Original Study

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Geometrization of a 3D numerical model of an underground facility based on the results of terrestrial laser scanning

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Abstract: The article proposes a method of combining CloudCompare, RHINO, and FLAC3D software, aimed at building numerical models of underground objects of natural or engineering origin, based on the results of measurements made using terrestrial laser scanning technology. This technology is one of the most advanced in mine survey as it enables accurate mapping of even the most complex geometries of underground facilities. This opens wide possibilities in the construction of more accurate numerical models of the behavior of the rock mass around such underground objects. The results of simulation of the behavior of the rock mass around the analyzed excavations, obtained by performing numerical calculations, allow predicting unfavorable phenomena that may occur as a result of the destruction of the rock mass and which may threaten the safety of users of underground facilities, for example, caves, tunnels, and mining excavations.

In this work, we carried out measurements using a terrestrial laser scanner and obtained a "point cloud" that reproduced the geometry of the underground facility. An example is a fragment of the adit St. Johannes, which is part of the underground tourist route "Geopark" St. Johannes Mine in Krobica in Lower Silesia in Poland in the neighborhood of Gierczyn and Przecznica. In the next step, the measurement results were processed, so that it was possible to import the generated geometry into the FLAC3D software and use it to build a numerical model of the adit, based on "brick" zones.

The aim of the article is to present in detail the methodology of geometrization of numerical models of underground objects with complex geometry. The author wanted the method to be as easy to use as possible, give full control over the surface structure, and not require many numerical modeling programs.

Keywords: Terrestrial laser scanning; mine survey; underground engineering.

1 Introduction

Over time, laser scanning has found new applications in many fields, including not only geodesy, but also civil engineering. Due to the simplicity of use and the ease of obtaining results in the form of "point clouds," scanning is replacing the photogrammetry method. Point clouds can be the basis for further modeling and 3D visualization of any object. Data obtained by laser scanning can be used as a basis for analyzing the deformation process, inventory, and even for testing the properties of the material from which the scanned object is made.

The principle of operation of a laser scanner is based on spatial polar measurement, in which the distance is determined based on the time the 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 pulsating laser beam to scan the object according to a given resolution, that is, according to a grid with a specific density. The position of each point is recorded in the local system using polar spatial coordinates. The measurement result in the form of a "point cloud" is processed using specialized software, which includes creating cross sections and planes, trimming and cleaning data from noise, creating files for presentation, and converting them to various formats, for example, (.las) and (.dxf).

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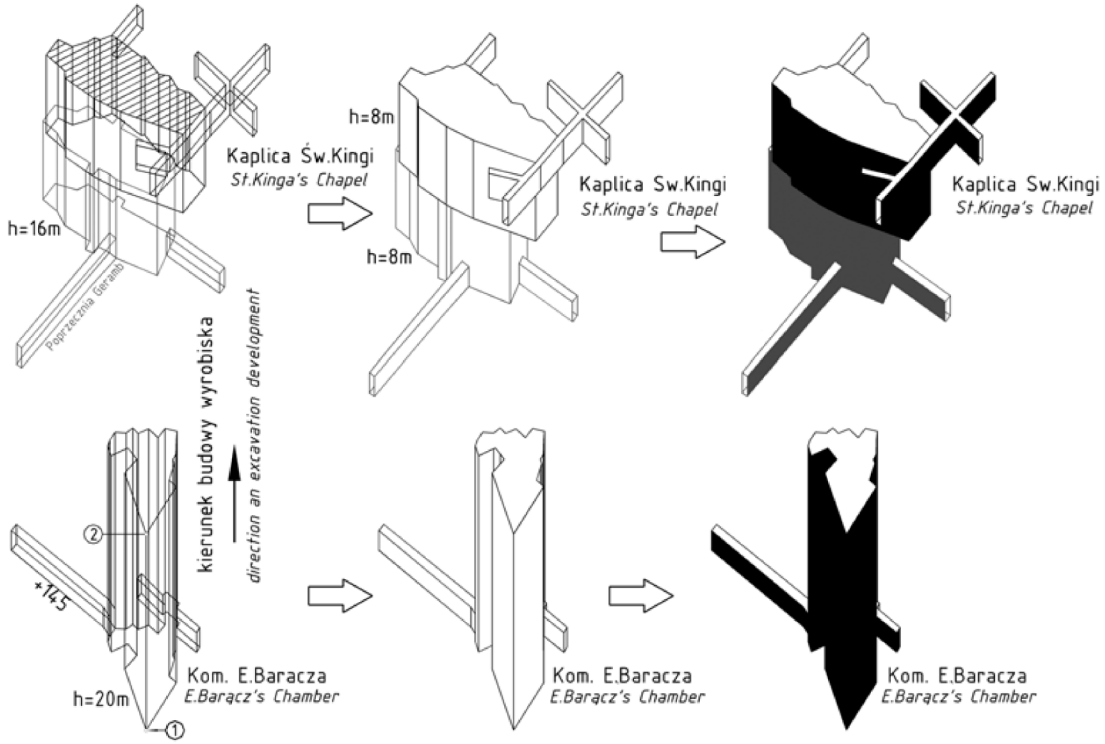


Figure 1: Stages of creating simplified spatial drawings on the example of selected excavations of the Chapel of St. Kinga and Erazm Barącz's chambers (Maciaszek et al., 2010).

