Use of photogrammetry to quantify tunnel overbreak

S. Zafari & M. Smith
Gamuda Engineering-Laing O'Rourke Consortium, Sydney, NSW, Australia

ABSTRACT: This paper presents a novel method of quantifying the overbreak or overcut experienced during tunnelling by using photogrammetry acquired during mined tunnel excavations on Sydney Metro West Western Tunnelling Package (WTP). Photographs were taken of each excavation advance and processed using photogrammetry software into as-built surface models of the rock. Models of consecutive advances were geo-located and imported into the 3D modelling software package 'Rhino 3D' using surveyed coordinates. A script to calculate overbreak was developed which would compare the model surfaces to a model of the planned excavation line (E-line). The output was a 3D colour contoured overbreak surface. The overbreak values calculated using the photogrammetry models were found to be in reasonably good agreement with excavation as-builts obtained by survey.

1 INTRODUCTION

Overbreak is the undesired fallout of material beyond the planned tunnel excavation profile (E-line) driven by an irregular breakage along defects or spalling of rock. Over cutting (for simplicity referred in this paper as overbreak), refers to excavation beyond the planned E-line of the tunnel either by accident, or through imprecise excavation methods. Excessive overbreak can increase the cost of construction and/or extend construction programs, so understanding whether the volume is within expectations can help the contractor make decisions on whether to implement additional control measures to reduce overbreak and by extension, backfilling requirements.

As-builts of the rock are obtained during the mined tunnelling process by the tunnel surveyor to inform construction whether the excavation has achieved the minimum required dimensions. Two commonly used methods to obtain rock as-builts are by total station or laser scan survey.

Total station survey involves surveying points on the rock in longitudinal arrays (typically spaced ~500mm apart), comprised of widely spaced, laterally surveyed points (200-300mm typical spacings). This method is relatively cheap, can be performed quickly, and has good accuracy; however, it provides an output of low data density.

Using the laser scanning technique, the rock is surveyed with a tripod or drone mounted laser scanner in the order of ~50,000 points per second (Wang et al., 2014), and by comparison, provides a much higher data resolution than manual total station survey. The method incurs higher labour costs, relies heavily on data, and requires expensive hardware and subscription-based software to collect and process the data. Both methods can provide a measurement of overbreak at any surveyed point.

Previous work has demonstrated that photogrammetric reconstructions of rock obtained using laser scanning, smartphone LiDAR or optical means can have applications for tunnel mapping (Torkan et al., 2023; Janiszewski et al., 2022; Garcia-Luna, 2019), tunnel monitoring (Attard et al., 2018) and rock slope stability analysis (Bonilla-Sierra et al., 2015; Kim & Gratchev, 2015). 3D photogrammetry presents a practical method for the creation of dense 3D models of tunnel surfaces without the high equipment costs of laser scanning. The technique relies on Structure-from-Motion (SfM) algorithms to transform a series of simple photographs into a detailed point cloud. The value of this approach has been proven in recent research, which now uses photogrammetric data for demanding engineering applications (Im et al., 2025).

In this paper we explore an alternative method of quantifying the overbreak experienced during mined tunnelling by integrating optical photogrammetric model reconstructions of the excavated rock with 3D modelling and scripting tools. Our process does not need to be carried out by a surveyor; it is quick and inexpensive and uses commercially available and user-friendly software to produce. This method could be useful where laser scanning data is not being collected, and where the magnitude of overbreak is of particular concern to the contractor.

2 BACKGROUND

The data presented in this paper was captured during construction of Sydney Metro West Western Tunnelling Package (WTP) in two tunnels excavated by roadheader. The tunnels include the Clyde junction caverns, with a span ranging 10-19m and excavated to a maximum crown depth of 23m in Hawkesbury Sandstone and the Westmead stub tunnels, with a span of ~7.5m and excavated at a crown depth of 25m to 30m, within the Ashfield Shale. Automated navigation systems guided the roadheader operators in both tunnels, which unlike the drill and blast method provides a high degree of precision and a control on overbreak.

3 METHODOLOGY

3.1. Image collection

For each excavation advance three reference survey targets were placed in front of the newly excavated and washed tunnel face. Two targets were placed at ground level adjacent to the sidewalls and one target was elevated and placed in the centre (Fig. 1). The targets were surveyed and their coordinates recorded.

