

Ihor BUBNIAK^{1A*}, Andriy BUBNIAK², Yevhenii SHYLO^{1B},
Mariia OLIINYK^{1C}, Mykola BIHUN^{1D}

¹Department of Engineering Geodesy of Lviv Polytechnic National University, 12, S. Bandery Str., Lviv, 79013, Ukraine
ihor.m.bubniak@lpnu.ua, mariia.a.oliinyk@lpnu.ua, ^{1A} <http://orcid.org/0000-0002-3548-8785>, ^{1B} <http://orcid.org/0000-0002-3838-5431>

² Institute of Geological Sciences, Polish Academy of Sciences, 6, Twarda Str., Warsaw, Poland,
e-mail andrewbubniak@yahoo.com

<https://doi.org/10.23939/istcgcap2023.97.005>

3D MODEL OF THE TURKA QUARRY

The aim of this work is to study the Turka quarry using terrestrial laser scanning, as well as to build a 3D model of the object. Method. The study of the outcrop was carried out with terrestrial laser scanning. The article describes the principles of operation of laser sensors and provides a classification of error sources. It also emphasizes the importance of achieving the maximum accuracy specified by scanner manufacturers. The location of the researched object. The studied quarry is located on the northern outskirts of the city of Turka, Lviv region. From the geological point of view, the object is situated in the Outer Ukrainian Carpathians that belong to the Carpathian mountain system. The inactive quarry is structurally confined to the north-western part of the Krosno nappe of the Ukrainian Carpathians. The characteristic Turka (Krosno) type of cross-section of the Oligocene-Miocene age is exposed in the walls of the quarry. This is a layering of massive packs of gray fine-grained sandstones with argillites and siltstones which are broken with joints. The joints are filled with longitudinal, transverse and differently oriented veins. They are often wedged out. Their thickness ranges from a few mm to 55 mm or more. Slickensides and leaching are observed along the cracks. The research results make it possible to analyze the geological structure without being directly near the object. The paper provides a workflow diagram of the terrestrial scanning workflow. This includes object reconnaissance, establishing and determining the coordinates of reference and control points. It also involves performing terrestrial 3D scanning, photographing an object, creating a cloud of points based on laser scanning data, developing a mesh model based on point clouds and digital images. The accuracy of the mesh model was defined by comparison of the coordinates of the control points obtained from the mesh model and tachymetric survey. The absolute spatial difference does not exceed five centimeters. The scientific novelty and practical significance are in the creation of a virtual model of the Turka quarry. For the first time, terrestrial laser scanning technology was used for the research of this object. As a result, a 3D model was obtained, which can be used for further research in the field of geology, in particular structural geology, sedimentology, mineral reserve calculations and geotourism.

Key words: terrestrial laser scanning, virtual outcrop, 3D model, workflow diagram, Turka quarry, Outer Ukrainian Carpathians.

Introduction

Quarries are extremely important objects of research in geology because they provide detailed information about the structure of a certain section of the earth's crust. Also, quarries are of special value for geologists, whereas there are not many outcrops. The majority of geological objects are covered by Quaternary sediments. Quarries bring large areas of rock to the surface. Complete information about rocks leads to accurate conclusions about geological processes. Processing such outcrops requires a lot of time and skills. It also includes measurements of the thickness of layers, of joints and faults, description of folds, etc. The use of modern digital technologies significantly shortens the field and cameral stages. One of these me-

thods is laser scanning which has been used in a number of geological studies [Trinks et al., 2005; Bellian et al., 2005; Jones et al., 2008; Arrowsmith and Zielke, 2009; Abellán et al., 2011; Laponi et al., 2011; Rarity et al., 2014; Calvo and Ramos, 2015; Matasci et al., 2015; Wang et al., 2017; Verma and Bourke, 2018; Oliinyk et al., 2021; Oliinyk et al., 2022; Bubniak et al., 2023]. The article "Analysis of literary sources on the topic "Virtual geological outcrop"" provides detailed description of the development of the use of modern technologies for the geological objects study [Oliinyk and Bubniak, 2022]. Analyzing the results of the work, it is necessary to emphasize time saving both in the field and while processing the collected data. A 3D model of the object is the product of the final result of research using the laser scanning method.

