its excavation. In the excavation roof, as a result of tensile stresses, the tensile strength of the rocks is exceeded, which results in cracking of the rocks and their detachment from the rock mass. The line separating the relaxed zone from the fractured zone is called the arching effect (Huang et al. 2002, 2021). The height of the roof arch can be determined by empirical methods, directly by *in situ* measurements or using numerical methods.

In the sidewalls of the excavation, because of compressive stresses, a zone of cracks (relaxation zone) is formed, in which the rock material is divided by cracks. The process of rock detachment usually begins after excavation and may take a long time. In principle, the designed mining support is required to at least take over

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the load from the side of the rocks of the stress-relieved zone, trying to move into the excavation space. In turn, the height of the pressure vault, apart from the geomechanical parameters of rocks, depends to an equally large extent on the shape and dimensions of the excavation cross section. In the case of mining excavations or tunnels, their cross sections are regular and most often, they take the shape of a circle, ellipse, horseshoe with a curved roof, square, rectangle, rhombus, or trapezoid. Determination of the stress distribution around such excavations does not generate major difficulties because (including geological exploration or depth below the ground level) they require knowledge of only a few dimensions, for example, the height and width of the excavation cross section. In the case of a trapezoidal excavation, it is only necessary to measure the width of the floor, the height, and inclination of the sidewalls. Building a numerical model with regular and symmetrical geometry is quick and simple, using software that enables automatic model discretization (mesh construction). The problem arises when the analyzed excavation does not fit into any of the above-mentioned simple geometric cases and has an irregular shape, which is difficult to reproduce. This type of situation is most often observed in (sublevel) open stoping mining methods and in the case of historical mining excavations, which were made by manual mining technique and drilled in such a way as to match the geological structure of the rock mass. In mining, before the massive use of explosives, adits were drilled to follow the veins of metal ores. The form and structure of shallow vein deposits exploited before the industrial era were highly complicated, often with very irregular concentrations of ore. As a result, excavations were drilled, which were located in accordance with the structure of the rock mass and mineralization.

Therefore, in this article, the methodology of mapping the complicated geometry of the excavation with an irregular cross-sectional shape will be presented to use it to build the geometry of the grid of a quasi-3D numerical model. This grid can be used to carry out numerical calculations, the results of which are the basis for designing the mining support of historical post-mining facilities.

2 Methodology of measurements

Terrestrial laser scanning (TLS) technology has already found wide application in industry. The principle of operation of the laser scanner is based on spatial polar measurement, in which the distance is determined based on the time that a light beam needs to cover the distance between the emitter–object–receiver (Kajzar et al., 2015). While maintaining the principle of spatial polar measurement, the scanning method differs from total station measurements in the number of measurements (thousands to hundreds of thousands of emitted pulses per second). The scanner uses a pulsed laser beam to scan the object according to a given resolution, that is, according to a mesh with a certain density. The location of each point is recorded locally using spatial polar coordinates. The measurement result in the form of "point cloud" is processed using specialized software, which includes the creation of sections, planes, data cleaning, creation of files for presentation and their conversion to various formats, for example, (.las) or (.dxf).

In mining and tunneling, its use includes as-built measurements (measuring underbreak and overbreak) (Fekete et al., 2010), deformation increment (Janus & Ostrogórski, 2022), and geological studies of the rock mass. In the study of Monsalve et al. (2018), this technology was used to study the rock mass and map the network of cracks for the conditions of an underground limestone mine. In the study, the "point cloud" was processed in the "I-Site Studio" software, which includes a set of geotechnical analysis tools that help engineers during the structural mapping process, allowing for more representative rock mass data. In the study Rozmus et al. (2021), the results of laser scanning measurements were used as the basis for redesigning communication routes in underground coal mining to ensure safe transport of loads. Laser scanning is also possible using mobile robots. In this way, the spatial form of the Gertrude adit in the former gold and arsenic mine in Złoty Stok in Poland was developed. The measurement results were used to develop spatial modeling of air flow through the historical mining excavation (Wróblewski et al., 2023). It can be assumed that in the future, laser scanning combined with the technology of automated robots will cover significant parts of entire mines, replacing traditional mining maps (Huber & Vandapel, 2006).

