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Advancing geotechnical construction phase workflows: leveraging digital tools for improved construction outcomes

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ABSTRACT: The design and construction of underground structures require robust geotechnical models and designs that can respond swiftly to geological conditions encountered during construction. This paper examines advances in geotechnical construction phase services (CPS) workflows and verification practices for Australia's major underground infrastructure projects, including tunnels and surface excavations over the past decade. Recent technological advancements, including photogrammetry, laser scanning, and cloud-based data transfer, have enhanced the precision and efficiency of geotechnical mapping by enabling real-time data collection and seamless information sharing among project stakeholders. Despite the advantages, challenges remain, including high initial investment, building team capabilities and awareness, reducing time on the critical path, and industry hesitance. Variable ground conditions and inefficient workflows have been identified as major contributors to cost overruns in tunnelling projects, underscoring the need for ongoing refinement in geotechnical data collection and design verification practices.

This paper evaluates multiple technologies for their abilities in collecting, processing, and conveying data to inform technical assessment and decision-making. Selected examples from recent Australian infrastructure projects demonstrate the practical benefits and limitations of various data collection and analysis tools, such as photogrammetry and laser scanning, in applications including digital mapping and automated structure identification. This study highlights the benefits of digital tools that provide reliable and unified datasets for multi-disciplinary use, including design analysis and optimisation, quality control, and model verification. Effective implementation of digital geotechnical workflows not only offers significant time and cost savings during construction but also simplifies future operational maintenance and design reassessment, ensuring safety and compliance across complex construction projects.

1 INTRODUCTION

Over the past two decades in Australia, ongoing investment in heavy civil infrastructure projects, including road, rail, and hydropower projects has driven the need for CPS workflows that can capture varying geological conditions as accurately as possible while minimising downtime in the construction cycle.

Cost overruns exceeding 50 percent are not uncommon in tunnelling megaprojects (Flyvbjerg, 2014) and in extreme cases have been reported at 900 percent (Paraskevopoulou & Boutsis, 2020). Multiple systematic reviews of time and cost overruns have identified variable ground conditions as a major contributor (Membah & Asa, 2015; Sharma & Gupta, 2020) and the primary contributor to cost overruns in tunnelling specific projects (Paraskevopoulou & Boutsis, 2020).

The design of excavations and underground structures relies on ground-structure interaction, support loading and stability assessments derived from geotechnical models. During the design phase, these models are informed by site investigations and, where available, previous experience in the area or similar ground conditions. The geotechnical model is updated during construction to validate design assumptions and respond to the ground conditions encountered on site.

Rapidly developing technologies such as photogrammetry, terrestrial and airborne laser scanning, and cloud-based data transfer provide increasing efficiency in delivering high-quality data sets. While these technologies offer clear benefits, challenges remain, including increased capital costs, bulky equipment and unrefined workflows. As these elements have matured, the widespread adoption into current construction projects is beginning to accelerate.

By integrating CPS workflows with digital tools like Building Information Modelling (BIM), construction teams can create unified datasets that support stakeholder decision-making, providing benefits throughout the project lifecycle (Sanfilippo et al., 2025). This paper compares data collection and analysis tools, and presents a workflow for the integration of digital tools into CPS operations based on current capabilities.

2 GEOTECHNICAL WORKFLOW METHODOLOGIES AND DEVELOPMENTS

The primary role of the CPS representative in a Design and Construct (D&C) contract is often to compare geotechnical conditions encountered during construction against the documented design assumptions and support selection criteria. Should the encountered conditions represent a departure from the design, a notice of geological change is provided for consideration by the design team and contractor respectively. The following sections describe an evolution of CPS tunnel mapping workflows while outlining the relative benefits and compromises.

2.1 *Traditional mapping*

Traditional geotechnical mapping begins with field sketches and notes, as presented in Figure 1. This method remains widely used due to its simplicity and timely approach for on-site assessment during construction. Transferring paper maps into digital platforms for spatial referencing, as presented in Figure 2, has proven beneficial, but can be time-consuming and prone to errors. Hybrid digital mapping tools, using tablets, have streamlined the mapping process. Engineers can readily record detailed geotechnical observations directly onto digital plans and templates, allowing for quick transfer of mapping records for review while still at the excavation face. However, depending on the adopted platform and template the data is not readily exportable for use in analysis.