In mining and underground engineering, laser scanning is used primarily in the post-construction inventory of underground facilities (Fekete et al., 2010c), including historical underground facilities (Maciaszek et al., 2010) and in monitoring the deformation of a rock mass (e.g., convergence) (Janus and Ostrogórski, 2022). Mine services, companies providing geodetic services, and scientific institutions are increasingly noticing the advantages of this method of performing measurements, and conducting analyses based on "point clouds" is becoming more and more common. It is reasonable to optimize the use of extensive databases in the form of spatial "point clouds" by searching for new areas of their application. One of them may be to use them as a basis for building numerical models to simulate the behavior of the rock mass around underground facilities.

In the past, successful attempts were made to digitally reproduce the complex geometries of underground workings and a number of techniques were developed (Maciaszek et al., 2010). In relation to the experience with numerical modeling of underground workings of the Wieliczka salt mine in Poland, a method was developed which, first of all, consists in obtaining data from the measurements performed, among others, with a laser scanner or based on calibrated map scans (in CadRaser, I/RAS B, Kalibronek programs) saved in the .tiff format and their transformation from a raster image to a vector image, using the digitization (vectorization) method. In the next step, 2D images are transformed into 3D in any CAD graphics program (e.g., AutoCAD, Microstation). As a result, simplified models in a generalized form are obtained, based on the projection of the floor of a road or chamber-type excavation and the knowledge of its average height (Fig. 1). It is also possible to build complex models based on an extensive set of spatial data derived from direct measurement of the excavation using geodetic and photogrammetric methods (Maciaszek et al., 2010).

Cieślik et al. (2009) presents the method of mapping the geometry of the Warszawa, Wisła, and Budryk chambers in the Wieliczka salt mine. Geometrization was carried out based on the maps of horizontal and vertical projections through the analyzed chambers. They enabled a spatial solid representation of underground workings, which omitted small geometric details and small workings that had no practical significance in numerical calculations. The discretization process was performed in the ABAQUS software, which generated tetrahedral finite elements (pyramids with a triangular base), appropriately concentrated in places of the expected highest stress concentration. When building numerical models of the

underground workings of the Wieliczka salt mine, it is very difficult to reproduce the geometry and mutual location of the chambers. The geometrization of models is usually performed based on surveying materials and descriptions of the technical condition. Often for reasons beyond the researchers' control, that is, lack of accurate data or due to a rocks-falls or backfilling of underground workings, a faithful representation of the geometry is impossible. However, there are also limitations due to the software used and the computing power of computers. For these reasons, it becomes necessary to simplify the model geometry (D'Obryn et al., 2013), which in turn translates into the quality of the obtained calculation results. For the reasons described, it seems reasonable to create and disseminate new ways of building complex geometries of underground workings for the purpose of conducting numerical simulations. This will certainly contribute to the development of research on securing underground facilities.

For problems where numerical simulations are to be used as a tool for predicting the behavior of the rock mass, as shown in Fuławka et al. (2022a, 2022b) and Pytel et al. (2023), the correct representation of the geometry is crucial. Therefore, enriching the numerical model with laser-scanned geometry may be the basis for achieving unprecedented computational quality.

Such initiatives have already been undertaken by other researchers. Here, it is possible to quote the article Mao and Zuo (2017), in which a modeling method based on RHINO-KUBRIX and FLAC3D software was proposed, using the example of a highway tunnel. The approach proposed in the above-mentioned work does not require users to have advanced programming skills or more than one numerical modeling program. In the RHINO program, the geometry is exported to a file with the extension (.stl), while in the FLAC3D software, the geometry is discretized and imported to a file (.flac3d).

Bock (2015) presents an open-source program that allows the conversion of discretized models prepared in ANSYS and SolidWorks to a format compatible with FLAC3D. The ANSYS-FLAC3D converter enables the transformation of a discretized mesh using tetrahedral, wedge, and brick zones. The mesh can be mixed with any of the types mentioned. The second discrete model converter created in SolidWorks allows the transformation of only tetrahedral zones. The main difference between the developed converters and the FLAC3D software and its built-in KUBIX is that the new converters already use discrete geometry, including the division of solids into specific parts (groups). This approach allows the use of complex geometry with a large number of groups, which is difficult to achieve with KUBRIX due to file (.stl) limitations.