A flood light provided consistent lighting between advances, minimising shadows and overexposure. Overlapping high-resolution images were captured of each cut using a Canon EOS 1500D DSLR camera. Multiple arrays of photographs were taken at different inclinations to ensure an abundance of overlapping points (tie points) in the data, like that shown in Figure 2.

Figure 1. Setup during photogrammetry data collection. Numbered survey targets are placed in the shot to allow orientation of the model

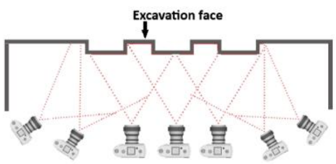

Figure 2. Geometric approach to photography used in obtaining photogrammetric data

3.2. Photogrammetry model processing

Photogrammetry software ‘3DF Zephyr’ used to create 3D as-built model of the rock surface using photographs. The 3DF Zephyr used metadata included in each image file to automatically figure out the internal camera calibration settings. This automatic calibration changed settings for our Canon EOS 1500D camera, which has a 21 mm focal length and a resolution of 6000 × 4000 pixels. This made sure that all photogrammetric models were accurate all the time. The workflow included:

3.2.1. Sparse point cloud generation

The first step was the initial processing of the raw photos. During this step, the software automatically checks each image, and identify matching points, between overlapping images. These tie points are then used to generate a sparse point cloud, which forms the foundational structure of the 3D model. To precisely scale and geo-locate the model, survey targets within the images are ‘picked’ and coordinates are assigned to each of them, ensuring accurate geo referencing of the final model. At this stage, processing was performed using the software's "high detail" reconstruction settings to maximise the accuracy and quality of the sparse point cloud, to find thousands of tie points across multiple images.

3.2.2. Dense point cloud generation

Following sparse point cloud generation, the second step involves producing a detailed, high-resolution (dense) point cloud. During this stage, the software analyses the sparse point cloud in greater depth, calculating precise spatial positions for a significantly larger number of points. This step greatly enhances the density and visual clarity of the data. In this paper, dense point cloud generation was conducted using the software's "high detail" reconstruction setting, to create a detailed depth map which contains millions of data points. This step is very important because it gives us the exact geometric model, we need to accurately recreate the tunnel surfaces. This model is then utilized to make realistic meshes and do accurate analyses of tunnel overbreak.

3.2.3 Mesh creation

The software converts the dense point cloud into a 3D mesh surface comprised of many interconnected triangles. It was found that the number of triangles comprising each photogrammetric mesh led to long processing times during overbreak calculation. To solve this problem, the number of triangles within each mesh was reduced.

To determine what reduction factor could be applied without significantly affecting the output, analysis of the output of various reduced meshes was compared to the complete mesh. These results are presented in Section 4, which found that a reduction of triangles to 25% of the original number did not make a considerable difference to the output, and this reduction factor was adopted for the models in this paper. Figure 3 shows a complete mesh alongside a 25% vertex mesh.

100% vertex density **25% Vertex Density**

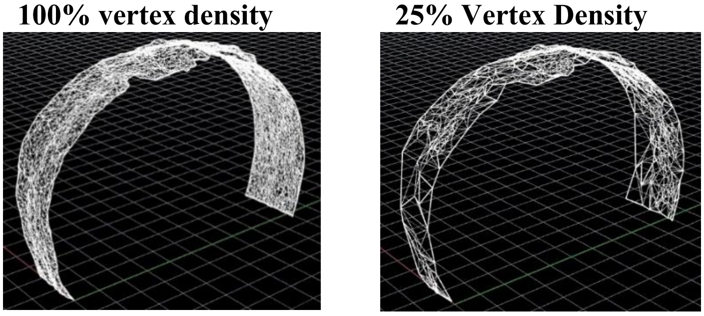

Figure 3. Comparison of meshes with different densities. Note the significant reduction of triangles in the 25% vertex density mesh

3.2.4 Textured mesh generation

A photographic image texture is then draped over the mesh to complete the model. The texture has no thickness so as not to affect the overbreak calculation and is useful in understanding if geological features contributed to the overbreak. A processed texture model is presented in Figure 4.