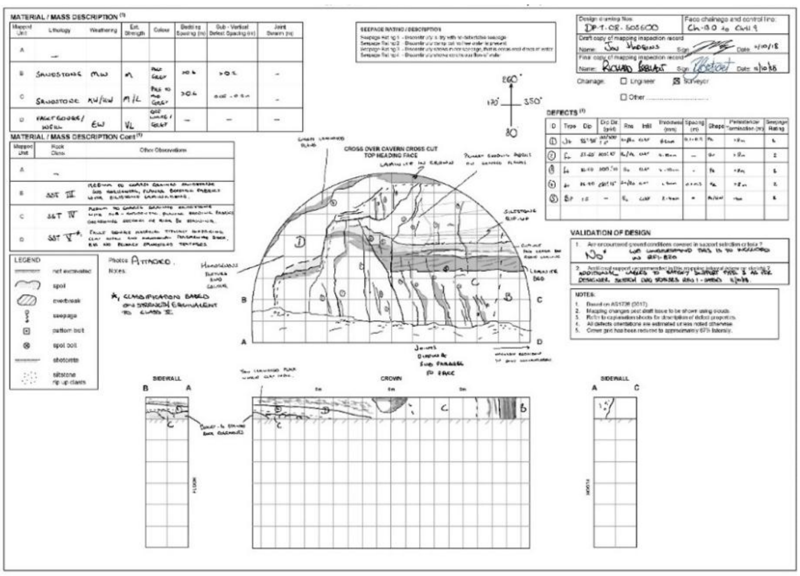

Figure 1. Example of typical geotechnical tunnel face mapping sheet digitised in the field using tablets

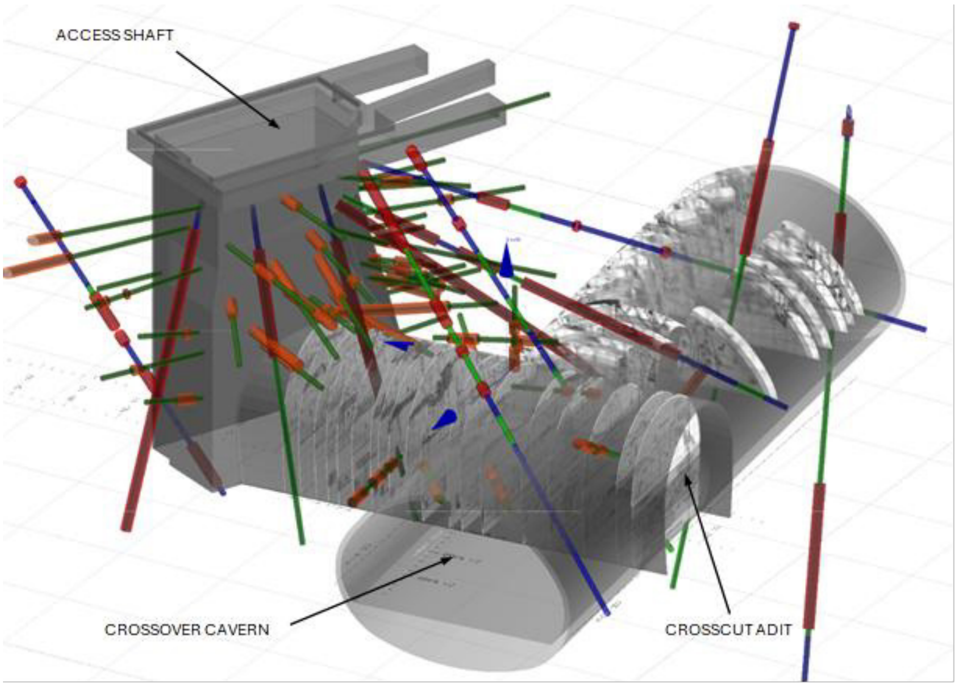

Figure 2 Example of face mapping sheets digitised in 3D space relative to design geometry and available site investigation (borehole) data from the Sydney Metro City and South-West Tunnel Station Excavation Project in 2018.