In recent years, significant progress has been made in obtaining spatially oriented information of natural objects such as outcrops [Oliinyk et al., 2022; Bubniak et al., 2023], quarries [Oliinyk et al., 2023], in tunnels [Wang et al., 2023], slope processes [Lukačić et al., 2023; Ismail et al., 2022]. The last description compares the use of a terrestrial laser scanner and an unmanned aerial vehicle for analyzing the stability of rock slopes, which allows for collecting accurate data based on a 3D point cloud, compared to manual mapping. In their publication, the authors [Lukačić et al., 2023] describe the importance of characterizing rock formations for engineering geological research and identifying their fractures, using terrestrial laser scanning to obtain 3D point clouds and textured models, which helps to collect more data. The article [Wang et al., 2023] discusses the use of terrestrial laser scanning to describe rock formations and analyze stability in tunnels. This permits to obtain detailed geometric information about the fracture system and create numerical models for detecting and evaluating potentially dangerous rock blocks. This method is less labor-intensive and safer compared to manual scanning during the research. The works [Oliinyk et al., 2022; Bubniak et al., 2023; and Oliinyk et al., 2023] describe the process of creating a virtual outcrop model using various techniques, including laser scanning, photography, and creating a mesh model, for geological studies in the Ukrainian Carpathians.

The aim

The aim of this study is to create a virtual 3D model of the Turka quarry using a modern method of terrestrial laser scanning. The research was conducted to use this model for structural geology, sedimentology, tourism, and for educational purposes.

The location of the studied area

The studied quarry is located on the northern part of the city of Turka, Lviv region (Fig. 1).

Geologically, the studied area is situated in the Outer Ukrainian Carpathians, which belong to the Carpathian mountain system. The Carpathians are traditionally divided into Western, Eastern and Southern. In cross-section, the Carpathians are divided into Outer and Inner. The Pennine zone

(nappe) is the boundary between these two tectonic units. The basis for such division is the time of final folding. For the Inner Carpathians, these were the processes that appeared in the Mesozoic, and for the Outer Carpathians, in the Cenozoic. There is foredeep in front of the Ukrainian Carpathians. And the Transcarpathian Depression is in the rear part of the Carpathians. Research in the Ukrainian Carpathians has more than two-hundred-year history. A great amount of work was conducted here, including mapping, geophysical, and drilling. This allowed building various tectonic schemes. Today, at least four of them are used by various researchers.

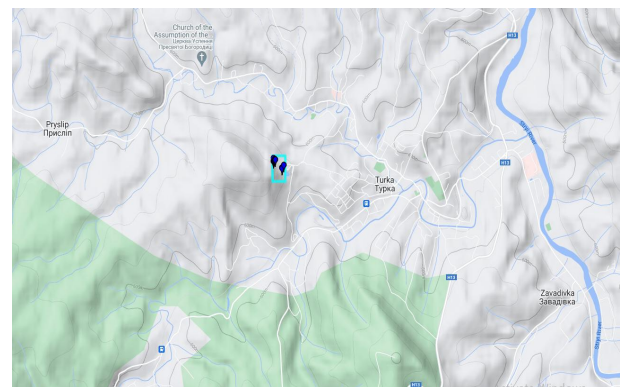


Fig. 1. Map showing the location of the Turka quarry

They differ in number and names of tectonic elements. In some schemes, they are called zones, and in others nappes. Thus, on the scheme proposed by the researchers of the Ukrainian Geological Exploration Institute, the following are highlighted (from northeast to southwest): Ukrainian Carpathian foredeep, Skyba, Krosno, Dukla-Chornohor, Rakhiv nappes and, Marmaros massif.

The Krosno tectonic unit (nappe) is the second nappe from the edge of the Ukrainian Carpathians. It is traced on the surface from the Polish-Ukrainian border to the Romanian border for a distance of about 200 km. From the northeast, it is thrust onto the Skyba nappe, and from the southwest it is limited by the Dukla-Chornohora. It is also limited by the Burkut nappe in the basins of the Black and White Tysa rivers.

It is 25–38 km wide in the northwestern part, in the central part – 18–25. And in the southeastern part, its width is from 20 km to almost complete overlapping.

Based on the lithological differences, the Cretaceous-Paleogene cross-section of the Krosno nappe is divided into two sub-nappes, the Turkivsky and Bitlyansky ones, which consist of thrust and sheets.

The Krosno nappe is composed of rocks of Cretaceous and Paleogene age, but their lithological composition differs sharply from the northeast to the southwest. So two separate subnappes are distinguished here – Turka and Bitlya. Outcrops of Upper Cretaceous deposits are described at three points: in the Rozluzh unit, in the areas of the villages of Mala Volosyanka and Yavory. They were recorded in the 2-Turka structural exploration well in the interval 545–660 m. Cretaceous deposits are represented by thin and medium-rhythmic alternation of gray argillites, sandstones and siltstones.

