Multi-Resolution Modeling of the Tufa Formation Dynamic using Close-Range Photogrammetry, Handheld 3D Scanner and Terrestrial Laser Scanner

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Abstract: Advances in geospatial technologies (GST) have revolutionized the ability to quantify spatio-temporal changes in various geomorphological forms at different scales. One of the most complex geomorphological forms are tufa and travertine cascades whose evolution is the subject of numerous research in various scientific fields. In this paper, we are presenting a new methodological framework for analyzing tufa formation dynamic (TFD) at three levels of research (macro-meso-micro) using the close-range photogrammetry (CRP) method, handheld 3D scanner, and terrestrial laser scanner (TLS). The results, 3D models and digital elevation models (DEMs), of the first (reference) measurement at three levels of research, are presented in this paper. Reference models were generated using *Agisoft Metashape*, *Artec Studio Professional 15*, and *SCENE* software. Measurements were done in an artificial tufa tunnel, located within the *Jaruga*, the second oldest hydroelectric power plant in the world constructed within National Park Krka, Croatia. This tunnel is a specific tufa-forming environment. The subject of the next paper will be the comparison of interval tufa 3D tufa models at three levels of research and the calculation of volumetric ($mm^3\ a^{-1}$) and linear ($mm\ a^{-1}$) tufa growth rates after two years of exposure to the Krka River. The presented methodological framework will expand the knowledge about TFD within this specific depositional sub-environment and can be applied in the dynamic formation analysis of other hydroprecipitates.

1 INTRODUCTION

Calcium carbonate (CaCO3) precipitation is a feature of many freshwater systems. Various names for hydroprecipitates formed by this process exist (Viles and Goudie, 1990). The most often are (1) tufa and (2) travertine (Bonacci et al., 2017) which can be found worldwide (Viles and Pentecost, 2007). Sometimes misinterpretation of these names occurs in the literature, although there are clear differences between them (Ford and Pedley, 1996; Capezzuoli, 2014; Bonacci et al., 2017). Travertine is by the most authors associated with the precipitate sedimented in warm and hot hydrothermal waters (Cukrov et al., 2010), while the tufa is secondary carbonate sedimented in freshwater at ambient temperature and usually includes the remains of micro- and macrophytes, invertebrates, and bacteria (Ford and Pedley, 1996; Pedley, 2000; Capezzuoli, 2014, Barešić et al., 2021). These hydroprecipitates represent one of the most spectacular depositional forms in karst landscapes (Šiljeg, et al., 2020) which have universal aesthetic and scientific values and are often included in the UNESCO *World Heritage List*.

Analysis of tufa and travertine formation dynamics are oriented to quantification of the growth and erosion rates which can be measured using various direct and indirect methods (Marić et al, 2020a) and expressed using different units. Accurate calculation of rates is important for several reasons (Marić, et al. 2020b). Recent advances in data acquisition sensors have revolutionized the ability to quantify different spatial-temporal changes on a wide range of scales. In the majority of TFD studies, very large variability in rates was recorded as a result of

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specific sedimentation conditions, their spatial distribution along the water body, and selected measurement method (Arenas et al., 2010, Arenas et al., 2014, Auqué et al., 2014).

In this research, we are presenting a new framework for monitoring the tufa formation dynamic (TFD) using the modern active and passive 3D coordinate measuring devices at three levels of research within the tufa tunnel. To demonstrate the new framework in the *Jaruga* hydroelectric power plant tunnel, located within National park (NP) Krka was chosen. The TFD will be analyzed using close-range photogrammetry (CRP) method - micro level, handheld 3D scanner - meso level, and terrestrial laser scanner (TLS) - macro level of research.