In today's mining industry, laser scanning is particularly needed in (sublevel) open stoping mining systems where ore is extracted from large, open chambers. These excavations are made by blasting; but so far, no method has been found to obtain the ideal, initially planned shape of the chamber. As a result, ore losses are generated or its depletion occurs. The way to optimize mining with this method is research that uses a combination of numerical modeling and laser scanning. In the study of Emad et al. (2014), the results of dynamic numerical simulations of the stopes were verified by comparing the geometry predicted in the FLAC 3D software with real profiles obtained from laser scanning.

Figure 1: Visualization of the entrance to the underground track "St. Johannes" Mine in Krobica (Kobylańska, 2012).

In the article, a section of the underground tourist route "Geopark" St. Johannes Mine in Krobica (Lower Silesia, Poland) was chosen as the testing ground. In the neighborhood of Krobica, Gierczyn, and Przecznica – the places located in the vicinity of the well-known health resort Świeradów Zdrój, where in the period from the 16th century to the first half of the 20th century, the exploration and exploitation of tin and cobalt ores were conducted (Madziarz, 2012). Geopark – the tourist and teaching path "along the footprints of old ore mining" was officially opened for visitors in May 2013. In a small area, where over a few centuries intensive mining works were conducted, their numerous remains survived, constituting the typical (not only the Lower Silesian mining) examples of relics of such kind of activity (Fig. 1). Having been cleared of wastes illegally dumped in them, properly secured, exposed, and made partly available to visitors, today it constitutes a great attraction for visitors, instead of the threat that it posed previously (Madziarz & Kobylańska 2014).

The underground tourist route in Krobica was created based on a set of historic workings of St. Johannes Mine and the 18th century St. Leopold working, where mining works were conducted in the years 1576–1633, 1755, 1770, and 1811–1816. St. John adit leads the tourists onto the surface at the foot of a picturesque rock outcrop over a mountain brook. Despite the small length of workings made available to visitors (about 350 m), their historical character – manifesting itself in very small cross section dimensions, winding run and numerous blind drifts – makes a great impression on visitors, making them aware of how difficult it was to conduct mining activity centuries ago, with the low level of knowledge and technique (Madziarz & Kobylańska, 2014).

The described measurements consisted in spatial scanning of approximately 7.5-m section of the St. John adit (Fig. 2) using a Trimble TX8 laser scanner (Fig. 3). According to the manufacturer, systematic distance measurement error of this measurement equipment is "1σ" <2 mm (up to 100 m) (Trimble, 2016). Measurements made from two scanner positions allowed to develop a spatial image of the excavation over a distance of about 7.5 m. For the orientation of "point clouds" from individual stations, six reference spheres with a diameter of 14 cm were used (resolution of 22.6 mm at a distance of 30 m). Analyzing the scan statistics, it was found that the maximum orientation error was 1.0 mm. Narrow and, at the same time, small adit made it difficult to choose the most optimal position of the scanner between the sidewalls. As a result, at individual stations, the scanner did not capture the shape of the sidewall closer than 60 cm (Fig. 4). Trimble RealWorks (TRW) software (TRW, 2023) was used to orient the "point clouds" from individual measurement stations relative to each other and to combine them into one object. The spatially oriented "point clouds" were merged and saved in the (.las) format, supported by the open-source CloudCompare software (CloudCompare, 2023). After the orientation of the “point clouds” was carried out in the TRW software, further work related to the processing of the measurement results was carried out in the CloudCompare software.

Trimming, filtering, and noise removal from the “point cloud” were made in this open-source software. The resulting “point cloud” (with a volume of 28.5 million points), together with the histogram of the intensity of the laser beam reflection, is shown in Fig. 5. Modern laser scanners record the intensity of the laser beam reflection from the observed object. This parameter is a quantity that is used, for example, to identify materials with different physical properties (Ulewicz & Pawłowicz, 2022). The absorption and scattering of the laser beam is affected by the color and roughness of the scanned surface, as well as the change in humidity (Hassan et al., 2017). In the study Humair et al. (2022), bruise intensity was used to detect the geometry of lithological structures in the Haute Chaîne of the Swiss Jura Mountains.