The Paleocene and Eocene in the Turka subnappe consists of two complexes. The first is mainly represented in the northwestern part of the subnappe. This is an undissected stratum of the Lower and Middle Paleogene. The second stretches in the central and southwestern part of the subnappe, in the Grozova, Yalynkuvate, and Gorgan thrusts, where the Yamna, Maniava, Vygoda, and Bystrytsia suits are distinguished.

Yamna suit is composed of thinly layered sandstones. There are layers of argillites and siltstones. At the bottom of the suit there is a variegated horizon of cherry-red and green argillites alternating with siltstones and medium-layered sandstones. The thickness of the suit is 200 m.

The Maniava suit is represented by a rhythmic alternation of sandstones, siltstones, and mudstones. Among the mudstones there are black varieties, and sometimes flints. The sandstones are several meters thick. They are gray, dark gray, greenish-gray, fine-, medium-variegated, siliceous and strongly siliceous, non-calcareous, with a thickness of 0.1–0.3 m. There are layers of thick-layered sandstones with a thickness of 1–2.5, and sometimes up to 5 m. The thickness of the suit in general is 150–200 m.

Vygoda suit lies on the Maniava one. The section is dominated by sandstones with interlayers of mudstones and packs of rhythmically alternating mudstones, siltstones, and sandstones. The sandstones are gray, dark gray, greenish-gray, fine-grained, multi-grained with gravel in the sole, massive, non-calcareous, siliceous, very strong, sometimes calcareous. The thickness of the Vygoda suit in the studied area is 100–200 m.

Upper Eocene sediments are represented by alternation of mudstones, siltstones and sandstones. In the Dovzhynski layers, the sections are dominated by sandstones. The thickness of the Upper Eocene is 370 m.

Oligocene deposits are represented by the Golovetsk and Verkhovyna horizons. In the northwestern part of the Turka subnappe, the Golovetsk horizon is divided into two sub-horizons: the lower clayey and the upper sandy one. The lower Golovetsk horizon is characterized by the presence of siliceous horizons. The upper Golovetsk horizon is dominated by sandstones. The thickness of the Golovetsk horizon is 700–850 m.

The Verkhovyna horizon is divided into three parts: the lower, middle, and upper Verkhovyna sub-horizons. A marking horizon of striated limestones was found at the base of the Lower Verkhovyna subhorizon. Above is a stratum of sandstones of the Krosno type. The thickness of sandstones is up to 10 m.

The Middle Verkhovyna subhorizon is composed of medium-rhythmic layering of gray, calcareous mudstones, siltstones, and fine-grained sandstones.

The reservoir “Blue Lake” belongs to the quarry in the vicinity of the city of Turka (Lviv region, Ukraine). It is structurally related to the northwestern part of the Krosno cover of the Ukrainian Carpathians.

The characteristic Turka (Krosno) type of section of the Oligocene-Miocene age is exposed in the walls of the quarry. This is a layering of massive packs of massive gray fine-grained sandstones with mudstones and siltstones which are broken by cracks filled with longitudinal, transverse and differently oriented veins. They are often wedged out. Their thickness ranges from a few mm to 55 mm or more. Slickensides and leaching are observed along the joints.

Method

The technology of terrestrial laser scanning was used for the research of the Turka quarry. Measuring range using laser sensors is based on three main principles: phase shift, time-of-flight and optical triangulation. The principles of operation of a laser scanner are described in detail in a number of papers [Lemmens, 2004; Van Genechten et al.,

2008; Colombo and Marana, 2010; Maar and Zogg, 2014; Jaafar, 2017; Puzikov, 2021]. While using this technology, it is important to be able to distinguish the deformations from the existing errors during scanning. Lichti and Gordon [Lichti and Gordon, 2004] experimentally proved that the accuracy of all scanned points was lower than the accuracy declared by the manufacturers. So, the authors emphasize the creation of such scanning conditions under which the maximum accuracy can actually be achieved. Staiger [Staiger, 2005] notes the existence of five sources of error, namely, related to the method of data collection, the environment, the object of research, the scanner, and calculation methods, where each source of error contains its own aspect (Fig. 2).