The basic objective of the research was to expand knowledge about TFD within this specific depositional environment and then compare it with the results of other tufa-forming systems in the world. A detailed overview of the TFD research is available in Marić et al. (2020a). Furthermore, the objective is to determine are there any differences in the TFD at different levels of research using the above-mentioned sensors. Also, since TFD will be analyzed on an empty and smooth limestone plate (PL) and rough substrate of the tunnel lateral walls, which is composed of tufa, plant fragments, microorganisms, and moss, it will be interesting to see whether the growth and erosion rate will be similar. Namely, in order for tufa formation to occur, in addition to $CaCO_3$ oversaturation, it is desirable that the water contains a suitable substrate for calcite deposition. They can be provided by organisms or organic substances such as plant fragments and moss. Therefore, one of the basic hypotheses of this and future research is that the expected growth rate will be higher on rougher surfaces (meso level of research), ie on already formed tufa (tunnel lateral wall).

Thus, it can be tested whether the tufa growth rate determined on the lower level of research can be extrapolated on the highest level of research. TLS was used on a macro level of research with the aim of examining the possibility of measuring TFD using this type of sensor since such research has not yet been done according to our knowledge.

2 STUDY AREA

Hydroelectric power plant *Jaruga* is located on the Krka River, in Šibenik-Knin County (Croatia). It is the second oldest hydroelectric power plant in the world and the first in Europe. It was built near the waterfall Skradinski buk.

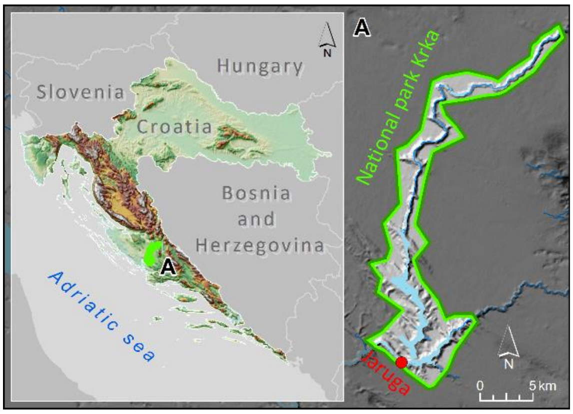

Figure 1: Location of Jaruga HE power plant in NP Krka.

The *Jaruga* system includes a separate supply structure within the small closed part of the Krka in the area of the Skradinski Buk waterfall. The supply structure consists of a tufa tunnel (Figure 3A) with gravity flow, a concrete channel with almost vertical sides (Figure 3B) leading to the water tank, and two water flow regulators leading to the turbines. The length of the tufa tunnel is around 82.7 meters (Holjevac and Kuzle, 2019). On these almost vertical sides of the tunnel tufa is forming (Figure 3B) and periodically removed, depending on the growth rate (Figure 2).

Figure 2: Removal of the tufa formed on the lateral sides of tunnel (URL 1).

Given the fact that during the year the flow rate and water level in this tunnel are more or less constant and that certain parts of the tunnel are completely in the dark (Figure 3C), while other parts are constantly exposed to light, it is obvious why this area is recognized as an excellent depositional environment for analyzing TFD using the advance active and passive sensors at a different level of research.

Figure 3: (A) Lateral sides of tufa tunnel; (B) formed tufa; (C) parts of tunnel in dark.

3 MATERIALS AND METHODS

3.1 Data Acquisition

Data acquisition was done using (A) coordinate measuring macro-photogrammetry device (CMD) (Marić et al. 2020a) at micro-level of research; (B) 3D hand-held scanner *Artec Eva* at meso level of research; and (C) TLS *Faro* M70 at the macro level of research. The water in the tunnel was stopped for the conduction of the measurements which were all made in one day.

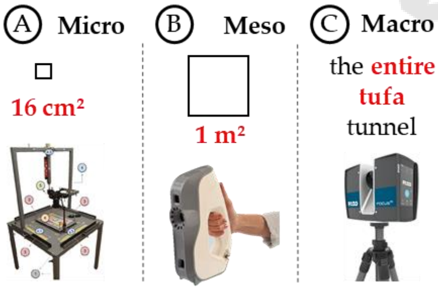

Figure 4: Sensors used in three level of research at tufa tunnel.