The above-mentioned methods are effective and comprehensively solve the problem, but they do not include the step of moving from the "point cloud" to a solid that can be exported to a file (.stl) and then to FLAC3D. Publications in this field do not present the described methodology in a technical and detailed way, which limits their practical dimension and the possibility of using the results of laser scanning in 3D numerical modeling by a larger number of engineers.

2 Methodology

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 Gierczyn and Przecznica – the places located in the vicinity of the well-known health resort Świeradów Zdrój, where, 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).

For the purposes of the work, spatial scanning of approximately a 7.5-m section of the St. Johannes Adit was performed using the Trimble TX8 laser scanner (Fig. 2). According to the manufacturer, systematic distance measurement error of this measurement equipment is "1σ" < 2 mm (up to 100 m) (Trimble, 2016). Measurements



Figure 2: Trimble TX8 laser scanner during measurements in the St. John Adit.

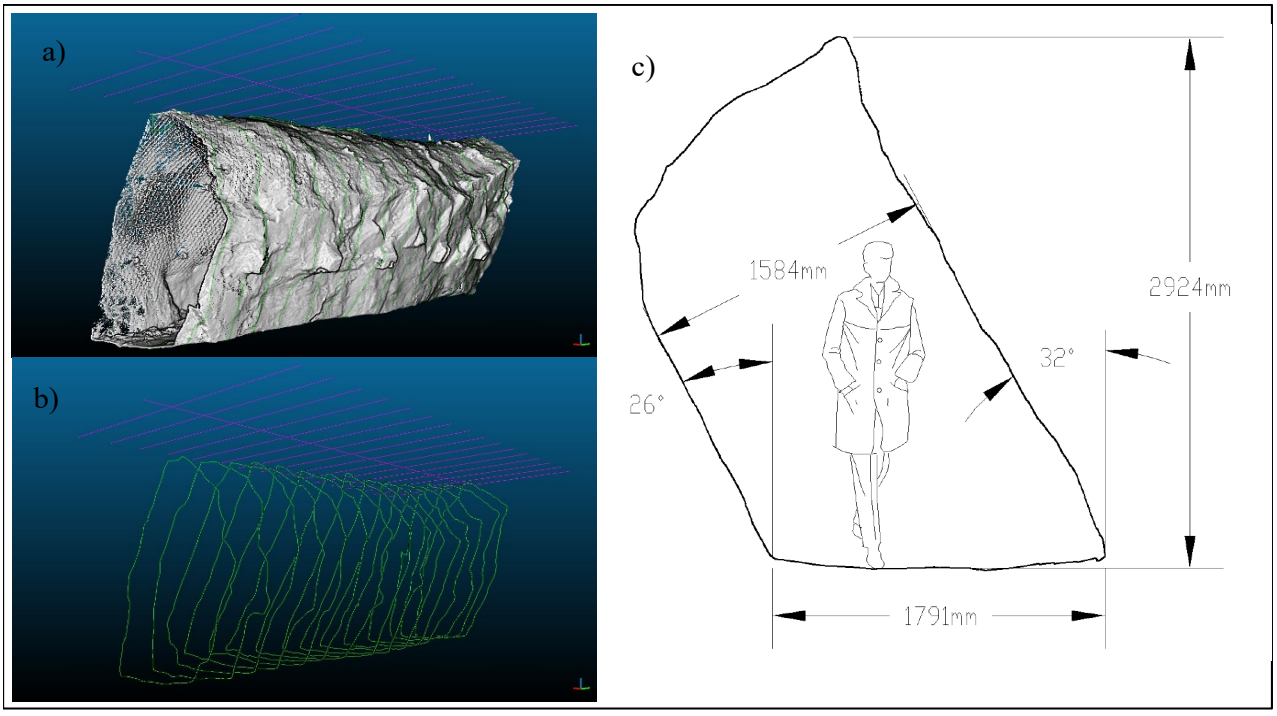


Figure 3: a), b) Generating 2D cross sections from a "point cloud" in the CloudCompare program and c) dimensioning the selected cross section.

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. Analyzing the scan statistics, it was found that the maximum orientation error was 1.0 mm.

The Trimble Real Works 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 opensource 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) is shown in Fig. 3a. ColudCompare was used to generate 15 flat cross sections to the axis of the adit, spaced every 0.5 m, assuming an active section width of 15 cm and a maximum length of the cross section edge of 15 cm (Fig. 3a, b). The cross-sectional boundaries were saved to a file in (.dxf) format supported by RHINO software (Rhino, 2024). Selected cross section of a fragment of St. John was less than 3.0 m high and less than 1.8 m wide at the bottom, while deviation from the vertical of the southern sidewall was 26° and from the northern sidewall was 32° (Fig. 3c).