In the next step, in the CloudCompare software, the cross sections of the adit were generated (Fig. 6). Fifteen cross sections, spaced every 0.5 m, assuming the thickness of the active section as 15 cm and the maximum length of the cross section edge as 15 cm (Fig. 6a–c), were generated. Section boundaries were saved to a format (.dxf) supported by AutoCad software (AutoCad, 2023). In this environment, one characteristic cross section was selected and dimensioned (Fig. 6d, e). Selected cross section of a fragment of the St. John adit was less than 3.0 m high, less than 1.8 m wide at the bottom, while the deviation from the vertical of the southern sidewall was 26^{o} and from the northern sidewall was 32^{o}.

In the next step, having a cross section through the excavation, it is possible to proceed to the proper stage related to the construction of geometry of the numerical model. Numerical modeling is commonly used to determine the distribution of stresses, deformations, or the range of relaxed zones around underground structures. One of the most popular tools in this area is FLAC 3D by Itasca, based on the finite difference method. It is a tool often used in geotechnical issues, which is confirmed by publications containing descriptions of cases of use in geoengineering projects (D’Obryn & Hydzik-Wiśniewska, 2013, 2017) and even presented methods of its coupling with other software (Wang & Zhang, 2010) to geometrize complex numerical models. In the study Mao and Zuo (2017), RHINO-KUBRIX and FLAC 3D software were used to build a 3D model of a tunnel drilled in a rock mass with a complex geological structure. The study Bock (2015) presents solutions for converting discretized models

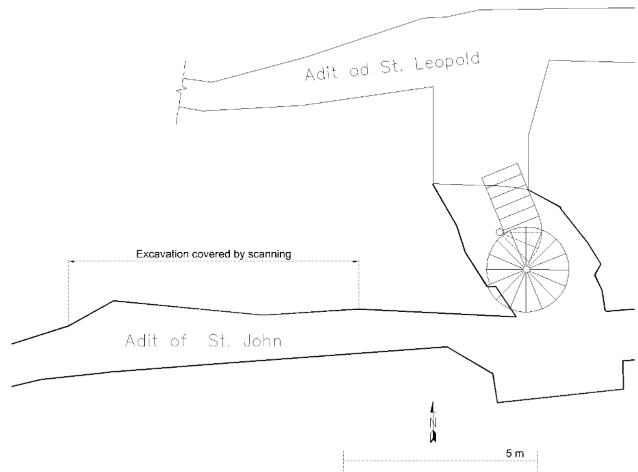

Figure 2: Location of the scanned 7.5-m fragment of the adit on the underground track “St. Johannes” Mine in Krobica. In the vicinity of the measurement site, there is a shaft connecting both adits (St. Leopold below and St John above).

Figure 3: Trimble TX8 laser scanner during measurements in the St. John adit.