3.1.1 *CMD*: Micro Level

On the micro-level of research, the TFD was monitored by CMD on an area of 16 cm². The CMD consists of six main parts and was designed by Marić et al. (2020a). It minimizes the frequent problems that occur in the CRP process and when using a modified micro-erosion meter (Drysdale, Gillieson, 1997). The area of 16 cm² represents the upper part of the limestone plate (PL) mounted on the lateral sides of the tufa tunnel (Figure 5A). A total of three PLs were mounted, one in the always illuminated area, the second in constant dark (Figure 5B), and the third at location with interchangeable conditions. The PL design is described in Marić et al. (2020a). PLs were measured with CMD before installation.

Figure 5: (A) Limestone PL measured with CMD; (B) instalation of PL on the lateral sides of tunnel in no-light condition.

3.1.2 *Artec Eva*: Meso Level

Artec Eva was used at the meso level of research. It is a lightweight and compact structured light 3D hand-held scanner that uses triangulation and structured light for data collection. Its 3D resolution is up to 0.5 mm at a distance of 40 cm to 1 m. The accuracy of the 3D is up to 0.1 mm (Marić et al., 2020b).

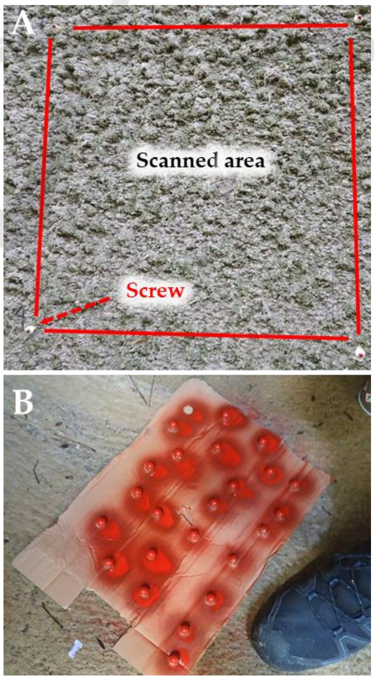

Figure 6: (A) Square surfaces scanned using Artec Eva; (B) colored caps used as GCPs.

The TFD was monitored by *Artec Eva* on three surfaces of around 1 m^2. Three square surfaces were marked and scanned on the lateral sides of the tunnel (Figure 6A). The frame square surfaces were marked with four screws that had colored caps (Figure 6B). The screws were used as ground control points (GCPs). Also, they were useful for the scanning procedure. GCPs were necessary because the 3D scanner axes (X, Y, Z) are relative to the scene being scanned. Therefore, the GCPs eases the alignment of the interval tufa 3D model enabling the interval comparison of the formed tufa and quantification of growth and erosion rates between interval models.

A distance adjustment indicator was used while scanning marked test surfaces. Localization of *Artec Eva* was achieved by moving it away or closer to surfaces in order to get the best scanning quality (Figure 7). The speed of scanning was around 13.5 fps. Scanning of the one test surface lasted around 3 minutes.

Figure 7: Scanning of test surface using Artec Eva.

3.1.3 *Faro Focus M70:* Macro Level

At the macro level of the research, terrestrial scanning of the whole tufa tunnel on October 10, 2020, was performed using a *FARO Focus M70* laser scanner (Figure 8). *FARO Focus M70* is a phase laser 3D scanner with a measuring range from 0.6 m to 70 m, with a measuring accuracy of ± 3 mm. It collects about 488,000 points per second and has a level of protection against water and dust.

There were a total of nine scanning locations. The total number of scans was determined with respect to available survey time which was only one day. Within that time, data acquisition had to be made at all three levels of research. Ideally, the number of TLS scanning locations can be higher. The optimal positions for survey reference targets were identified in the field following examples of good practice (Domazetović et al., 2020). Survey reference targets (spheres) were used for faster and easier registration of the multiple scans. Spheres were set at a distance of 15–20 meters to enable target registration. Since, this type of research requires an interval comparison of 3D tufa models on all three levels of research, four targets (spheres) have been fixed on exact XYZ location. The X, Y, and Z coordinates of spheres will not differ between interval scanning. The XYZ coordinates of the spheres were not measured using GNSS receivers because in this type of research the location of the tunnel or survey area within the global coordinate system is not important. However, the relative positional accuracy is very important, ie overlapping of interval models. Therefore, all spheres were fixed and their location will not change between interval scanning.