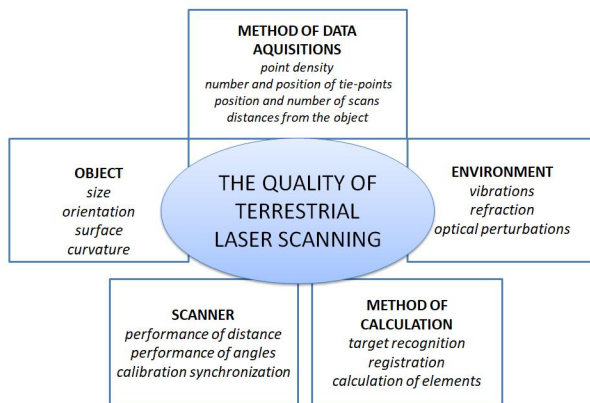


Fig. 2. Modified scheme of parameters affecting the quality of scanning [Staiger, 2005]

Another group of scientists [Holst and Kuhmann, 2016; Kaasalainen et al., 2011; Soudarissanane et al., 2008; Soudarissanane et al., 2009; Soudarissanane et al., 2011] identify four sources of error:

- accuracy of the hardware mechanism precision, so-called instrumental errors (angular uncertainty, axis errors);
- properties of the object (roughness, reflectivity, color);
- atmospheric conditions (ambient light, humidity, temperature);
- scanning geometry, e. g. incidence angle, range differences.

Some researchers [Hodge et al., 2009; Hodge, 2010] add data processing (e. g. registration), and data resolution to these sources [Van Genechten, 2008].

Workflow

The results of investigation are presented in the form of a diagram (Fig. 3)

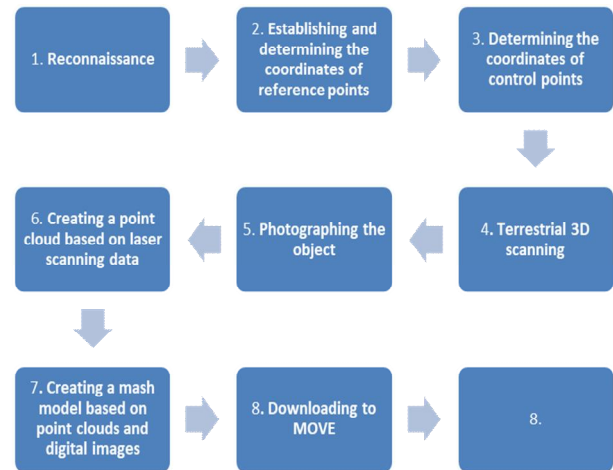


Fig. 3. Diagram of the workflow

1. *Reconnaissance of the object.* At this stage, a detailed review of the object of research is conducted. According to the technical task, we determine the future position of control and reference points, as well as standing stations for the laser scanning, tacheometric surveying, and photography.

2. *Establishing and determining the coordinates of reference points.* Six black and white marks are placed on the body of the outcrop. Below is their schematic placement on the space photo taken in August 2019. Fig. 4 shows that points 3, 4, 5 are placed on a flooded area, however, this area was dry during the surveying (02.10.2022).



Fig. 4. The scheme of reference points' location

The coordinates of these points (Table 1) were determined by the GNSS receiver South Galaxy G1 in RTK mode from the GeoTerrace network. Coordinate system UTM34N.

Table 1

Coordinates of the situated points

| No. | X, m | Y, m | H, m | RMS determination of the planned position, m | RMS determining the altitude position, m |
|-----|-------------|------------|---------|--|--|
| 1 | 5446655.342 | 646528.607 | 660.380 | 0.020 | 0.053 |
| 2 | 5446664.538 | 646516.180 | 660.530 | 0.018 | 0.054 |
| 3 | 5446656.510 | 646501.416 | 660.501 | 0.018 | 0.055 |
| 4 | 5446633.707 | 646524.211 | 661.053 | 0.033 | 0.086 |
| 5 | 5446653.417 | 646510.921 | 659.144 | 0.026 | 0.050 |
| 6 | 5446665.429 | 646502.999 | 659.242 | 0.074 | 0.130 |

3. *Determining the coordinates of control points.* Natural joints were used for this purpose. The coordinates of the control points were determined with an electronic total station Leica TCR 405. The total station was oriented in the coordinate system with an inverted serif on reference points, and then the natural contours chosen by us were fixed on the body of the outcrop (one of these contours is shown in Fig. 5). Mean squared error inverted serif is $X=0.008$ m, $Y=0.016$ m, $Z=0.018$ m, angle is $1'36''$.



Fig. 5. A picture of the eyepiece of the optical tube aimed at the control point

In this way, other six control points were fixed to control the future 3D model.

4. *Terrestrial 3D scanning.* Laser scanning was performed with a Leica ScanStation C10 scanner. Fig. 6 shows the diagram of the scanning network. Three scanning stations are located in the lowest part of the outcrop and are located approximately on the same lane with a step of 25 and 15 m. The fourth station is located on the top of the

right slope of the quarry, the excess is 29 m. The area of the object that needed to be displayed in more detail was scanned from this station.

