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PREPARATION OF A CANDLESTICK-SHAPED STALAGMITE'S DIGITAL 3D SHAPE

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Abstract: Tall stalagmites, also known as candlestick stalagmites, are considered vulnerable, since their break has a relatively high probability in the event of an earthquake. Their existence has implications on the maximum magnitude of recent earthquakes, which highlights the importance of recording their dimensions and shape accurately. This study introduces the acquisition and processing of terrestrial laser scanner data over the tallest and most vulnerable stalagmite in the Plavecká priepast (Detrekői-zsomboly) in the Little Carpathians (Slovakia). In addition, the 3D point cloud that was captured from three scan positions in 2024 was compared to a TIN model representing an earlier state of stalagmite dated back to 2015. The comparison of the present 3D point cloud and the former TIN model provides information not only on the temporal change of the stalagmite over the past nine years, but also on the discrepancies between the two surveys taken at the different epochs.

Keywords: *laser scanning, 3D point cloud, stalagmite, karstic cave*

1. INTRODUCTION

Since 2013, several measurements and analyses in Plavecká priepast have been carried out. These include resonance measurements of stalagmites, age determination of stalagmites, mechanical laboratory analysis of broken stalagmite fragments (Gribovszki et al., 2017a, 2017b), stalagmites' shape analyses and laser scanning. The main goal of the existing studies is to estimate the long-term seismic hazard values for the close surroundings of the cave. In this paper, we report on the laser scanning of a slim and vulnerable, 4.3 m high standing stalagmite, and the creation of a 3D point cloud.

This stalagmite is located in a shallow cave close to the surface (Gribovszki et al., 2017a) and is therefore suitable for earthquake hazard assessment, either for the present day or backwards in time (think here of the surface amplification of earthquake waves coming from the deep earth). By examining vulnerable dripstones, information can be obtained on the maximum magnitude of earthquakes (M_{max}), e.g. the maximum horizontal acceleration or velocity that the dripstone can "withstand" without fracturing (Szeidovitz et al., 2005, 2008a, 2008b; Gribovszki et al., 2008, 2013a, 2013b, 2017a, 2017b, 2018, 2020; Paskaleva et al., 2006, 2008; Zembaty et al., 2023).

Usually, the first step in the stalagmite-based numerical studies for seismic hazard used to be the calculation of natural frequencies of the stalagmite and its higher harmonics. These kind of numerical eigenfrequency calculations (FEM: Finite Element Method) have been done not only by Hungarian and Polish researchers (Gribovszki et al., 2018; Zembaty et al., 2023), but in other caves in Europe (Martin et al., 2020; Bottelin et al., 2020) as well. Martin et al. (2020) applied 3D laser scanning to build a detailed 3D numerical model of the Minaret stalagmite in Han-sur-Lasse cave. They used this 3D numerical model to calculate the stalagmite natural frequencies with FEM. Bottelin et al. (2020) investigated very fragile soda straws in Choranche cave (France) by FEM both for eigenfrequency and maximal tensile stress calculation, but they did not use laser scanning for building the numerical model of the soda straws. They have first simulated the resonance amplification of speleothems, particularly for very slender soda straws. Kovács and Takács (1980) dealt with the theoretical considerations of finite element analysis of bending vibrations of straight-axial beams like stalagmites or stalactites.

In 2023, we conducted a complete survey with a laser scanner of one of the cave's chambers (the Chamber of Dripstones) in Plavecká priepast. The complete processing of the collected data is still in progress. So far, one 3D digital model of the same 4.3 m high stalagmite has been produced in 2015. This study shows the comparison of the recently prepared and the previous model as well.

2. AIMS AND METHODS

The aim of this present investigation was to create a 3D point cloud of the highest stalagmite in the cave, using data collected by laser scanning in the Plavecká priepast in the Little Carpathians (Slovakia). The cave survey was made difficult by the fact that the cave can only be approached through a 30 m deep ravine and that access to the cave is subject to a permit.