The following scanning settings were set: 1/4 resolution (with a point distance of approximately 6 mm at 10 m distance) and 2× quality. Also, the HDR texture was set. The scanning per one location took 6–7 min.

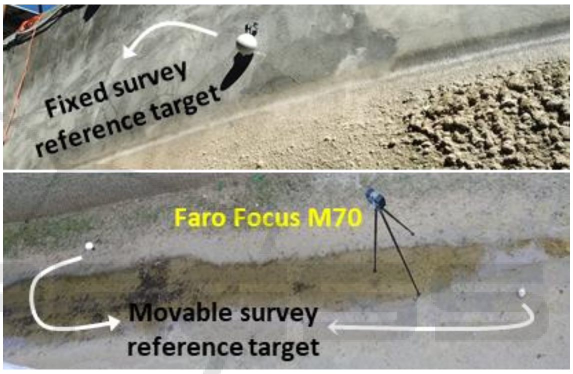

Figure 8: Terrestrial laser scanning of tufa tunnel.

3.2 Data Processing

3.2.1 Micro Level Data Processing

At the micro-level of research image workflow process (capturing + processing) was done following the guidelines proposed by James et al. (2019). Image capture was done using CMD which contained system sensors *NIKON D5300* and macro-lens *Venus LAOWA 60-mm f/2.8*. Each PL was represented with more than 180 overlapping (>80%) images. Initial (reference) 3D tufa models and digital elevation models (DEMs) were derived in *Agisoft Metashape 1.5.1*. The overall methodological process is shown in Figure 9. Four GCS and four CP (checkpoint) were used to georeference and assess the X, Y, and Z accuracy of the models.

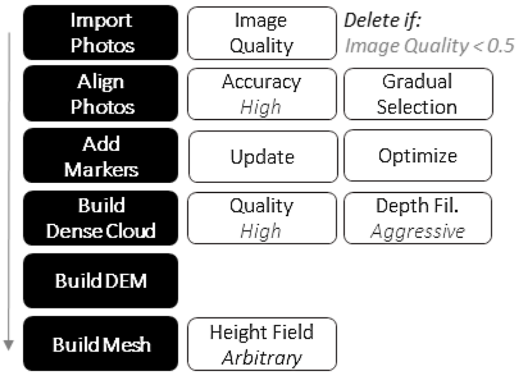

Figure 9: Image processing in *Agisoft Metashape*.

3.2.2 Meso Level Data Processing

At the meso level of research, scanned surfaces were processed using *Artec Studio 15 Professional*, software for professional 3D data processing. The overall methodological process is given in Figure 10.

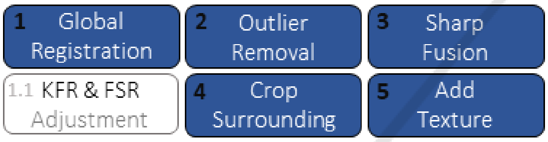

Figure 10: Data processing in Artec Studio 15 Professional.

After the second and subsequent scans, which will be presented in future research, the data processing will include the sixth step (alignment). It refers to the placement of the interval 3D tufa models in the same coordinate system. Align of interval models will be done using the *Rigid Align* option. The center of the colored caps mounted on top of the screws (Figure 11) will serve as fixed GCPs for each reconstructed 3D model. Then using the *Measure* option which contains the *Distance map and Section*, *volume*, tufa growth, and erosion rates will be measured.

Figure 11: Fixed GCP used in meso level of research.

3.2.3 Macro Level Data Processing

At the macro level of research collected 9 scans were processed using *FARO SCENE 2019* software. It was used for scan registration and creation of dense point cloud and polygonal model of whole scanned site (tufa channel). Scan registration was done using *Target Based* mode in the *Automatic Registration* option. This setting causes SCENE to look only for artificial targets (spheres) in scans. Figure 12 shows recognized spheres at the eighth scan location.