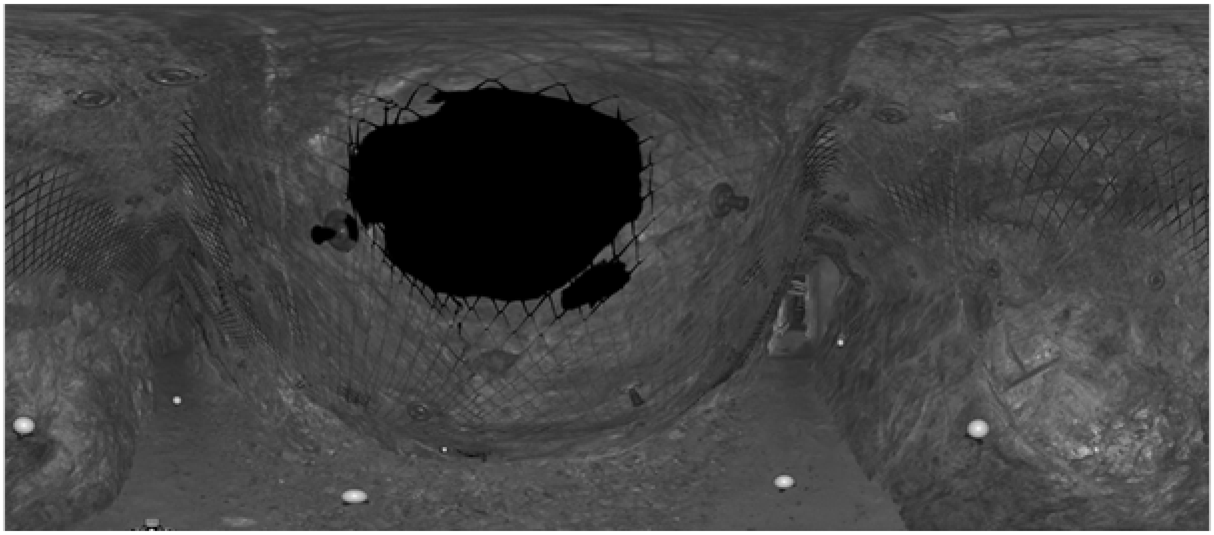

Figure 4: The intensity of the laser beam reflection in the adit (the black spot is a fragment of the sidewall closer than 60 cm from the scanner).

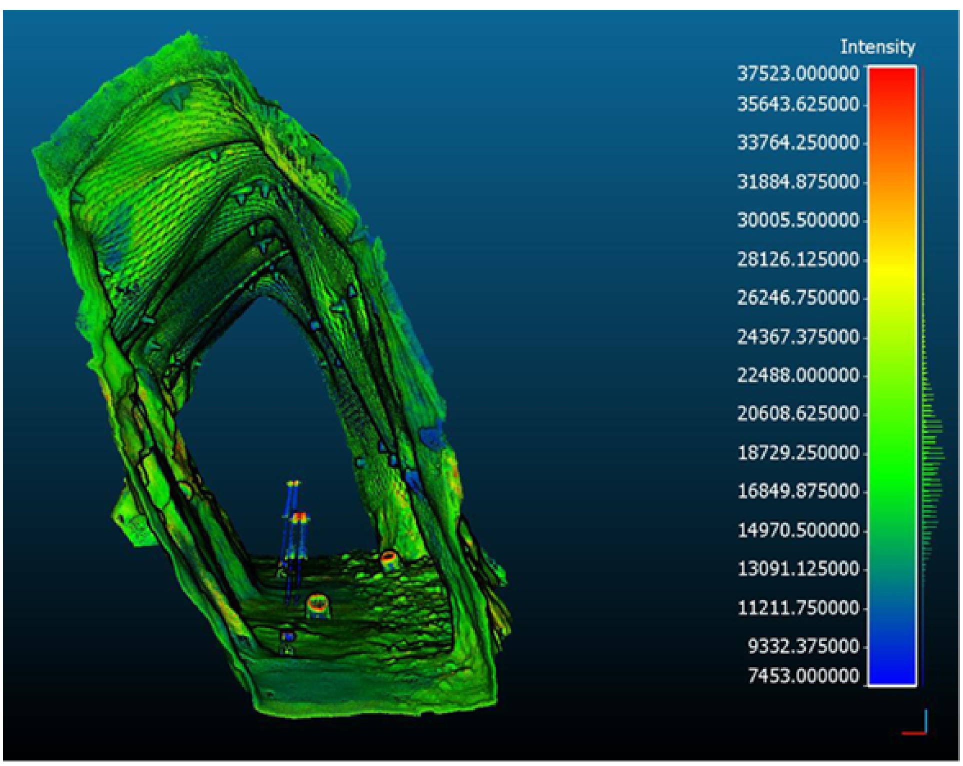

Figure 5: "Point cloud" visualization of a fragment of the St. John adit, displayed by the value of the reflection intensity parameter.

prepared in ANSYS and SolidWorks programs to a format compatible with FLAC 3D. ABAQUS, MIDAS software (Itasca, 2023), and Rhino/Griddle (Xu et al., 2022) work with the latest version of FLAC 3D v.9.0.