2.2 *Photogrammetry*

Stereoscopy is a technique that enables three-dimensional visualisation by combining images taken from different positions, where the displacement between images provides depth perception (Nowicki, 1942). By the early 20th century, aerial photogrammetry had become an established tool for topographic mapping, engineering surveys, and military reconnaissance (Linder, 2009). In modern CPS workflows, photogrammetry models incorporate stereoscopic imaging principles to produce high-resolution 3D point clouds, used for geotechnical assessment and design verification. Drone-based photogrammetry captures stereo images to generate digital elevation models (DEMs), allowing for volumetric calculations, slope geometry assessments, and monitoring of construction progress. Over the past 15 to 20 years photogrammetry software has evolved considerably, with improvements in user experience, processing speeds, and model accuracy making it a more practical tool in the right conditions.

Structure-from-Motion (SfM) photogrammetry provides a cost-effective solution for generating high-resolution point cloud models. Photos can be captured from handheld cameras or smartphones and SfM technology automatically solves camera pose and surface geometry using overlapping images (Wang, Zhang & Li, 2023). 3D point clouds and textured meshes are then converted from relative coordinates to project coordinates by referencing a control point. Several other studies have reported favourable outcomes adopting photogrammetry workflows underground (Duffy, Macklin, Henry and Macintosh, 2023; Garcia-Luna et al., 2019).

Over the past decade PSM has conducted several underground photogrammetry trials in numerous tunnelling environments. Challenges with data acquisition and processing reliability remain key to the successful implementation of this method:

- Accurate scaling and georeferencing of the scan depend on the surveyor supplying coordinates for the reference points captured within the image. Errors and inaccuracies introduce distortions in the 3D model.
- Poor or inconsistent lighting, dust, rain and obstructions affect feature-matching, leading to errors in camera orientation estimation.

- Image overlap and photos from different locations are needed to minimise pose errors, see Figure 3. 15 or more high-quality images were found to be sufficient to reconstruct a tunnel face of ~50 m² (Garcia-Luna, Senent, Jurado-Pina & Jimenez, 2019).
- High quality image capture in tunnel environments may require manual exposure settings and camera stabilisation, increasing the time required per photo.
- High density point clouds comparable to laser scans can take anywhere from 45 minutes (with approximately 20 photos) to greater than 4 hours (with approximately 50 photos) (Garcia-Luna et al., 2019). PSM trials indicated that 50-100 minutes was typical for a typical top heading tunnel advance.

Lighting available in a tunnel environment, such as from portable lights or a face drill rig, has been reported to be sufficient (Garcia-Luna et al., 2019), dispelling a typical criticism of this method. In addition to the practical advantages of using a camera or smartphone, SfM can better capture complex geometry that may otherwise be under sampled in laser scanning, such as shadowing behind protrusions in blocky ground (Duffy et al. 2023). Nevertheless, reliance on well-lit, low-dust environment free of obstructions such as machinery, is not always practical in a tunnelling environment.

Figure 3 Photogrammetry model for TBM cross-passage during the Sydney Metro West Tunnel Station Excavation (TSE) project in 2016, including relative photo capture locations. Note, this model capture benefitted from having "supported ground" for favourable camera positioning which is not always possible during production cycles.

2.3 *Laser scanning*

2.3.1 *Professional scanners*

Terrestrial laser scanning (TLS) has been widely implemented in surveying of underground constructions (Sharma & Gupta, 2020). TLS reflects laser pulses on the rock surface to capture millions of data points, including spatial positioning, colour, and surface reflectance (only some scanners are currently capable of this) to develop a 3D point cloud surface.