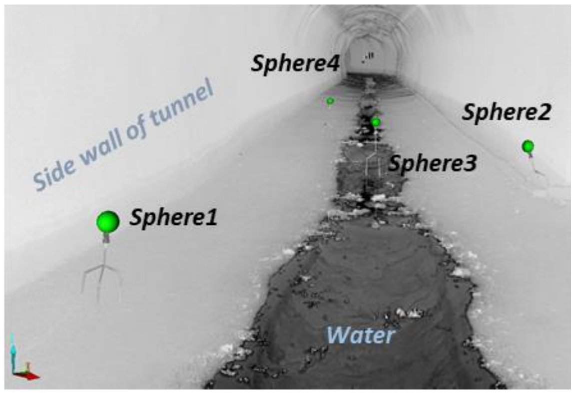

Figure 12: Recognized spheres at eighth scan station.

4 RESULTS

This paper was conceived as an introduction to the possibility of using different sensors in analyzing the TFD and to expand knowledge about TFD through various aspects mentioned in the introduction. Therefore, the results section contains only the initial models that will be used in further research. Namely, numerical results comparisons between derived models were not done because it requires another data acquisition process at all three levels of research that has not yet been carried out.

4.1 3D Tufa: Micro Level

3D tufa models at the micro-level of research were created in *Agisoft Metashape*. Polygonal mesh models of PLs were generated based on the reconstructed dense point cloud. The *Surface type* parameter was set to *Arbitrary* (3D). The *Face count* parameter to "0" to skip the decimation stage so the model has all the reconstructed faces. Based on this reference and new interval 3D models which will be recorded in the following periods (2-year interval), volumetric ($mm^3\ a^{-1}$) TGRs will be calculated. Also, DEMs of PLs were derived. Based on them and new interval tufa DEMs linear TGRs ($mm\ a^{-1}$) will be calculated (Figure 13). Volumetric ($mm^3\ a^{-1}$) TGRs will be calculated in *Artec Studio 15 Professional* after two years of exposure PLs to water. Linear TGRs ($mm\ a^{-1}$) will be calculated in *ArcMap* software.

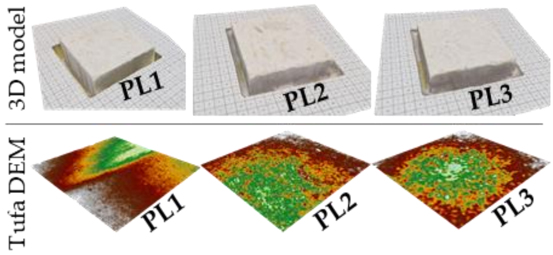

Figure 13: Derived reference 3D models and tufa DEMs on micro level of research.

A field survey was done one year (October 2021) after the PLs were mounted and a few interesting things were spotted. Tufa-forming organisms of tubular shape were observed on the PL which was placed in complete darkness (Figure 14B). No organisms were observed on the other PLs. We visually estimated that the highest TGR was on the PL that was most exposed to the light (Figure 14A).

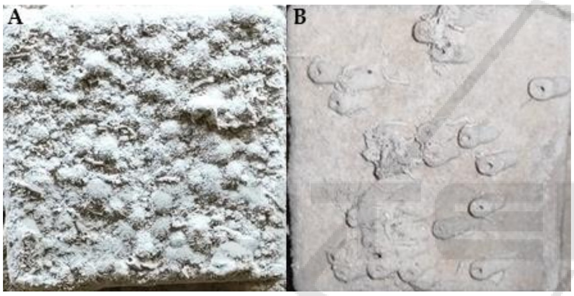

Figure 14: (A) PL with highest increment after one-year; (B) observed tufa-forming organisms.

4.2 3D Tufa: Meso Level

3D tufa models at meso level of research were created in *Artec Studio 15 Professional*. Figure 15. shows reconstructed models of two scanned surfaces (A and B).

It will be very interesting to measure the erosion of tufa in interval scanning periods. Namely, erosion occurs mainly due to intensive flow due to increased precipitation, dry periods during summer that leads to drying and weakening the tufa structure, human factor, measurement which coincides with the phase of periphyton loss due to emigration or more intensive grazing, etc. The PLs and test surfaces at the micro and meso level of research are located at a depth of a few meters while the water level and water flow rate are constant, which is why no significant erosion rates are expected. Also, it will be interesting to see is there any difference in the erosion of tufa located in constant darkness (inside the tunnel) for two years and tufa exposed to light.