After the laser scanning of the stalagmite from three positions, the registration of the point clouds was carried out using the software packages Leica Cyclone and CloudCompare. The registered point cloud can be used as input data for future stalagmite growth assessment, modeling of natural frequencies and harmonics (Gribovszki et al., 2018; Zembaty et al., 2023), to determine the elastic parameters of the stalagmite (Zembaty et al., 2023) and to calculate the ground acceleration or velocity required for stalagmite fracture (Paskaleva et al., 2006, 2008; Zembaty et al., 2023).

The measurement was carried out using Leica BLK360 instrument, which performs laser ranging with a precision of ±6 mm at 10 m distance, with approximately 100 kHz scanning frequency. Furthermore, the instrument has three integrated HDR cameras, with which RGB colors can be assigned to point measurements (Leica Geosystems, 2017). Two tripods, five 4.5" retro-reflective targets and two 6.5" retro-reflective targets were used. The light weight, and compact size of the instrument enables its use in the cave where rough terrain conditions, and narrow corridors set limitations for using larger equipment.

Three scan positions were established in the “Chamber of dripstones” *(Figure 1a)* to get multiple views of the highest stalagmite in the cave. The next step was to position retro-reflective targets that are used as tie-points for the orientation and merging of individual point clouds. Minimum three tie points were visible from each scan position, and their distance from the instrument was less than 10 m. *Figure 1b* shows an intensity image of part of the cave. The figure also shows two retro-reflective targets.

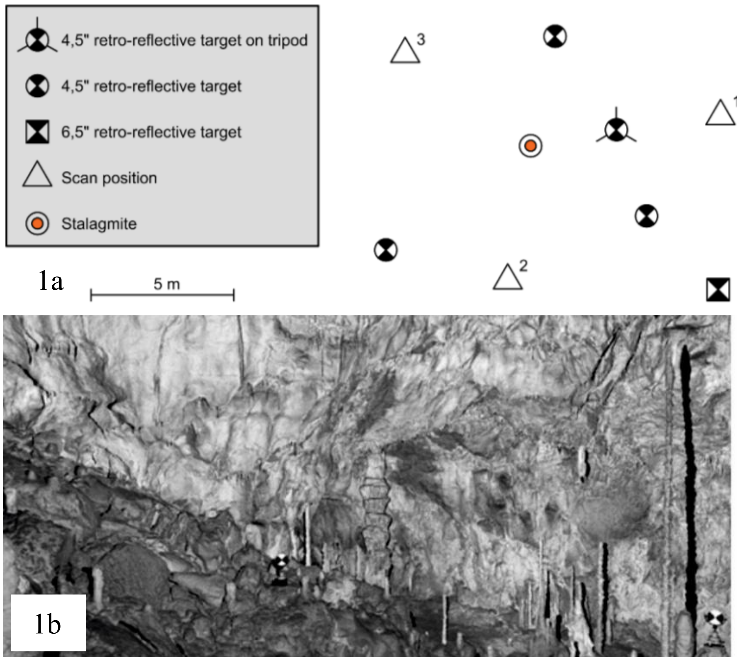

Figure 1
a) Locations of the scan positions and tie-points in the cave area in the “Chamber of dripstones”, with the location of the stalagmite under investigation, b) intensity image of a part of the cave with 2 retro-reflective targets

In 2015, a triangulated irregular network (TIN) model of the stalagmite was made by Anton Arpáš, Branislav Balžan and Matej Ruttkay researchers from the Institute of Archaeology of the Slovak Academy of Sciences (SAS). This TIN model from 2015 has been uploaded to the Mendeley database (Zembaty et al., 2022). The 3D point cloud presented in this study has been compared with the TIN model prepared by the researchers from the Institute of Archaeology in 2015. The comparison was made using the CloudCompare software (Girardeau-Montaut, 2011).

3. DESCRIPTION OF THE CAVE AND THE STALAGMITE

The stalagmite is located in Plavecká priepast *(Figure 2)*. The Plavecká priepast is situated in the Little Carpathians, in the western part of Slovakia, close to the Vienna Basin, and close to the Slovak (Bratislava), and Austrian (Vienna) capitals as well.