The next step was to import a file (.dxf) with flat cross sections into the RHINO graphic software. Rhinoceros (referred to as RHINO) is a drawing software based on Non-Uniform Rational B-Splines (NURBS) and is widely used in 3D animation, industry, and design. The extensive surface-building capabilities and high-quality generation of model structures make the creation of high-precision 3D model surfaces convenient and efficient, although the software is small and has low hardware requirements (Mao and Zuo, 2017). Sections in the form of closed curves became the basis for generating an open polyplane (Fig. 4a), which was possible thanks to the "Loft" option. However, it was necessary to create a solid shape, which required closing the resulting surface. This is easy in the RHINO software as it has a "Cover Flat Holes" feature. The surface closed in this way becomes a solid (Fig. 4b), which is finally saved in a file with (.stl) format.

The next stage of work included importing the solid geometry in a file format (.stl) to the FLAC3D software from Itasca. 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 and

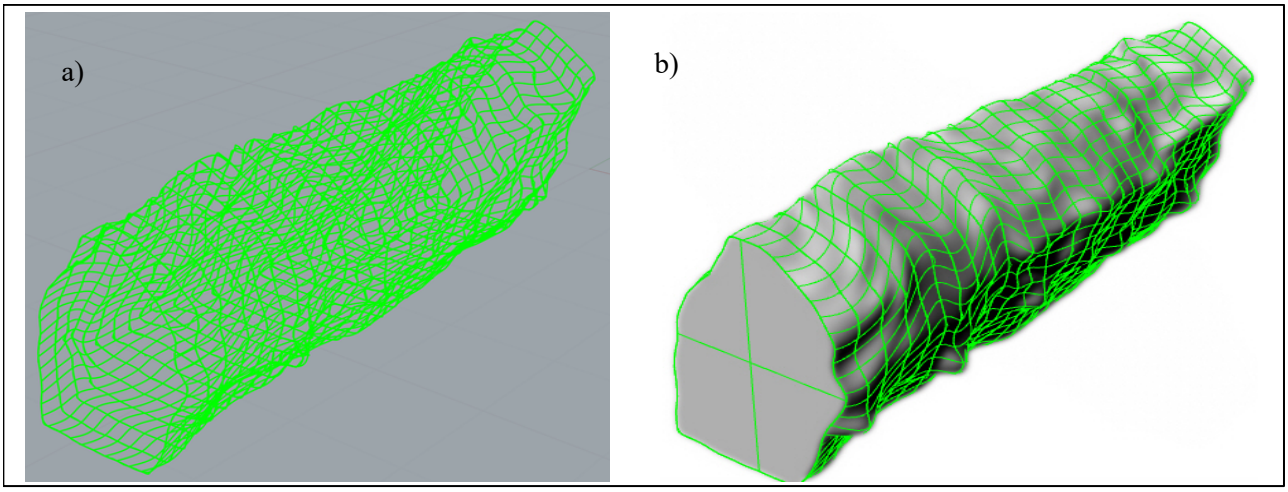


Figure 4: a) Open polyplane of the adit, generated in the RHINO program. b) Rendering of the solid generated in the RHINO program.

Hydzik-Wiśniewska, 2013, 2017) and even presented methods of its coupling with other software (Wang and Zhang, 2010, Mao and Zuo, 2017) to geometrize complex numerical models.

This article shows an example of generating zones based on "brick" geometry, which can be handled by the basic capabilities of FLAC3D and the accompanying KUBRIX application. Moreover, this program enables the generation of unstructured tetrahedral and hexahedral zones. However, if the geometry of the numerical model exceeds the built-in capabilities of KUBRIX, the use of Itasca's Griddle tool should be considered. It represents the most advanced approach to creating complex zones for FLAC3D (Itasca, 2024). One of the simplest and practical ways to build a mesh based on complex geometry in the FLAC3D software is to use "brick" zones and the "zone densify" command using the "repeat" keyword, which allows you to create a mesh of zones using the "octree" method. The FISH code used is presented in Table 1. A similar example is presented in the FLAC3D software manual (Itasca, 2024). The keyword "segment" used indicates that each level of density will divide the zone by 2 in each direction, resulting in eight new zones. The "gradient-limit" keyword affects the zones marked as dense. This ensures that the maximum size difference between zones is one density level. The keyword "edge-limit" combined with the word "repeat" indicates that zones will be marked for compaction if their edge length is greater than 0.1 m.