Modern, lightweight portable laser scanning instruments provide high-resolution data capture (e.g. accurate to 4mm at 10m) which have proven to be successful for self-performed scanning by CPS teams. Calibrated surface reflectance value, which is independent of light conditions and range in some scanners, enables detection of humidity/water. Scans are therefore more reliable and accurate than photogrammetry in low light, low-texture and low-contrast rock environments.

In certain applications (surface excavations), integrated GPS can register scans without the need to establish reference points. However, over larger project extents such as tunnels, survey targets are required to convert GPS coordinate system readings to design coordinates (e.g. MGA). The scale factor between these systems is 0.9996 and accounts for the earth's curvature.

The Leica BLK 360 scanner was used extensively on the Lake King William Hydropower Upgrade Project in Tasmania. The use of TLS has delivered numerous project advantages:

- TLS scans provided a transparent, accurate and repeatable approach to recording as-built conditions, see Figure 4. Scans were provided to the head contractor and asset owner, which informed decision making on site and enabled proactive identification of issues such as geometry non-conformance.
- Improved safety with data capture occurring beneath "supported ground".
- Integration with survey workflows, including shotcrete scanning thickness verification.
- Georeferenced scans and automatic defect identification software supplemented traditional mapping, see Figure 5, reducing time required by geologists at the face, while also providing redundancy with the availability of accurate data when a geologist was not available (e.g. night shift). This was especially valuable in a drill and blast operation in blocky ground, where mapping individual defects would be otherwise very time-consuming.

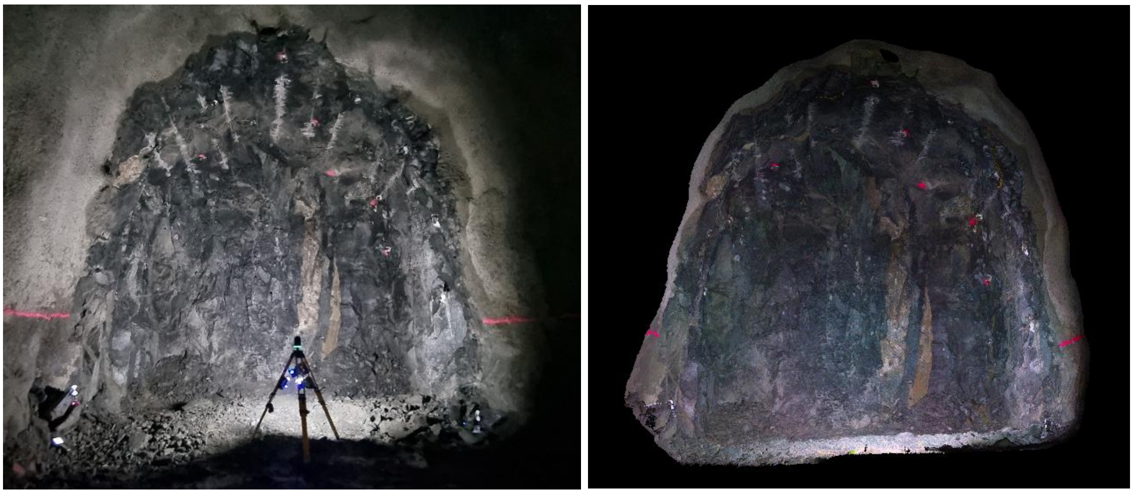

Figure 4 TLS capture of a drill and blast tunnel excavation (left) with corresponding georeferenced point cloud output (right)