The karst area on the western edge of the central part of the Little Carpathians is the Plavecký karst. The cave is situated inside the hill on which the Plavecká Castle was built in the thirteenth century. The entrance to the cave is located on the western slope of the castle hill, near the village of Plavecké Pohradie. The castle hill and the adjacent Pohanská Hill contain several caves.

The cave was formed in Triassic limestones which contain layers of dolomite. The Plavecká priepast is a hypogene cave. This origin was first verified by Bella et al. (2019a, 2019b, 2022) during their detailed studies of the surrounding caves – Pec, Plavecká Jaskyna.

The formation of hypogene karst caves is caused by warm or lukewarm waters along regional flow paths. The process is determined by the dissolving effect of these waters and by additional hypogene phenomena specific to the process. Hypogene acids are generated independently of the surface, usually at greater depths in a reductive environment. They usually occur as aqueous solutions of deep CO_2 and H_2S. In addition to carbonic acid dissolution, sulphuric acid cavitation can also occur. In general, deep cavities are unrelated to the surface topography. Nearly equidistant passages, called labyrinthine or networked, usually follow the direction of previous fractures or fissures. The formation of multi-level cave systems is not uncommon (Virág, 2016).

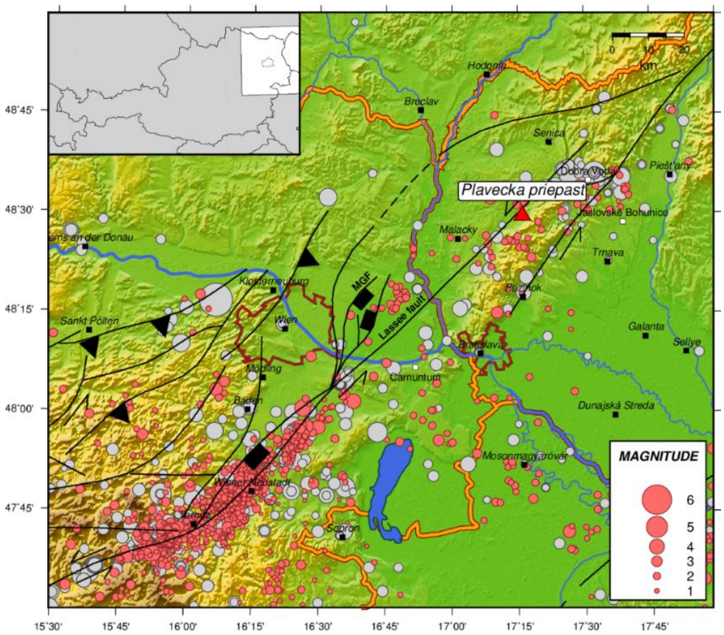

Figure 2

Location of the Plavecká priepast (red triangle) in the Little Carpathians of Slovakia, near the Vienna Basin Transfer Fault System and the other major faults, furthermore grey circles represent the historical and red ones represent instrumental epicentres of earthquakes (Gribovszki et al., 2017a modified by Péter Mónus, GeoRisk Earthquake Engineering Ltd)

The object of our research is a certain 4.3 m high, intact but vulnerable candlestick-shaped stalagmite *(Figure 3)*. Our basic assumption for the earthquake hazard is that these formations survived all earthquakes that have occurred over thousands of years, depending on the age of the stalagmite. Their 'survival' requires that the horizontal ground acceleration has never exceeded a certain critical value within that time period. Such investigations of the mentioned dripstone were reported in detail in Gribovszki et al. (2017a and 2017b) and Zembaty et al. (2023).

The present work aims to compare the models created in 2024 and in 2015, and to assess their usability as input data for future seismic vulnerability-related dripstone studies for various model calculations.