However, the keyword "repeat" indicates that a single compaction pass will be made over the zones. This operation will be repeated until there are no zones left to compact because they are either out of range or already smaller than the specified edge limit. The "range geometry-distance" keyword selects zones that are within a set distance from the adit body. In this case, the spacing is 1.0 m. The keyword "extent" indicates that the distance from the surface should be assessed based on the Cartesian extent of the zone, not just the centroid of the zone (Itasca, 2024). Before starting the actual calculations, use the "zone attach by-face" command to attach all nodes. Before the actual mesh generation, in the code presented in Table 1, a block of "brick"-type zones was generated in such a way that it included the adit body "zone create brick size (),"" and the adit geometry file "geometry import 'Excavation. stl'" was imported. As a result, the adit geometry had 5 559 nodes, 16 671 edges, and 11 115 polygons. On its basis, a model with 119 788 walls and 69 341 "brick" zones with the smallest edge dimension of 0.1 m was generated (Fig. 5).

3 Results

To sum up, developing a numerical model of an underground excavation with complex geometry is not a simple task and often requires more than one program to perform numerical calculations. Unfortunately, most often, researchers focus on aspects of models involving the adoption of the rock strength criterion or the selection of physico-mechanical parameters of materials. However, a significant part of the work on the numerical model is related to the construction of its geometry, to faithfully reproduce the shapes of the tested object and, at the same time, ensure optimal calculations. Too complex model geometry may significantly lengthen the calculations. Therefore, in a situation where there is no need to most precisely match the surfaces of the walls of an underground facility, the user does not yet have advanced

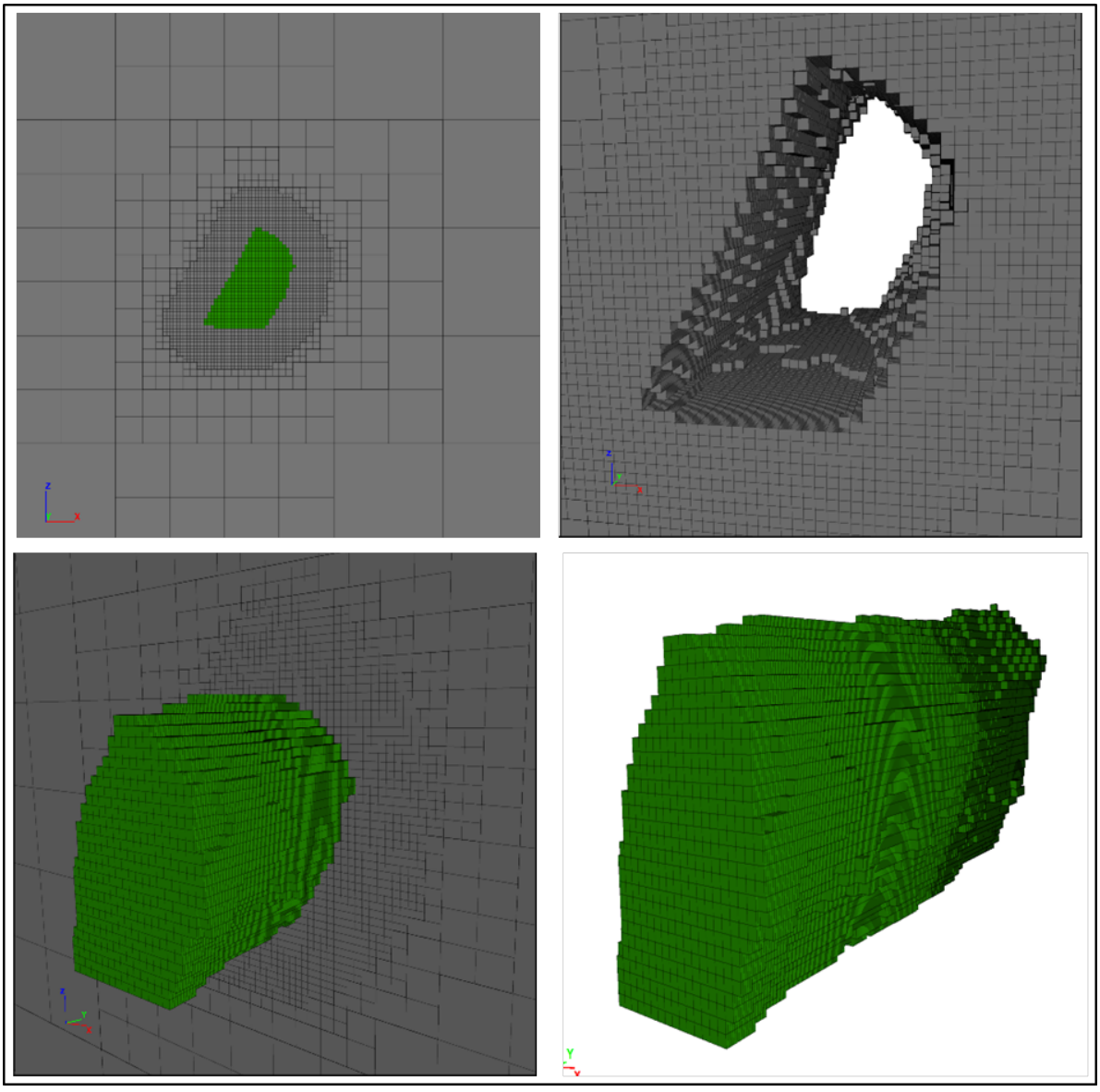


Figure 5: "Brick" zone mesh with "octree" density, generated in FLAC3D.