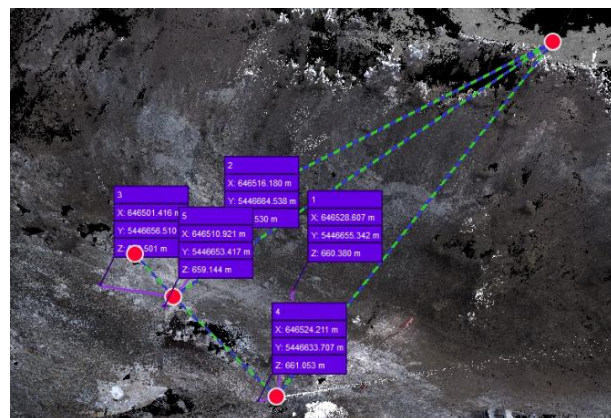


Fig. 6. Scheme of the scanning network with reference points

5. *Photographing the object.* This procedure is necessary to improve the quality of the future mesh model, some details and textures. Canon Mark 3 5D digital camera was used for this (Fig. 7). Shooting was performed at scanning stations, as well as along the foot of the slopes. A total of 344 pictures were taken.

6. *Creating a point cloud based on laser scanning data.* Processing was carried out in the program Leica Cyclone Register 360. To orient the point cloud in the coordinate system, five reference points were used. The obtained RMS during balancing are shown in the Table 2.



Fig. 7. Camera shot with Canon Mark 3 5D

7. Creating a mash model based on point clouds and digital images. We performed this step in the Reality Capture program. Picture 8 shows images of the processing. Cube images with black

faces correspond to scanning stations, and rectangles to camera images. The figure shows three scanning stations at the lowest point of the pit. The accuracy of the mash model was assessed by comparing the coordinates of the control points obtained from the mash model and the tacheometric survey. The absolute spatial difference does not exceed five centimeters.

Table 2

Five control points with RMS

| No. Control point | RMS, m |
|-------------------|--------|
| 1 | 0.018 |
| 2 | 0.016 |
| 3 | 0.022 |
| 4 | 0.030 |
| 5 | 0.039 |