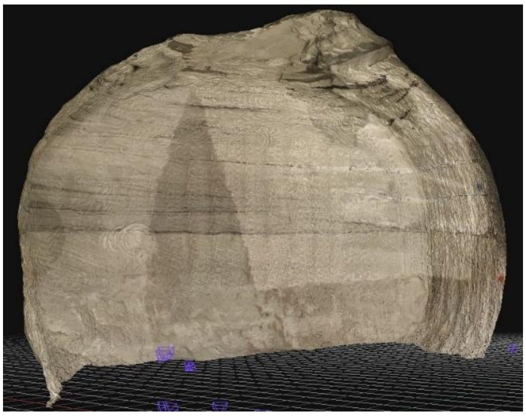

Figure 4. Shows a completed 3D textured photogrammetry model of a cut in the Clyde junction cavern

3.3 Integration with modelling software

To produce the E-line surface in which to compare the overbreak surface, a BIM of the construction line (C-line) was imported into Rhino3D and expanded outward by the sum of the various lining and convergence tolerances used during construction.

Each photogrammetry model was then imported into Rhino3D. As survey coordinates were embedded within each model, they were automatically geo-located to overlay our E-line. The face of each cut was not required in the overbreak calculation and was trimmed at the end chainages of that cut, precisely at the location where the transition from the crown to the face began. A series of four consecutive photogrammetric models representing a 12m length of tunnel is shown in Figure 5.

3.4. Overbreak analysis

A script was developed in Grasshopper (Rhino3D's scripting tool) to undertake overbreak analysis of the photogrammetry models (Fig. 6). The macro performed two main functions: Calculating and contouring the overbreak and highlighting any underbreak.

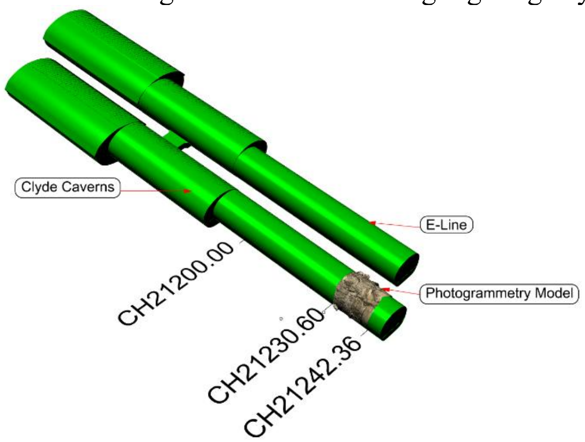

Figure 5. A series of photogrammetry models in the smaller span of a Clyde junction cavern overlay our E-Line model

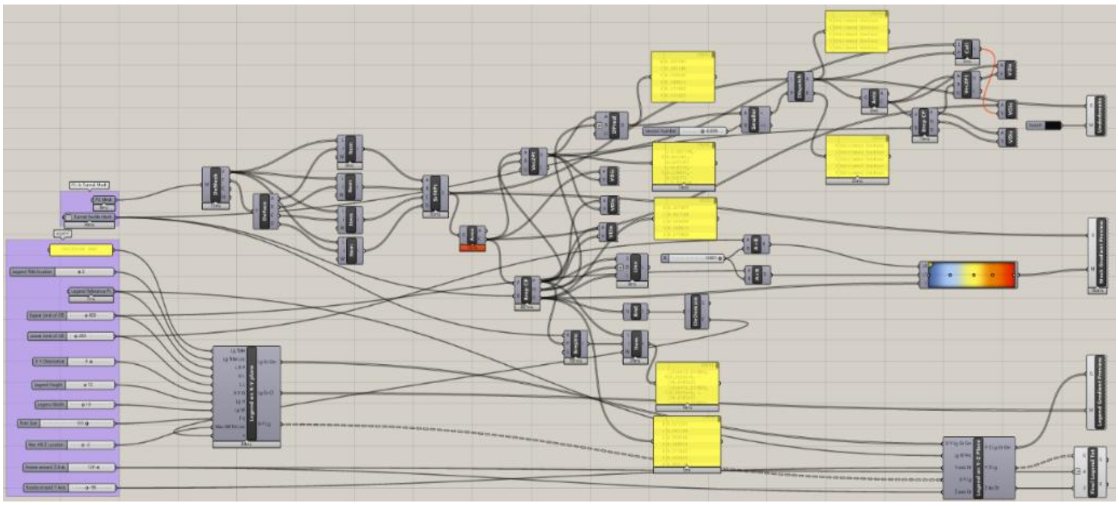

Figure 6. Grasshopper Script used to calculate the colour-contoured overbreak surface

3.4.1. Overbreak calculation

The script converts the wire mesh from each model into a poly-surface by creating small 2D interconnected surfaces between the vertices of each wire triangle. The point at the centre of each of these triangles defined the average distance of the triangle to the E-line and was measured. A colour was assigned to each triangular surface based on the magnitude of measured overbreak, with the colour range defined using the maximum and minimum overbreak magnitudes within the modelled area. The hottest colours represent areas with maximum overbreak, while the coolest colours denote minimal or zero deviation from the E-line.