Table 1: Code in FISH to generate a grid of "brick" zones with "octree" density.

```
model new
;generate zones of rock mass around underground excavation
zone create brick size (5,10,5) point 0 (-9, -5.6, -8) point 1 (7,-5.6, -8) point 2 (-9, 1, -8)...
point 3 (-9, -5.6 ,7)
;import .stl file with solid of underground excavation
geometry import 'Excavation.stl'
;density of zones at the contact of the solid surface with rock mass zones
zone densify segment 2 gradient-limit maximum-length 0.1 repeat range geometry-distance 'Excavation' gap 1.0 extent
zone group 'Excavation' range geometry-space 'Excavation' count odd
zone attach by-face
```

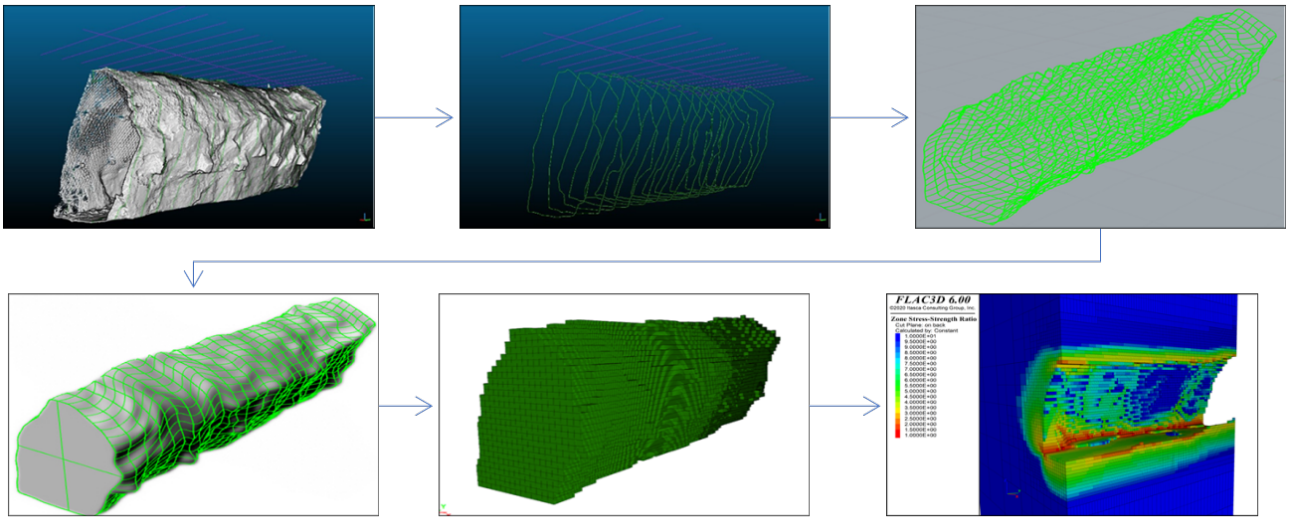


Figure 6: Graphical representation of all stages of geometrization of the numerical model, based on the results of laser screening measurements.

skills, wants to obtain results possible in a short time, and has access to only one numerical modeling software, the methodology presented in this article is optimal. First, in the CloudCompare software, you need to perform basic processing of the "point cloud" and generate cross sections transverse to the axis of the workings, in the form of closed curves. If necessary, cross sections can be corrected in other CAD software after exporting them to a file with the extension (.dxf). Generating geometry based on cross sections allows you to omit unnecessary "point cloud" details that will only disturb the process of building a numerical model, for example, protruding anchors and other elements of the infrastructure of an underground facility. Moreover, this type of approach makes the user independent of imperfections in the "point cloud," that is, surfaces that the laser beam did not reach and which make it difficult to generate the surface. The next step involves generating an open surface in the RHINO software using the "Loft" function and then a solid by closing the flat surface holes with the "Cover Flat Holes" function. The solid should be saved in a file in the (.stl) format. It is recommended to increase the default tolerance when converting to a (.stl) file. In the last step, in the target FLAC3D program, use the code presented in Table 1 in the FISH programming language, developed based on the manufacturer's guide (Itasca, 2024). Figure 6 shows the visualization of all generated files, starting from the "point cloud" (.las), then through closed curves (.dxf), open surface, and solid (.stl), ending with a numerical model based on "brick" zones and carrying out appropriate numerical calculations. In a schematic form, the methodology adopted in the article is presented in Figure 7.