Figure 3

The 4.3 m high stalagmite under study in the Plavecká priepast

(Gribovszki et al. 2017b)

4. DATA PROCESSING

4.1. Registration of individual scans using targets

The point clouds surveyed from different scan positions are referenced in the sensor's own coordinate system, so they need to be transformed into a common one to obtain a spatially consistent, merged point cloud. This process is known as registration, or relative orientation. The point cloud from scan position 2 was chosen as the reference to which the other two point clouds were aligned. The transformation parameters were determined by locating the center of retro-reflective targets in the overlapping parts of the point clouds. Target center coordinates were extracted automatically using Leica Cyclone software package. The RMSE values of the registration were 2 and 3 mm for scans 1 and 3, respectively. The transformation that is defined by a spatial offset vector and three rotation angles about the three coordinate axes, is known as the Helmert transformation. To model the complete shape of the stalagmite, the three point clouds were merged *(Figure4)*. Registration, transformation, and point cloud merging were carried out using the Cloud Compare software package.

To check the correct fit of the individual point clouds, horizontal cross-sections with a 2 cm thickness were taken along the height of the stalagmite. Figure 5 clearly shows that the alignment of the individual scans is fair, except in the upper-middle part, where unexpected but significant spatial inconsistency is visible.

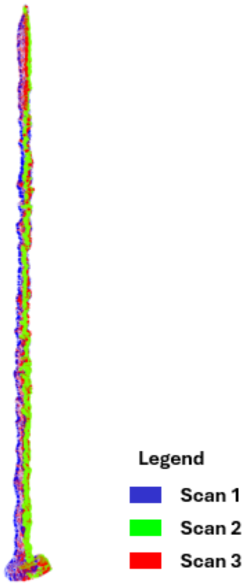

Figure 4
The merged point cloud of the stalagmite. Colors of the points correspond to the scan positions they originate from.

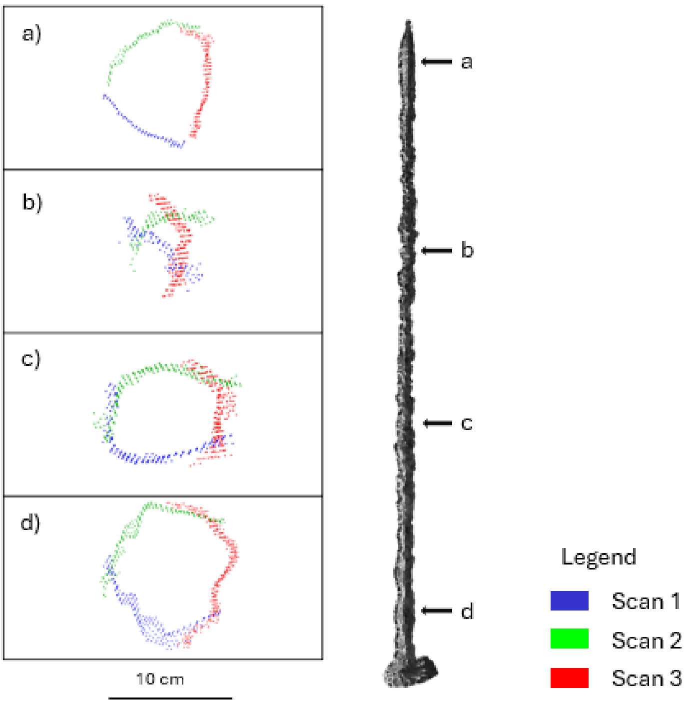

Figure 5
Horizontal sections of the point clouds registered using targets only. Section heights are 0.3 m (a), 1.5 m (b), 2.7 m (c), and 3.9 m (d). Colors correspond to individual scans

4.2. Improvement of the registration

The inconsistency along the middle part of the stalagmite arose from an apparent shift among the individual scans in the radial direction. The magnitude of the shift changes up the stem without showing any systematic pattern. To fix the issue, the individual point clouds were subdivided into 20 cm height slices. Point slices from scan positions 1 and 3 were manually adjusted to that of scan position 2, applying horizontal translation so that the point slices match in the overlapping region. The radial offset vectors resulting from the translation varied both in direction (inward / outward) and in length of up to 3 cm *(Figure 6)*. The merged point cloud with improved alignment is regarded as the structural model of the stalagmite.