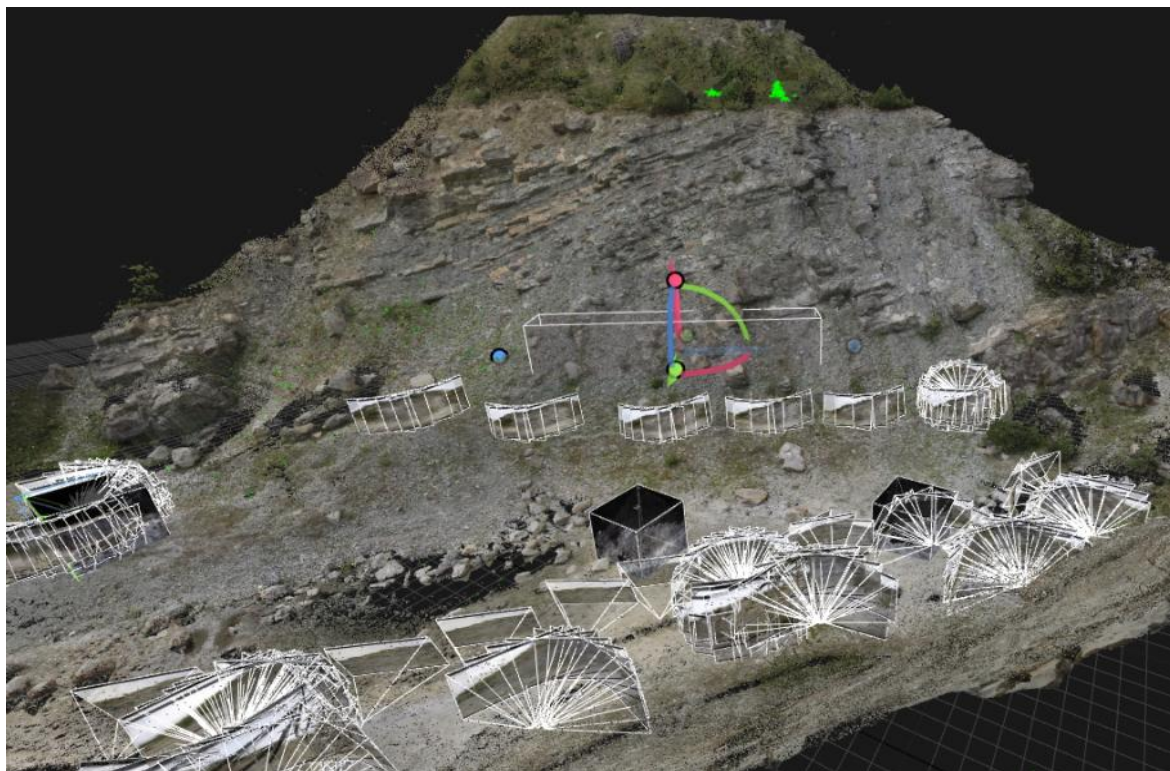


Fig. 8. Screenshot of the processing in the Reality Capture program

Results

In this work, we demonstrate the use of a 3D model for structural geology purposes. The IPM-Move software is used to process the results. The program's toolkit allows for the same measurements to be made on the model as geologists do in the field. This primarily involves the orientation of

structural elements, both linear and planar. Fig. 11 shows the bedding elements of the formations obtained from all parts of the quarry.

The obtained data are used to construct geological sections which are depicted on a Wolf (Schmidt) net using the appropriate software (Fig. 12).