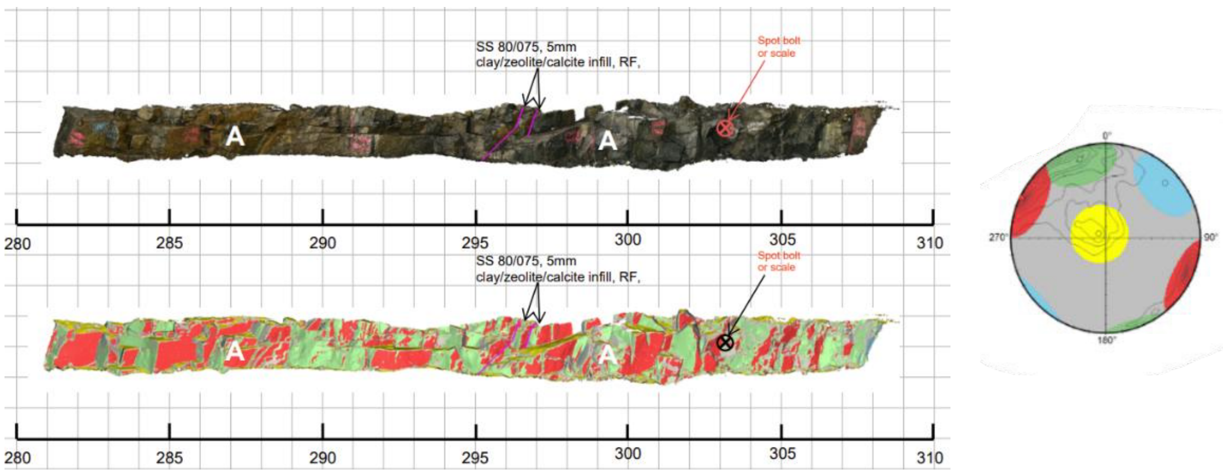

Figure 5 Mapping example using RiScan Pro LIS GeoTec: Upper plots show red, green, blue (RGB) coloured point cloud while lower plot illustrates automated defect detection with corresponding stereograph.

- 3D models enabled continuity of mapping and accurate tracking and projecting of adverse structure allowing for early identification and support selection. For example:
  - Figure 6 illustrates how scan records were used to accurately calculate the size and location of wedges requiring additional support. Scans allowed for accurate and safe defect orientation measurements when the face was inaccessible due to site safety protocols.
  - Combining field mapping observations with scanning data identified adversely dipping structures at the tunnel portal. To verify support capacity, a kinematic sliding analysis was carried out based on wedge geometries from the scans. Follow-up mapping and scanning at the portal face and within the tunnel were then used to verify design assumptions.

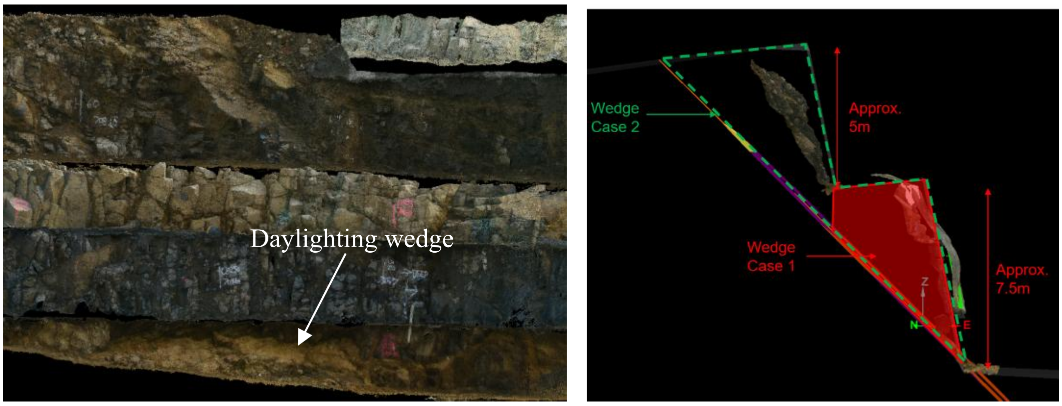

Figure 6 Visualisation of daylighting wedge using TLS data allowing for review of kinematic sliding mechanisms and potential load cases.

While TLS scanning has proven to be highly beneficial, the following limitations are noted:
  - Processing and cleaning high-resolution point clouds can be a time-intensive exercise requiring high computational effort.
  - Trials involving multiple underground scans did not always produce accurate true colour datasets. However, the intensity (reflectance) data provides redundancy and perspective to supplement interpretations.
  - Single scans occasionally resulted in small data gaps behind protruding rock or recesses. These were considered minor and were supplemented with photos and visual mapping.