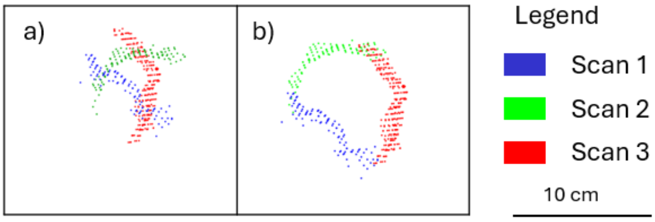

Figure 6
Horizontal sections of the point clouds before (a), and after (b) manual improvement at a height of 2.7 m. Green points of scan 2 were fixed in position, blue and red points of scans 1 and 3 respectively were translated

4.3. Co-registration with the TIN model (2014)

The merged point cloud was compared to the Triangulated Irregular Network (TIN) model created in 2015 (Zembaty et al., 2022). As the point cloud and the TIN model had different local coordinate systems, the former was aligned with the latter using Helmert transformation. The optimal values for the transformation parameters are obtained through the Iterative Closest Point (ICP) procedure, which minimizes the sum of squared distances between the closest point pairs of two data sets.

5. RESULTS

The merged 3D point cloud that represented the surface of the stalagmite consisted of 152.227 points. The total height of the stalagmite measured between the points depicted in *Figure 7* was 4.28 m.

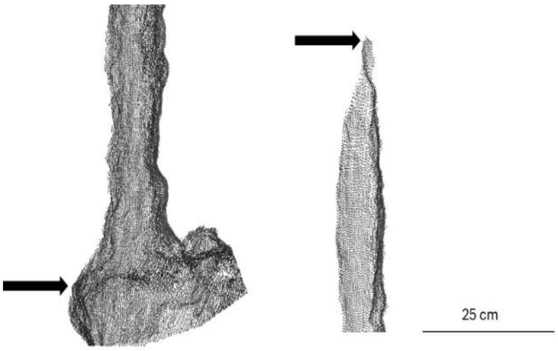

Figure 7
Measurement of the stalagmite's height between the marked points resulted in 4.28 m

The mean directed distance of the closest pair of points in the point cloud and the TIN model was –3 mm. The minus sign indicates that the resultant vector is pointing inward, i.e. from the TIN model towards the point cloud. The standard deviation of the distance between the closest point pairs was 8 mm, with a minimum of –28 mm and a maximum of 62 mm. *Figure 8* depicts the spatial distribution of the residuals. Points with green color lie as close as a few millimeters to the surface of the TIN model. Blue points are inside the TIN model; red points are outside. It is important to note that there is not any extended region along the stalagmite that introduces systematic deviation. Assuming significant growth of stalagmite during the past nine years, most of the points would be expected outside the TIN model. Actually, small errors in data capture (e.g. ranging error of the instrument), registration (e.g. inaccurate location of target centers), and co-registration (e.g. subtle differences in shape) introduce a mixture of errors that together exceed the growth in radial direction, which is far below 1 mm over nine years.

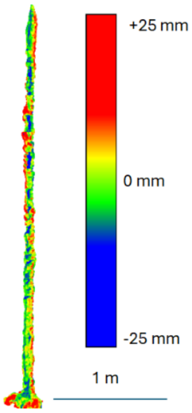

Figure 8
The measure of the directed distances between the two models. For better visuality, the color ramp is clipped to ±25 mm; however, distances range from –28 to 62 mm

Although radial growth is too small to be detected, the largest vertical difference that was observed between the TIN-model and the point cloud may indeed reflect a temporal change, i.e. karst formation, that took place at the base of the stalagmite *(Figure 9)*.