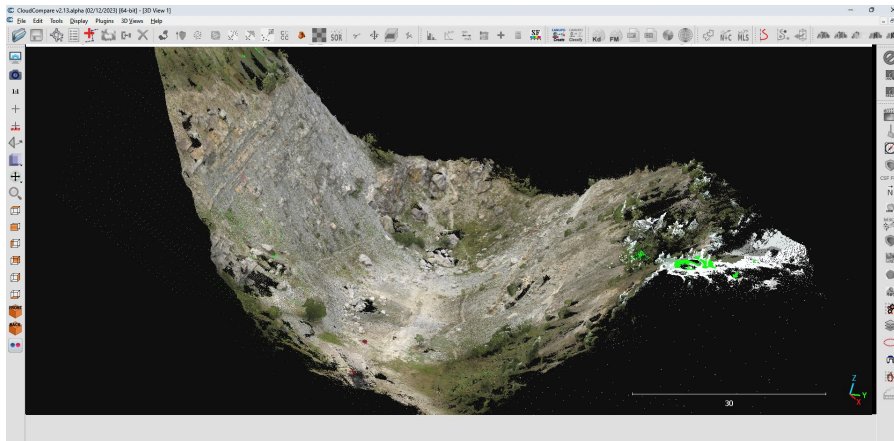


Fig. 9. 3D model of the Turka quarry in the IPM-Move program window

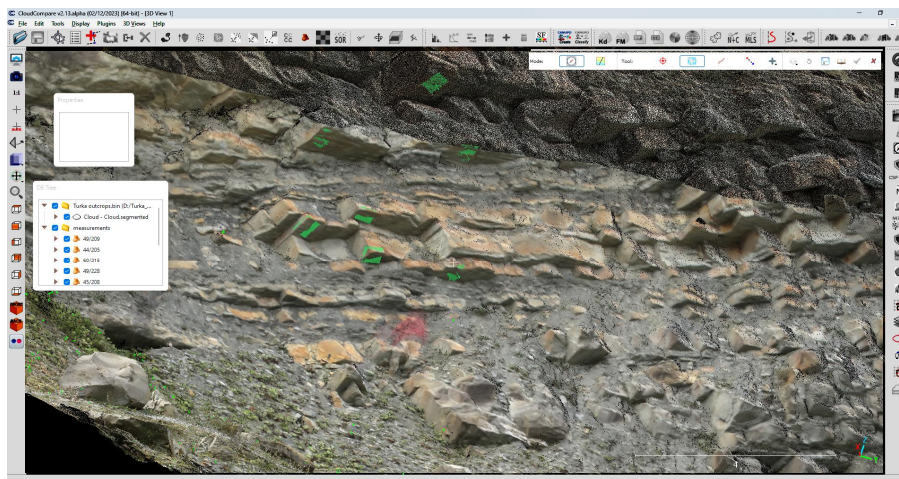


Fig. 10. Fragment of the structure of the Turka quarry's flysch formation

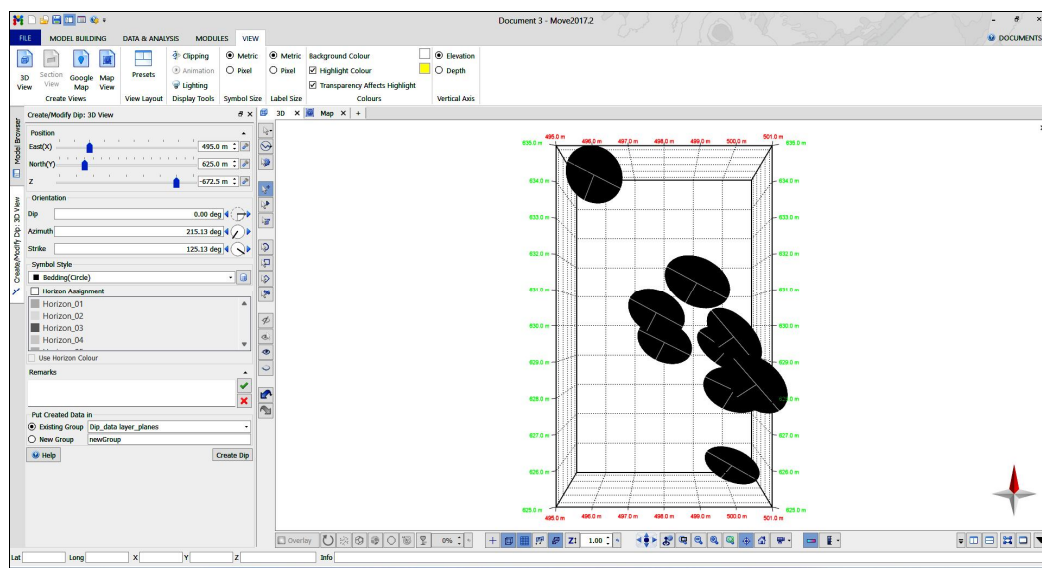


Fig. 11. Bedding elements of the Turka quarry's flysch complex

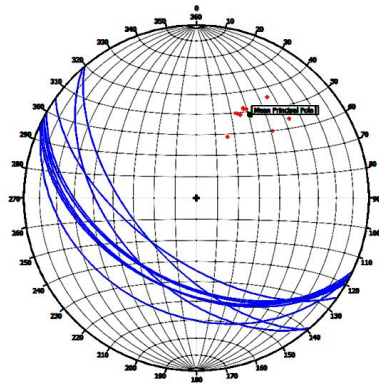


Fig. 12. Bedding elements in the Turka quarry

Another useful application of the 3D model in structural geology is the study of fracturing. The study of fracturing in structural geology is quite a laborious process. Using a geological compass, the orientation of the fracture – the azimuth of the dip and the dip angle – is measured. There should be at least 100 such measurements. The use of computer programs makes it possible to measure fractures in automatic or semi-automatic mode. This reduces subjectivity compared to manual measurement. Especially important is the ability to measure in hard-to-reach places. The number of measurements also increases significantly. The results of studying joints are used in planning work at quarries, laying roads. Significant attention is paid to crack formation in petroleum geology.

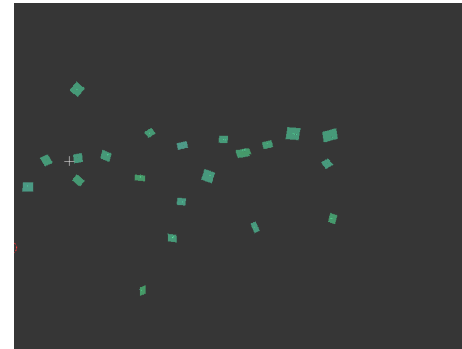
The scientific novelty and practical significance

Terrestrial laser scanning was used for the first time to create a virtual geological model of the Turkiv quarry. The 3D model can be utilized for further research in the field of geology, in particular structural geology, sedimentology, for calculations of volumes of useful components extracted in the quarry. Using the model for tourist purposes is equally important, as this location is known for the lake called the Blue Lake because of the fantastic color of the water, especially in sunny weather.

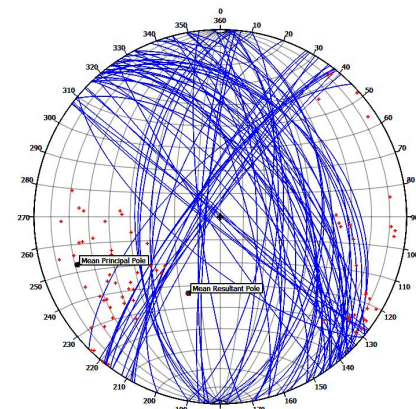
3D model was obtained, as a result of the survey work carried out in the Turka quarry using terrestrial laser scanning (Fig. 9). This model can be used for many purposes, especially, for visualization. Thanks to the obtained model, we can observe the details of the geological structure of each section of the quarry, especially those that are difficult to access (Fig. 10).