3.4.2. Underbreak identification

To identify underbreak, the following vector calculation was performed for each triangle:

$$\vec{\boldsymbol{A}} \cdot \vec{\boldsymbol{B}} = |\mathrm{A}||\mathrm{B}| \cos(\theta)$$

Where:

$\vec{\boldsymbol{A}}$: The vector from the centre of the mesh triangle to the closest point on the E-line surface

$\vec{\boldsymbol{B}}$: The normal vector of the points on the E-line surface projected from centre of the triangle

θ: The angle between vector A and B

If $\vec{A} \cdot \vec{B} < 0$, then the mesh triangle lies inside of the E-line surface and was identified as under-broken. A positive dot product indicated that overbreak had occurred at the triangle. Triangles that showed underbreak were coloured black to distinguish them from the coloured over broken areas.

4 RESULTS AND VALIDATION

Both textured and overbreak contoured surfaces constructed from a series of photogrammetric models of the Westmead stub tunnels are presented in Figures 7-8 respectively.

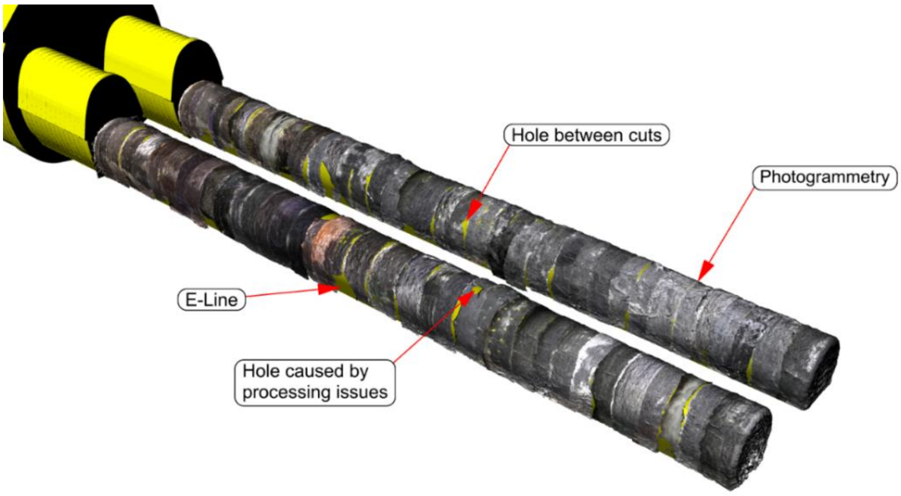

Figure 7. Complete photogrammetric model of the Westmead stub tunnels overlay the E-line used in construction

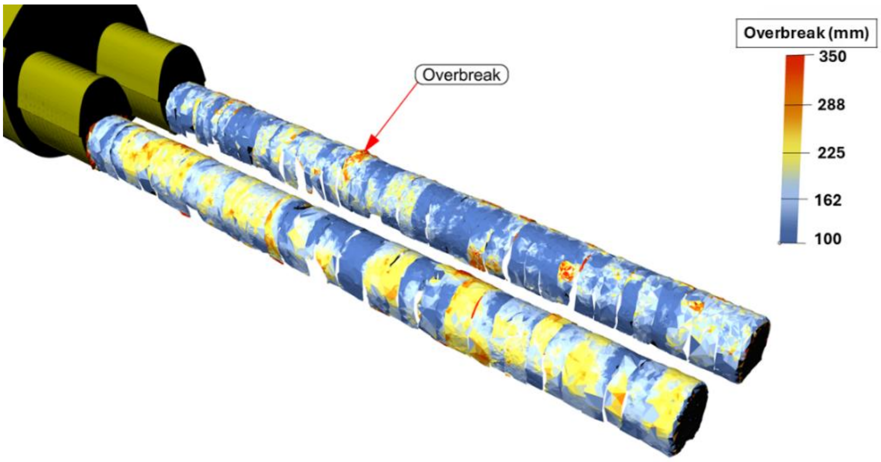

Figure 8. Output after running the Grasshopper script: A contoured plot showing overbreak along the Westmead stub tunnels

Several issues with the output were noted which may have led to some reduction in accuracy. These issues and some possible solutions are listed below:

- Holes in the photogrammetry were created when manually trimming the faces from the sidewalls/crown of each individual model. Trimming adjacent models at a specific chainage (rather than by eye) would lead to smoother transitions between cuts and reduce holes in the models.
- Further holes in the models are thought to be caused by issues processing photos within Zephyr3D. These issues are likely due to a variety of data collection issues including blurry photographs, too few photographs, insufficient tie points between photos and/or uneven lighting.
- Problems in geo-locating some of the models required them to be manually adjusted into position. We believe this issue is due to uneven lighting and too few photos/insufficient tie points between photos. A more streamlined data collection process will be trialled in future iterations.

4.1. Mesh vertex density comparison

To demonstrate how vertex density affects the overbreak magnitudes in the output, Figure 9, visualises four overbreak contour surfaces created from the same excavation advance and processed using different vertex reduction factors. The results are summarised in Table.1, which show that reducing the mesh to 25% of its original density resulted only in a 1% reduction in accuracy, while significantly decreasing model size and improving calculation speeds.

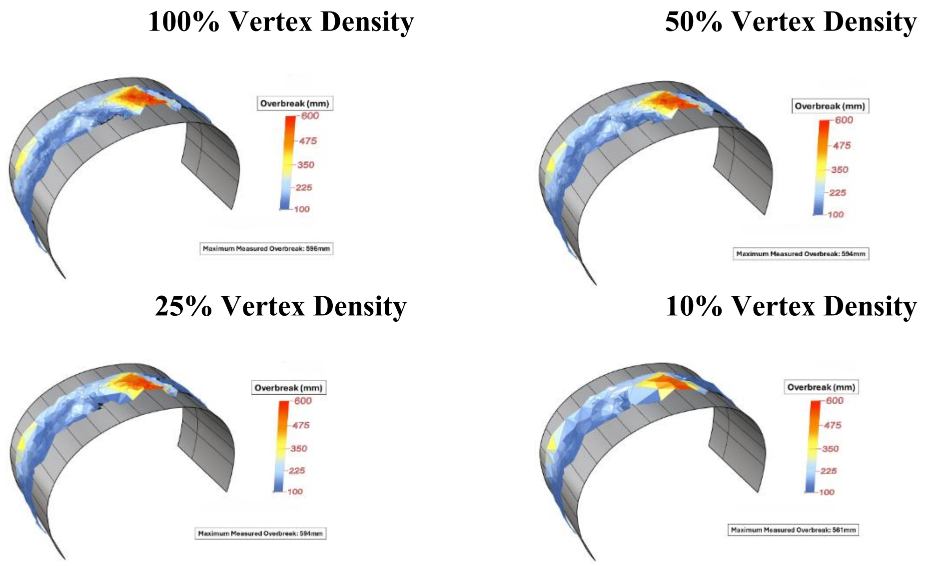

Figure 9. Comparison of overbreak contour surfaces created using various vertex reduction factors

Table 1. Comparison of overbreak magnitudes of meshes with various reduction factors applied

Mesh Density	Max Overbreak (mm)	Relative Accuracy (%)
100%	596	100
75%	594	~99
50%	594	~99
25%	594	~99
10%	561	~94

4.2. Survey validation

The accuracy of the photogrammetry-based overbreak calculation was compared to laser survey measurements taken at the same chainage. The Grasshopper script calculated a maximum over-break of 594mm (Fig. 10a) whereas the laser survey recorded 589mm in the same cut (Fig. 10b), a difference of 5 mm. This demonstrates a close correlation between the photogrammetry and traditional methods.

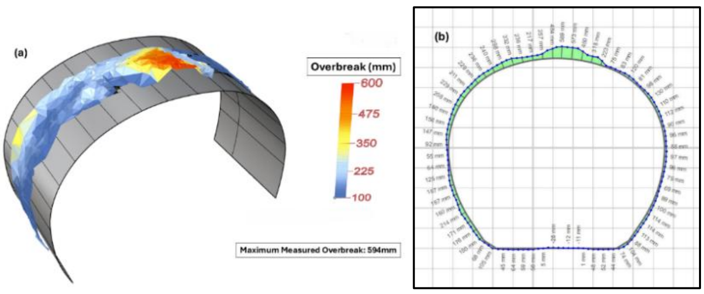

Figure 10a. Overbreak contour surface from an advance in the RT02 Clyde junction cavern. Figure 10b. The rock as-built report at a chainage through the same advance produced from laser scanning data acquired by a Leica Nova MS60. Over broken area shown in green. E-line shown in grey.