The advantages of the described method include its simplicity, speed, not requiring more than one numerical modeling software, and a low risk of failure when discretizing the model based on "brick" zones. It also provides greater control over the process of generating a solid based on a "point cloud" by generating cross sections in advance. However, a significant disadvantage of the presented procedure is the less-accurate mapping of the object's surface compared to models built on the basis of "hexahedral" or "tetrahedral" zones.

Due to the difficulties in building the geometry of 3D numerical models, it is reasonable to create new methods using the latest technologies. This is justified because simplification of the geometrization process will result in more frequent use of 3D numerical models and their quality, which in turn will increase the safety of using underground workings. For this purpose, it is necessary to publish articles that describe geometrization methods in detail to reach as many engineers as possible.

The next stage of work will include the development of a methodology for geometrizing the numerical model using "hexahedral" or "tetrahedral" zones, also based on the interconnection of CloudCompare, RHINO, and FLAC3D software.

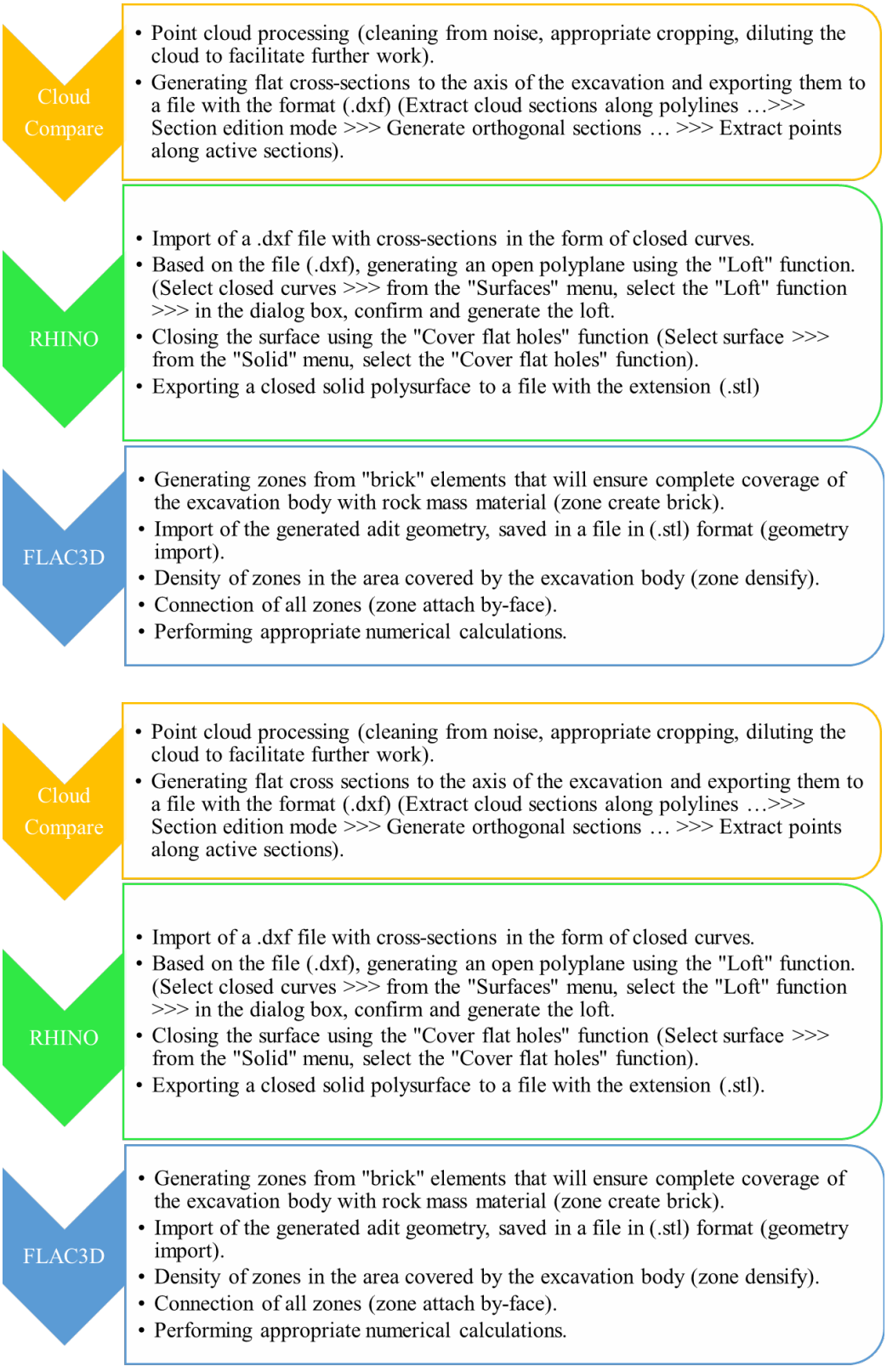


Figure 7: Schematic representation of the numerical model geometrization process based on “point cloud” and FLAC3D using “brick” zones.