2.4 *LiDAR equipped tablets*

The use of LiDAR-equipped tablets or phones can provide a quick, cheap and accessible alternative to survey grade TLS. The simplicity of data collection means scans can be performed by CPS personnel, eliminating the need for surveyors. Data can be uploaded within minutes over Wi-Fi, enabling remote teams to commence near real time reviews, leading to rapid decision making. LiDAR-equipped iPads scans were performed by CPS on Brisbane's Cross River Rail project and integrated into a 3D model delivering the following project benefits:
- Improved continuity in mapping, especially where excavation and support occurred in small increments due to construction constraints.
- Since scans could be rapidly shared with remote design teams, potential wedge volumes and support requirements were assessed in real time, reducing construction delays.
- As an example, scans of a mined tunnel invert foundation were captured on-site and transmitted within minutes to the design office, where removal and replacement of weak material beyond the stated design tolerances could be confirmed, see Figure 7. The as-built slab treatment could also be compared against pre-treatment scans, ensuring design compliance without requiring on-site survey support. This enabled quick validation of prescribed treatments and reduced delays.

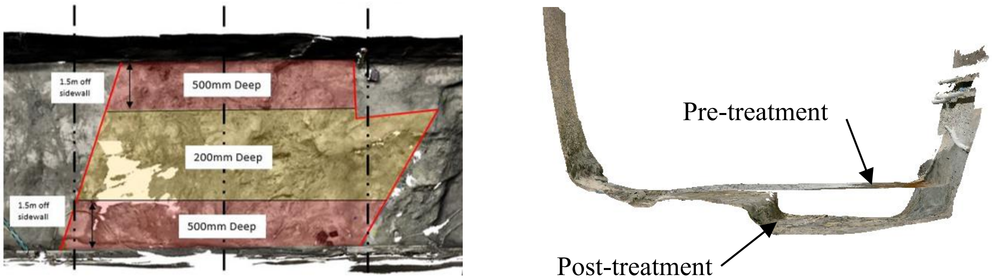

Figure 7 Example slab foundation material excavation directed from scans (left) and assessed in cross-section (right)

However, collection methods and the accuracy of this LiDAR scanning methodology have notable limitations:

- Tablet acquired scans produced lower resolution datasets compared with professional grade scanning equipment.
- The scale of the subject was limited to approximately 50m^2 per scan to minimise distortion.
- Control points were often not immediately available following excavation, aligning scan data accurately was difficult. Wall chainage and floor level are typically provided for geotechnical mapping, limiting scan alignments to approximately +/- 300mm.
- Scan acquisition requires careful planning to ensure consistent face offsets are maintained without doubling back on early captures using a sweeping type motion. This proves particularly challenging when capturing blocky rock mass in an excavated face. This is therefore impractical for tunnel headings and walls greater than 3m height while also contending with "unsupported ground".

Despite these limitations, LiDAR-based tablet scanning has proven to be a highly effective and cost-efficient solution for specific geotechnical purposes.

2.5 *Time comparison*

Time spent on the critical construction path and post-processing of scans are key considerations when considering adoption of specific methods. Table 1 compares scanning times for a typical tunnel advance and surface excavation (approximately 60m^2 area) using the respective data acquisition techniques. As technologies advance and equipment becomes lighter and more efficient, these will only continue to improve.

Table 1. Scanning and processing time comparison

	Tunnel		Surface excavation	
Method	Total scan time (minutes)	Post-processing (minutes)	Total scan time (minutes)	Post-processing (minutes)
LiDAR equipped tablet	Not applicable		5-10	10-20
Professional survey grade laser scanning	10-25	50-70	10-20	50-70
SfM photogrammetry	10-20	50-120	10-20	50-120

3 SOFTWARE DEVELOPMENT

The effective use of TLS and photogrammetry in geotechnical workflows relies on the capability of post-processing and visualisation software. Software packages vary in their ability to process point clouds, efficiently extract geotechnical features, and integrate with 3D geological modelling platforms.