In the presented example shown in this article, a sketch of the flat geometry of the model (2D), saved in the .dxf format, was the basis for the preparation of a quasi-3D numerical model. The construction of the model was carried out in the FLAC 3D Itasca software in the latest version 9.0 (Itasca, 2023) because FLAC 3D has already been widely used in geotechnical issues and has a convenient sketch function, previously "extrusion" for building quasi-3D models. The software allows you to create meshes based on 2D geometries that are extruded

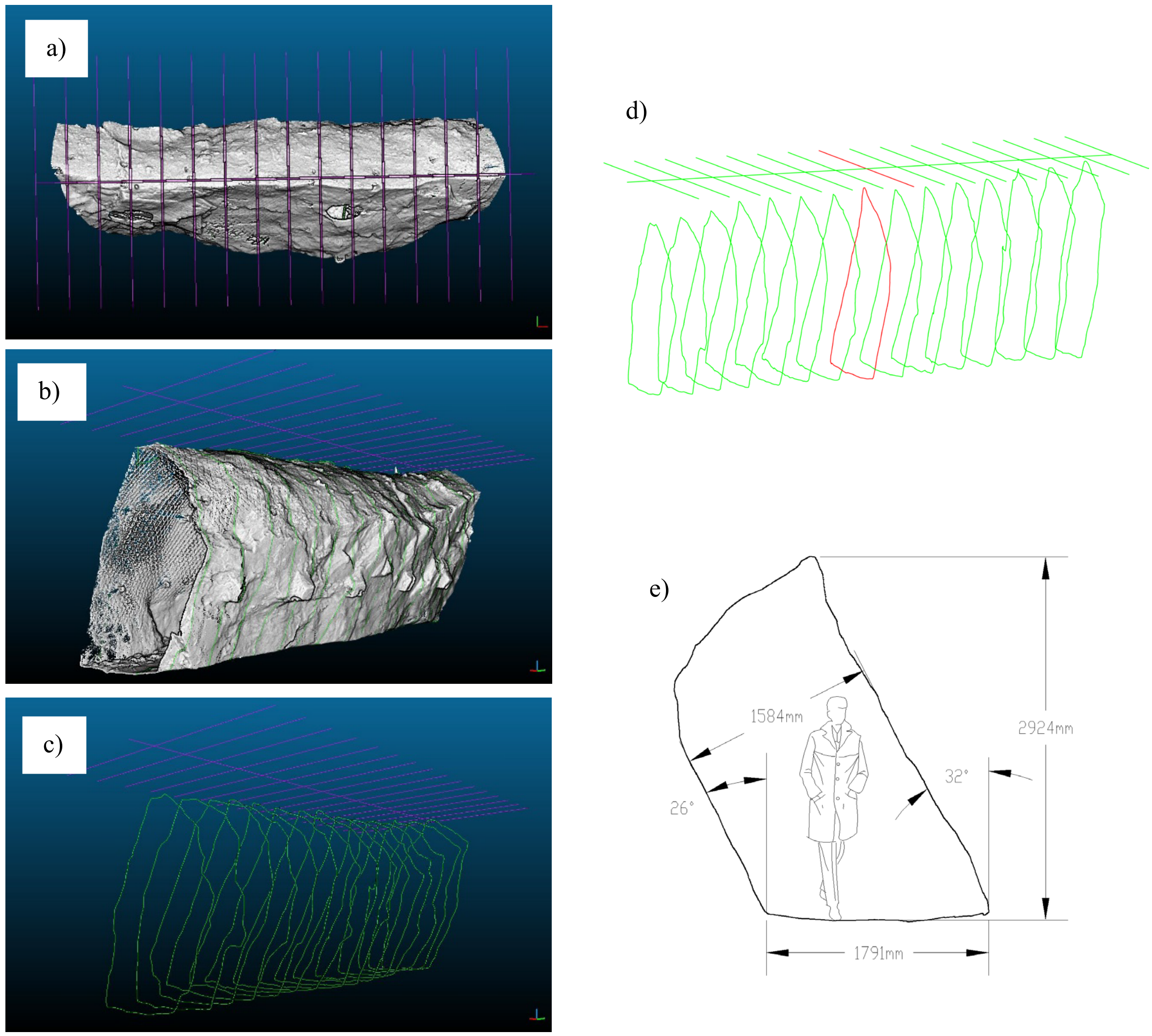

Figure 6: (a–c) Generating 2D cross sections from (a) "point cloud" in CloudCompare software and (d, e) dimensioning of a selected characteristic cross section.