4.3. Measurement Uncertainty

There are a few things that can influence the accuracy of photogrammetric measurements. For instance, lighting conditions often change between excavation stages, and this can create shadows or uneven contrast that affect image quality and how well tie points are detected. Moreover, the variability in the angle and distance of captured photos can affect the accuracy of the constructed model. Errors in survey data, particularly in picking up the coordinates of targets, can also affect model scaling and alignment. Furthermore, the automatic internal camera calibration which is done by the software is based on image metadata and software algorithms which can introduce small deviations if the camera settings drift. Overall, these factors can contribute to minor discrepancies in model accuracy, particularly in poorly lit regions of the tunnel.

5 DISCUSSION

This work demonstrates proof of concept, that it is possible to quantify overbreak using photogrammetry without the need for a surveyor. In this paper, the photographs were collected and processed during routine face mapping activities by the geologists and geotechnical engineers of the WTP project and as such, did not incur additional labour costs or production delays.

The results were found to be less accurate when compared to survey methods. However, we conclude that the accuracy is sufficient for the purpose of informing the decision-making process of the contractor. The accuracy of the modelling could further be improved by standardising data acquisition and data processing procedures. We acknowledge that the overbreak observed in this study was minimal and that the method would be better demonstrated when applied to excavations in poor ground or in tunnels excavated by the drill and blast method.

The use of this technique could easily extend to quantifying shotcrete thicknesses by comparing a shotcrete model surface to the rock as-built surface, or one shotcrete layer to a previous layer. This of course could not provide real-time thickness data and could not replace laser scanning at the tunnel face during the application of shotcrete.

Further to this work, an additional script could be developed to undertake volumetric calculations, which could quantify the overbreak by measuring the volume between the photogrammetry and E-line surfaces or even calculating the volume of spoil stockpiles.

6 REFERENCES

3Dflow. 2023. *3DF Zephyr* (7.531) Verona: 3Dflow srl.

Attard, L., Debono, C.J., Valentino, G. & Castro, M. 2018. Tunnel inspection using photogrammetric techniques and image processing: A review. *ISPRS Journal of Photogrammetry and Remote Sensing* 144: 180–188. https://doi.org/10.1016/j.isprsjprs.2018.07.010

Bonilla-Sierra, V. 2015. Rock slope stability analysis using photogrammetric data and DFN-DEM modelling. *Acta Geotechnica* 10: 497–511. https://doi.org/10.1007/s11440-015-0374-z

Garcia-Luna, R., Senent, S., Jurado-Pina, R. & Jimenez, R. 2019. Structure from motion photogrammetry to characterize underground rock masses: Experience from two real tunnels. *Tunnelling and Underground Space Technology* 83: 262–273. https://doi.org/10.1016/j.tust.2018.09.026

Im, H., Kurauchi, T., Sato, N., Kawamura, Y., Jang, H. & Topal, E. 2025. Tunnel overbreak prediction: An integrated approach using 3D photogrammetry and machine learning. *Mining, Metallurgy & Exploration* 42: 1441–1457. https://doi.org/10.1007/s42461-025-01278-1

Janiszewski, M., Torkan, M., Uotinen, L. & Rinne, M. 2022. Rapid photogrammetry with a 360-degree camera for tunnel mapping. *Remote Sensing* 14: Article 3791. https://doi.org/10.3390/rs14215494

Kim, D.H. & Gratchev, I. 2015. A photogrammetric approach for stability analysis of weathered rock slopes. *Geotechnical and Geological Engineering* 33: 443–454.

Robert McNeel & Associates. 2023. *Rhinoceros 3D*. Seattle: Robert McNeel & Associates.

Torkan, M., Janiszewski, M., Uotinen, L. & Rinne, M. 2023. Method to obtain 3D point clouds of tunnels using smartphone LiDAR and comparison to photogrammetry. *IOP Conference Series: Earth and Environmental Science* 1124(1): Article 012016. https://doi.org/10.1088/1755-1315/1124/1/012016

Wang, W., Zhao, W., Huang, L., Vimarlund, V. & Wang, Z. 2014. Application of terrestrial laser scanning for tunnels: A review. *Journal of Traffic and Transportation Engineering* 1(5): 325–337. https://doi.org/10.1016/S2095-7564(15)30279-8