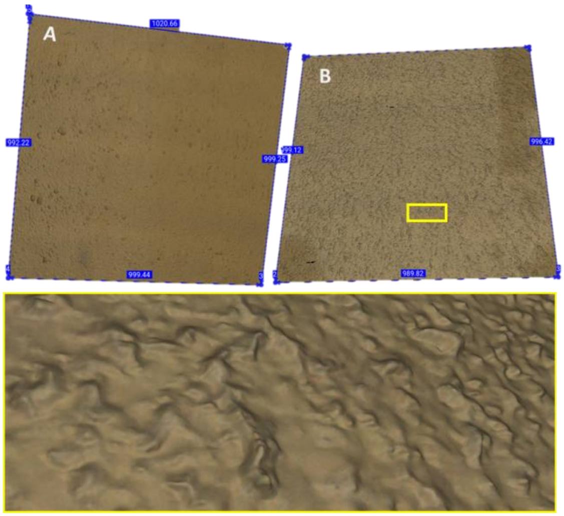

Figure 15: 3D model of two scanned surfaces in tufa tunnel.

One year after the scanning it was observed that the tufa grew faster on the lateral walls which are more exposed to the light and rich with moss (Figure 16A). Also, differences in tufa hardness are obvious. The tufa that forms in conditions of constant darkness is much harder (Figure 16B), while the others are softer and more porous.

Figure 16: (A) Test surface with highest increment; (B) hard sedimented tufa inside the tunnel.

4.3 3D Tufa: Macro Level

At the macro-level of research, scans were registered using manual registration mode. The mean horizontal target error was 0.4 mm, while the mean vertical target error was 2.0 mm. Registered scans were used for the creation of dense point cloud (Figure 17). It covered the entire area of the tufa tunnels' lateral sides. After the two years of exposure to water TFD on these lateral sides will be calculated using *CloudCompare* software.

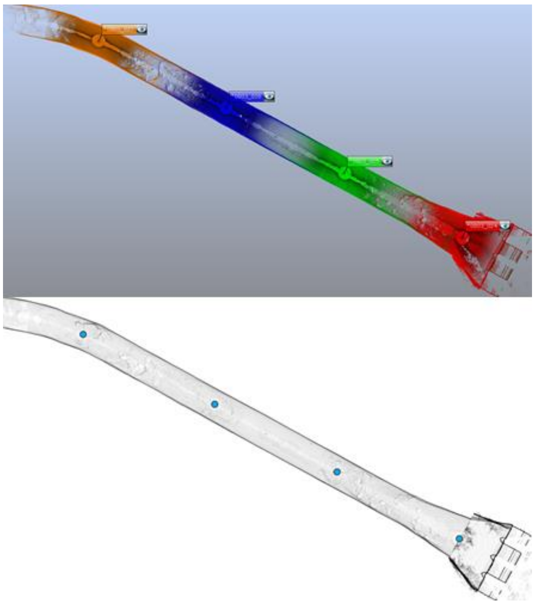

Figure 17: Point cloud of tufa tunnel section with four scan location.

5 CONCLUSIONS

In this paper, we presented a new methodological framework for analyzing (TFD) at three levels of research using state-of-art active and passive sensors.

The 3D models of the first (reference) measurement are presented fot three levels of research. Although the next measurements will be made in a year, interesting occurrences have already been noticed. Tufa-forming organisms of tubular shape were observed on the PL which was placed in complete darkness. Furthermore, tufa grew faster on the lateral walls which are more exposed to the light and rich with moss than in the locations within complete darkness and on smooth surfaces of PLs.

The subject of the next paper will be the comparison of derived 3D models at all levels of research and the calculation of the volumetric ($mm^3 a^{-1}$) and linear ($mm\ a^{-1}$) tufa growth rates. Also, in future research, we are considering implementing a hyperspectral camera at the micro and meso level of research in order to analyze spectral reflection and detect the plant fragments and macroinvertebrates accumulated on the tufa surface.

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