(stretched linearly) in the third dimension. Building the geometry in the presented example consisted in importing a sketch of the given geometry in a file, saved in the .dxf format (Fig. 7a). The FLAC 3D program allows you to automatically outline the sketch using polylines; however, to avoid generating a too complex model, this operation was done manually (Fig. 7b). Points are connected into edges, which in turn are closed into blocks. Edges can be linear or curved. In the next step, it is possible to discretize the created blocks and assign them to individual zone groups. Structured and unstructured meshes consist of triangular or quadrilateral elements (Itasca, 2023). An unstructured mesh is generally easier to construct and geometrically less stringent. Thanks to this, it is possible to create numerical models with complex geometry easier and faster based on the results of laser scanning. Any closed polygon can be meshed in the sketch. Structured mesh can be used only for simply connected three- or four-sided polygons, while unstructured mesh can be applied to any closed polygon. The following parameter values were adopted to control the mesh construction process:

- Create unstructured meshes only: False
- Use only quads in unstructured meshes: False
- Target zone size: $f \geq 0$. The default value is 0.
- Max gradation: $f \geq 0$. The default value is 0.5.
- Optimization level: $0 \leq i \leq 10$ for the unstructured mesher. The default value is 5.
- Shape quality weight: $0 \leq f \leq 1$ for the unstructured mesher. The default value is 0.7.
- Weight on quadrilaterals: $0 \leq f \leq 1$ for the unstructured mesher. The default value is 0.75. The default value (0.75) gives a significant preference to the quad/triangle ratio over the mesh quality (Itasca, 2023).