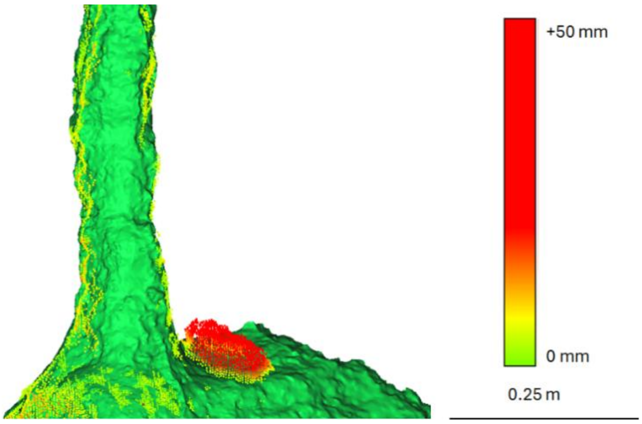

Figure 9
The largest deviation is observed at the base of the stalagmite, which might result from karst formation. The TIN model is displayed in green color; the color ramp applies to the point measurements

Another important difference was revealed at 1.61 m, at a bottleneck, which was regarded as the most vulnerable point of the stalagmite according to statical simulations performed on the TIN model. The shape of the bottleneck seems different in the point cloud; smoother, and the ‘nose-shaped’ enlargement that is present in the TIN model is absent from the point cloud *(Figure 10)*. The resulting modification in the shape might change the outcome of statical simulations on what magnitude earthquake would cause the breaking of the stalagmite.

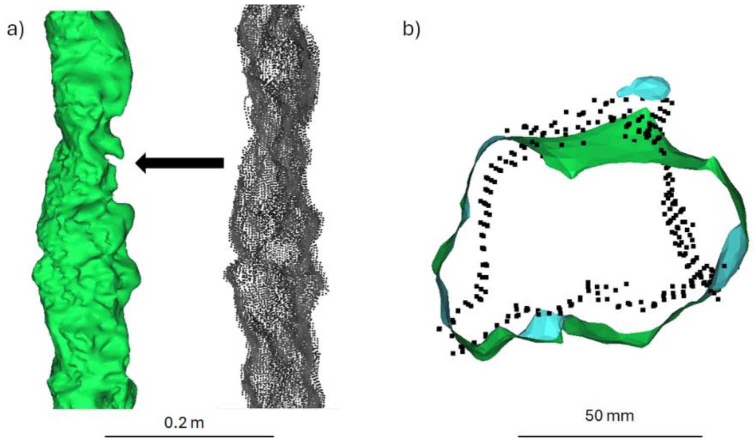

Figure 10

TIN model (2015) and point cloud (2024) at the marker height of 1.61 m, which is regarded as the most vulnerable point of the stalagmite. The point cloud reflects a smoother surface (a), and a lack of the nose-shaped part (b), which might change the outcome of statical simulations on what magnitude earthquake would cause the break of the stalagmite

6. CONCLUSIONS

The main objective of this work was to create a registered point cloud of the highest stalagmite in the cave, Plavecká priepast in the Little Carpathians (Slovakia) using laser scanner data from multiple scan positions. The registration turned out to be challenging as an unusual spatial inconsistency among the transformed point clouds was encountered, which affected mostly the middle part of the stalagmite. Since the misalignment was not systematic, it was fixed by manual translations in height sections. The total height of the stalagmite was measured to 4.28 m. The registered point cloud was compared to a TIN model that had been created from terrestrial laser scanner data nine years before. The co-registration of the two data sets took place using the Iterative Closest Point algorithm, and resulted in a bias of –3 mm, and RMSE of 8 mm. The comparison revealed that the cross-section at the height regarded as the most vulnerable point of the stalagmite has a different shape in the point cloud and in the TIN model. Modification in shape might cause a change in the output of mechanical simulations aiming to estimate the magnitude of earthquakes that cause the break of the stalagmite. In addition, a significant vertical change in the base was identified, which might indicate natural karst formation over the past nine years. However, neither the data capture nor the registration proved to be accurate enough to detect reasonable temporal change in radial direction.

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