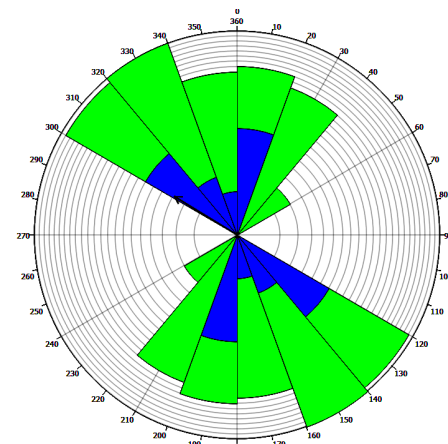
a



b



c



d

Fig. 13. Results of the study of joints in the Turka quarry: a – joints in the flysch complex; b – approximation of cracks to planes; c – cracks of the Turka quarry shown on the Wolff grid; d – cracks of the Turka quarry in the form of a rose diagram

Conclusions

For the first time, a 3D model of the Turka quarry was built using terrestrial laser scanning. During surveying, a work plan is proposed that can be used for other objects in the Ukrainian Carpathians and other mountain areas. An assessment of the accuracy of surveying was performed. The created model will be used in the future to solve problems in the field of geology, while calculating mineral reserves (in our case, sandstone volumes). The conducted research demonstrated the high efficiency of terrestrial laser scanning in the creation of three-dimensional models of geological objects.

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Ігор БУБНЯК^{1A*}, Андрій БУБНЯК², Євген ШИЛО^{1B}, Марія ОЛІЙНИК^{1C}, Микола БІГУН^{1D}

¹ Кафедра інженерної геодезії, Національний університет "Львівська політехніка", вул. С. Бандери, 12, Львів, 79013, Україна, ел. пошта: igor.m.bubniak@lpnu.ua, maria.a.oliinyk@lpnu.ua,

^{1A} <http://orcid.org/0000-0002-3548-8785>, ^{1B} <http://orcid.org/0000-0002-3838-5431>

² Інститут геологічних наук, Польська академія наук, вул. Тварда, 6, Варшава, Польща, ел. пошта: andrewbubniak@yahoo.com

3D МОДЕЛЬ ТУРКІВСЬКОГО КАР'ЄРУ

Мета цієї роботи – дослідження Турківського кар'єру за допомогою наземного лазерного сканування, а також побудова 3D моделі об'єкта. Методика. Дослідження відслонення виконувалось за допомогою наземного лазерного сканування. Зазначено принципи роботи лазерних датчиків, надано класифікацію джерел похибок та наголошено на важливості досягнення максимальної точності, зазначеної виробниками сканерів. Положення досліджуваного об'єкта. Досліджуваний кар'єр знаходиться на північній окраїні м. Турка Львівської області. У геологічному відношенні об'єкт знаходиться у Зовнішніх Українських Карпатах, які належать до Карпатської гірської системи. Закинута каменеломня структурно приурочена до північно-західної частини Кросненського покриву Українських Карпат. У стінах каменеломні відслонюється характерний Турківський (кросненський) тип розрізу олігоцен-міоценового віку. Це перешарування потужних пачок масивних сірих дрібнозернистих пісковиків із аргілітами та алевролітами, які розбиті тріщинами, залікованими повздовжніми, поперечними та різноорієнтованими жилами і прожилками. Вони часто виклинюються. Їхня товщина коливається від декількох мм до 55 мм і більше. По тріщинах спостерігаються сліди ковзання і вилугування. Результати досліджень дають змогу проаналізувати геологічну будову, не знаходячись безпосередньо біля об'єкта. В роботі наведено схему робочого процесу наземного сканування: рекогностування об'єкта, встановлення та визначення координат опорних точок, визначення координат контрольних точок, виконання наземного 3D сканування, фотографування об'єкта, створення хмари точок за даними лазерного сканування, створення mash моделі на основі хмари точок та цифрових знімків. Оцінку точності mash моделі виконували шляхом порівняння координат контрольних точок, отриманих з mash моделі та тахеометричного знімання, абсолютна просторова різниця не перевищує п'яти сантиметрів. Наукова новизна та практична значущість полягають у створенні віртуальної моделі Турківського кар'єру. Вперше для досліджень цього об'єкта було використано технологію наземного лазерного сканування. В результаті отримано 3D модель, яку можна застосувати для подальших досліджень в області геології, зокрема структурної геології, седиментології, підрахунків запасів корисних копалин та геотуризмі.

Ключові слова: наземне лазерне сканування, віртуальне відслонення, 3D модель, робоча схема, Турківський кар'єр, Зовнішні Українські Карпати.

Received 27.01.2023