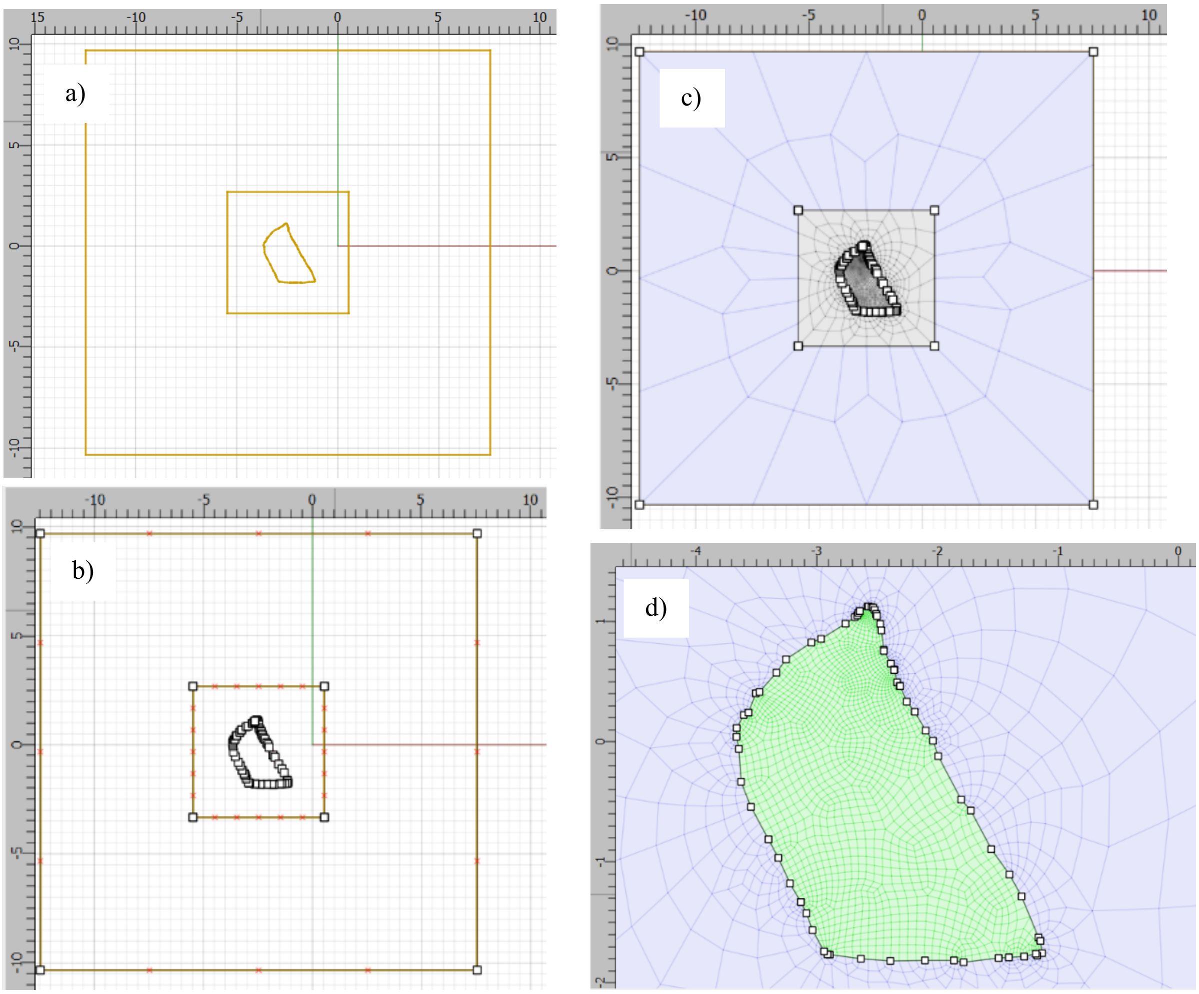

Figure 7: (a, b) Creating the cross sectional geometry of the scanned fragment of the adit and (c, d) its discretization in FLAC 3D Itasca v.9.0 software, sketch option.

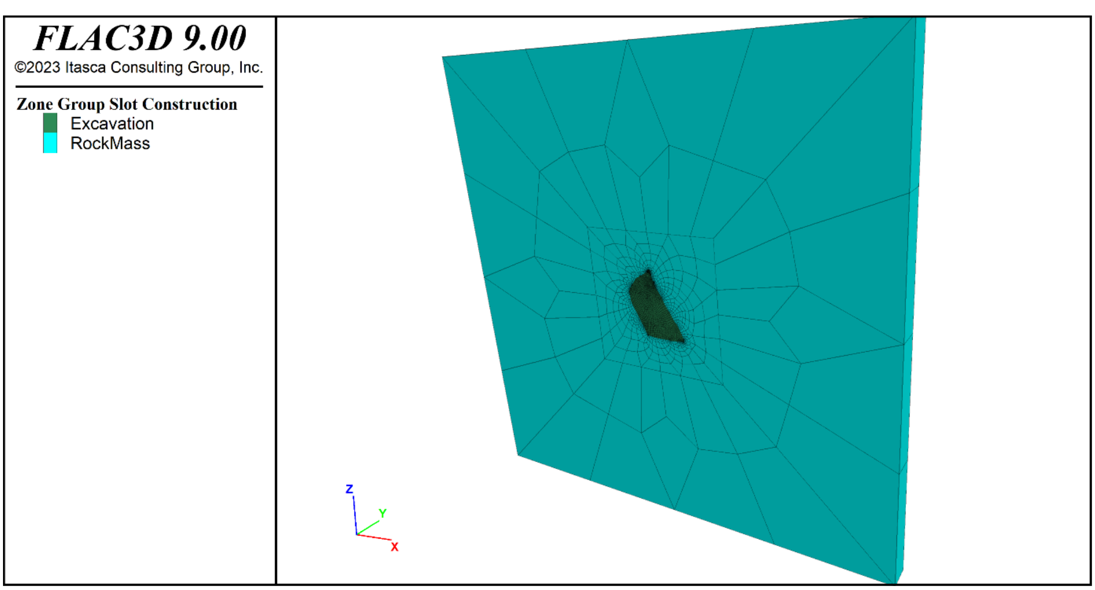

Figure 8: Geometry obtained for the quasi-3D numerical model of the underground excavation in the FLAC 3D Itasca v.9.0 program.