References

[1] Fuławka, K., Pytel, W., Szumny, M., Mertuszka, P., Pałac-Walko, B., Hartlieb, P., Jakić, M., Nöger, M., (2022). Prototype of Instrumented Rock Bolt for Continuous Monitoring of Roof Fall Hazard in Deep Underground Mines. Sensors, 23(1), 154. https://doi.org/10.3390/s23010154.

[2] Fuławka, K., Stolecki, L., Szumny, M., Pytel, W., Jaśkiewicz-Proć, I., Jakić, M., Nöger, M., Hartlieb, P., (2022). Roof Fall Hazard Monitoring and Evaluation—State-of-the-Art Review. Energies, 15(21), 8312. https://doi.org/10.3390/en15218312

[3] Mao, J.Z., Zuo, G., (2017). Modeling method of FLAC3D based on RHINO-KUBRIX and deformation analysis of tunnel lining structure. *Advances in Engineering Research, 112, pp. 520–528.* http://doi.org/10.2991/icreet-16.2017.87.

[4] Wang, S., Zhang, Q., (2010). A Coupling Modeling Method with MIDAS/GTS-FLAC 3D and Its Application. Journal of Civil, *Architectural & Environmental Engineering, 32(1), pp. 12-17.*

[5] Kajzar, V., Kukutsch, R., Heroldová, N., (2015). Verifying the possibilities of using a 3D laser scanner in the mining underground. *Acta Geodynamica et Geomaterialia 12(1), 177.* https://doi.org/10.13168/AGG.2015.0004

[6] Maciaszek, J., Gawałkiewicz, R., Gawałkiewicz, I., (2010). Od modelu do numerycznej mapy przestrzennej. *Geologia, 36(3), pp. 331-344. (in polish)*

[7] Janus, J., Ostrogórski, P. (2022). Underground Mine Tunnel Modelling Using Laser Scan Data in Relation to Manual Geometry Measurements. *Energies 15(7), 2537.* https://doi.org/10.3390/en15072537

[8] Fekete, S., Diederichs, M., Lato, M. (2010). Geotechnical and operational applications for 3-dimensional laser scanning in drill and blast tunnels. *Tunnelling and Underground Space Technology 25(5), pp.614-628.* https://doi.org/10.1016/j.tust.2010.04.008

[9] Cieślik, J., Flisiak, J., Tajduś, A., (2009). Analiza warunków stateczności wybranych komór KS „Wieliczka" na podstawie przestrzennych obliczeń numerycznych. *Górnictwo i Geoinżynieria, 33(3/1), pp. 91-102 (in polish)*

[10] D'Obryn, K., Hydzik-Wiśniewska, J., (2013). Selected aspects of numerical modelling of the salt rock mass: the case of the „Wieliczka" salt mine. *Archives of Mining Sciences, Vol. 58 (2013), No 1, p. 73–88.* DOI:10.2478/AMSC-2013-0005

[11] D'Obryn, K., Hydzik-Wiśniewska, J., (2017). Assessment of rock mass stability in the historic area of levels IV-V of the „Wieliczka" salt mine of the „Wieliczka" salt mine. *Archives of Mining Sciences, Vol. 62 , No 1, p. 189-202.* DOI 10.1515/amsc-2017-0014

[12] Bock, S., (2015) New open-source ANSYS-SolidWorks-FLAC3D geometry conversion programs. *Journal of sustainable mining, 14, pp. 124-132* https://doi.org/10.1016/j.jsm.2015.11.002

[13] Madziarz, M. (2012). Historical ore mining sites in Lower Silesia (Poland) as geo-tourism and industrial tourism attraction. *International Twin Conference GEOTOUR & IRSE 2012 Geoparks, Geoheritage and Geoconservation IRSE: History of Central European Mining, Salgótarján, Hungary 04–06 October.* https://doi.org/10.13140/RG.2.1.3702.4803

[14] Pytel, W., Fuławka, K., Pałac-Walko, B., Mertuszka, P., (2023). Numerical and Analytical Determination of Rockburst Characteristics: Case Study from Polish Deep Copper Mine. Applied Sciences, 13(21), 11881. https://doi.org/10.3390/app132111881

[15] CloudCompare - Open Source project . 3D point cloud and mesh processing software.

[16] FLAC (FLAC2D/FLAC3D) — Itasca Software 9.0 documentation (itascacg.com). Itasca Consulting Group

[17] Trimble Inc.: Laser scanner TX8 technical data sheet

[18] Trimble RealWorks - Trimble Geospatial. Point cloud processing and analysis software for 3D laser scanning professionals.

[19] Rhino - Rhinoceros 3D. Design, Model, Present, Analyze, Realize... (rhino3d.com)