3.1 *Automated and semi-automated mapping software*

Automated structure picking tools are becoming increasingly common with many CPS workflows adopting these as a means of supplementing traditional mapping data. These packages work by querying surrounding points to fit planes and generate discontinuity sets from point cloud data. This process is especially valuable in blocky rock masses or within in drill and blast excavation, where defects are typically well expressed in the excavated face and manual mapping can be time-consuming. However, users must be conscious of input assumptions used by structure picking algorithms which include:

– Algorithms favour defects with well-exposed surfaces, where a larger number of surrounding points are available to define a plane.
– True discontinuities that do not present a clear planar face in the scan, such as thin seams, tight fractures, or features sub-parallel to the scan angle, are often under sampled. Its effectiveness therefore decreases significantly in smooth excavation environments (e.g., roadheader, rotary cutter, or smooth blasting).
– The sensitivity of the defect search function (e.g., smoothing parameters and minimum point count for plane fitting) creates a trade-off between accuracy of captured planes and picking up defects that are not well expressed in the face. Smooth excavated surfaces may mistakenly be interpreted as valid discontinuities.
– Its effectiveness decreases with increasing scan area.

As with any automated process there must be QA/QC processes employed with regular review using field data to calibrate and maintain accuracy of outputs. Typical post-processing workflows included the following to mitigate these limitations:

– Filtering discontinuities based on total area to avoid over-interpretation of spurious features.
– Validating automatically identified structures against field mapping records.
– Manually querying and cross-correlating additional defects using 3D geotechnical modelling software that were not captured by the automated picking process.

While automated structure picking is not a substitute for experienced engineering judgement, it is a useful tool for supplementing face mapping in appropriate conditions. As software and processing algorithms continue to advance, the accuracy and reliability of automated defect mapping are expected to improve.

Semi-automated digital mapping tools, such as 3GSM's ShapeMetrix, are inherently integrated with engineering judgement throughout the mapping process. They can be a useful tool for faster and more accurate remote mapping while creating reliable inputs for inclusion into as-built engineering geological model and subsequent geotechnical analysis, including:

– Defect set clustering and statistical analysis.
– True defect spacing measurements on planes orthogonal to the defect orientation.
– Defect plane mesh generation to measure waviness.

3.2 *3D visualization software*

Scanned construction data forms the foundation for a digital twin of the asset, supporting project-wide collaboration, enhanced QA capabilities, and future maintenance planning and asset management. 3D geotechnical software packages (e.g Maptek Geologycore) are often used for geotechnical digital twin models where it can be integrated with site investigation and design data, see Figure 8. On some projects, digital twins may be kept on federated platforms due to the need for cross-disciplinary, real-time collaboration, and integration with BIM, structural, and operational systems. Federated platforms, for example Autodesk Navisworks, provide the advantage of readily sharing and viewing of data, and are future-proofed for file longevity to be used in operation and maintenance of the asset.