The process of building the mesh for the numerical model is shown in Fig. 7 c, d. As a result of the work related to the inventory of adits using the laser scanning method, “point cloud” processing, cross sectional area generation, and discretization, the geometry for the numerical model was created with dimensions 20 m × 20 m and a thickness of 1 m. The number of zones in the grid was 2 858, with the number of grid points being 5932 (Fig. 8).

3 Results

A significant limitation in the free use of numerical calculations is the difficult and time-consuming construction of the model geometry, which will reproduce the shape of the examined excavation as faithfully as possible. The laser scanning method and software producers meet the needs of engineers. In this part of the article, based on the results of the described test, a proposal for a procedure of building the geometry of a quasi-3D numerical model of an underground excavation with a complex cross-section geometry will be presented.

Inventory of underground excavations:
- performing laser scanning of the tested excavation from several positions.

Actions done in TRW software:
- orienting “point clouds” made from individual stations with respect to each other, for example, using reference spheres,
- connection of “point clouds” and their conversion to a file supported by open-source CloudCompare software (.las extension recommended).
  Home >>> Import and Registration
  Production >>> Home >>> Export Selection

Actions done in CloudCompare software:
- noise removal and “point cloud” filtering,
- generation of excavation sections and their conversion to a file supported by AutoCad software, that is, (.dxf).
  File>>>Open>>>File.las
  Extract cloud sections along polylines ...>>> Section edition mode >>> Generate orthogonal sections ... >>> Extract points along active sections
  File>>>Save>>>File.dxf

Actions done in AutoCad software:
- selecting a representative excavation cross section, so that it imitated the examined excavation to the greatest extent,
- possible correction of the polyline and spatial orientation of the cross section,
- saving the drawing in .dxf format.

Actions done in FLAC 3D v.9.0 software:
- importing a plan projection sketch of a model in .dxf format,
- contouring a sketch in the sketch mode, the model should not be too complex to ensure proper discretization,
- carrying out the proper discretization and giving the model a third dimension (“line extrusion”).
  File >>> New >>> Sketch Set >>> Import background image... >>> Point/Edge Tools >>> Mesh Tools >>> View Selector – Bottom >>> Create Zones

4 Conclusions

The article managed to create a quick and easy way to build the geometry of quasi-3D numerical models for mining excavations with complex cross-sectional geometry. For this purpose, measurements were made, based on the TLS technology, of a fragment of St. John adit, which is part of the underground tourist route “Geopark” St. Johannes Mine in Krobica in Lower Silesia in Poland, in the neighborhood of Krobica, Gierczyn and Przecznica – the places located in the vicinity of the well-known health resort Świeradów Zdrój. In the construction of the numerical model, software such as TRW was used to orientate individual “point clouds” from measurement stations. CloudCompare software was also used to generate cross sections to the adit axis and AutoCad software for processing and spatial orientation of a selected characteristic cross section. Using the latest version of the FLAC 3D v.9.0 software, the excavation cross section geometry obtained from measurements was mapped to and discretized (i.e., meshed), giving it a third dimension at the same time.

This proposed procedure can be useful for engineers designing mining protection of historical post-mining excavations to make them available for tourist traffic. The next logical step is to perform appropriate numerical calculations of the behavior of the rock around the excavation to determine the rock pressure that the mining support must carry. The method can be used because it is based on popular and open-source software such as CloudCompare. This opens wide possibilities in the construction of more accurate numerical models of the behavior of the rock mass around such underground objects. As a result, more reliable calculation results are obtained, which are the basis for designing mining support protection, for example, with rock bolting. This translates into an improvement in the safety of underground excavations, in the conditions of exploitation in mining as well as in historical post-mining excavations made available to tourists.

In further work on the use of laser scanning in the construction of the geometry of numerical models, attempts will be made to generate a complete 3D geometry, also using the FLAC 3D Itasca software.

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