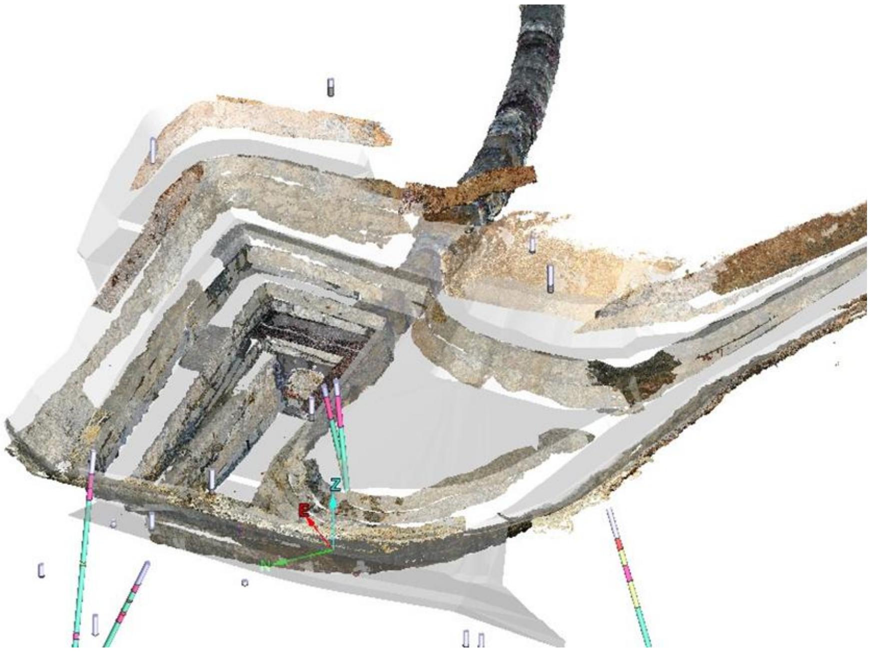

Figure 8. 3D geotechnical model including TLS rock face scans integrated with design geometry (in transparent grey) and available site investigation (borehole) data.

4 CURRENT WORKFLOW

The workflow presented in Figure 9 was developed to incorporate field inspection, TLS scanning, and 3D model refinement. It is important to note that the benefits and limitations of digital tools vary across every project, and the workflow development should be objectively driven.

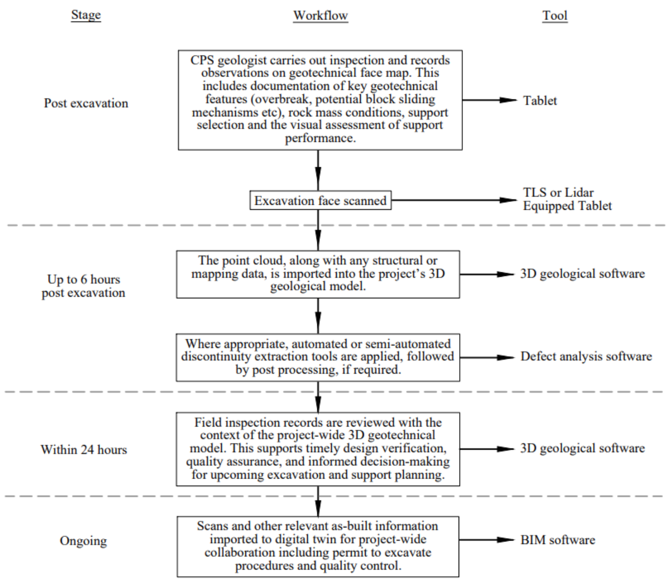

Figure 9 CPS workflow incorporating digital tools

5 CONCLUSIONS

Digital tools are transforming geotechnical construction workflows by enabling faster and more accurate visualization of ground conditions, and more collaborative decision-making during construction. When used poorly, 3D scanning can result in 'pretty pictures' without accurate data and timely construction support. When developing a CPS workflow for a project, the benefits and limitations of each tool should be considered along with ground conditions, site conditions, project objectives and project constraints. In the opinion of the authors:

- Survey-grade TLS remains the preferred option, where budget allows, as it is more practical for use on site, can be integrated with survey workflows, and its accuracy and repeatability supports high-confidence model and design verification.
- Handheld LiDAR offers a low-cost and less resource-intense alternative to TLS in surface excavations where budgets are constrained, and a lower scan accuracy can be accepted. It can provide adequate detail for face mapping, support assessment and design validation.
- Photogrammetry offers the advantage of low setup costs and minimal hardware requirements, making it a viable option if sufficient lighting and a low dust environment can reliably be provided. However, photogrammetry outputs offer limited additional benefit compared to TLS in typical construction settings. Due to its inconsistent reliability in real-world tunnel conditions, photogrammetry is not currently considered the preferred option.
- Supplementing traditional face mapping with automated or semi-automated mapping software can provide useful outputs for geotechnical analysis and design verification, if the limitations are understood and accounted for.
- Integrating scans and other data captured on site into a 3D geological model and/or digital twin is beneficial for stakeholder decision making during construction and operation.

The broader implementation of these technologies brings demonstrated benefits to geotechnical workflows, construction outcomes and operational management. Addressing the remaining challenges requires continued software development, improved integration with design platforms, and clearer guidance for tool selection and workflow design.

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