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High-resolution ground-deformation and support monitoring using a portable handheld LiDAR approach

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Abstract

Light detection and ranging (LiDAR) technology plays a strategic role in the design and maintenance of underground support systems. Ground deformation, and by extension, ground support monitoring, are typically performed using tripod or wall-mounted survey-grade tools, single-point to multi-point measurements or by simple visual inspection. These traditional data-collection practices offer limited quality control, decreased accuracy and minimal standardisation across geotechnical personnel.

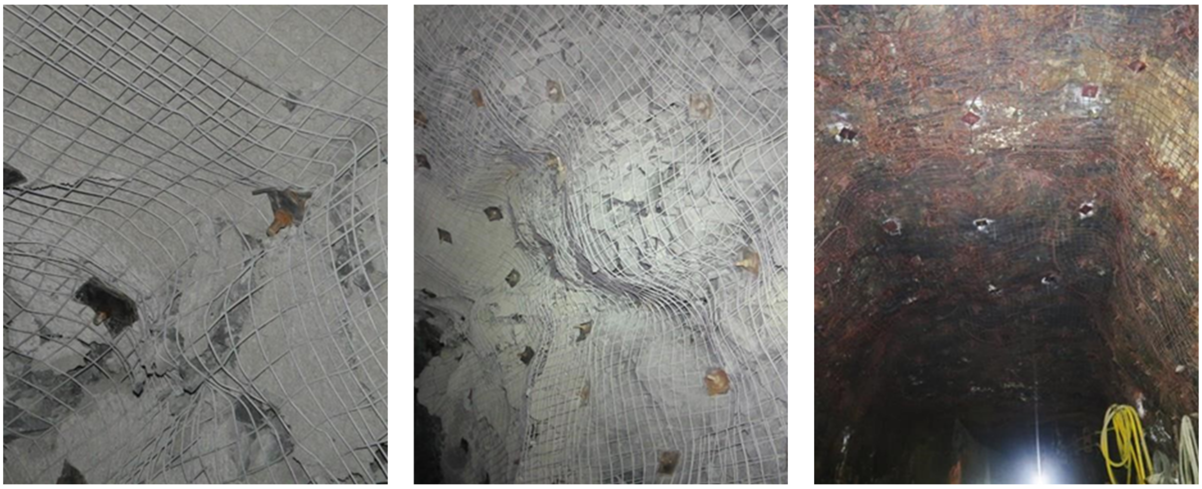
As more portable underground LiDAR solutions become available, mine sites are integrating them into their daily underground inspections. Using a LiDAR-based approach, ground convergence and subsequent deformation monitoring can be completed using a model-to-model comparison between two scans taken at the same location but at different points in time. The comparison uses a distance computation to calculate the relative change between the two scans and generates a heat map based on the results. This paper presents a case study on the lowest reliable detection threshold for relative ground deformation by a handheld LiDAR solution.

Mine sites with relatively small ground displacements require very high-resolution point clouds to achieve useful results in a model-to-model comparison. This paper aims to demonstrate that handheld LiDAR solutions can meet point cloud resolution and productivity requirements to efficiently capture small ground displacements in underground mining operations. This is achieved through the use of a portable infrared LiDAR device, which contains an integrated onboard attitude and heading reference system (AHRS). The combination of the infrared LiDAR and AHRS allows for the capture of georeferenced scans in seconds, which increases the efficiency of the data capture and downstream post-processing workflow. Improving the fidelity of the data captured for ground deformation and support monitoring can result in safer excavations for both personnel and equipment, as well as more economical design and timelier support rehabilitation interventions.

Keywords: *deformation monitoring, LiDAR scanning, damage mapping, digitisation*

1 Introduction

Ground support plays a critical role in providing a safe work environment in an underground excavation and in maintaining operations throughout the life of a mine. Regular ground support inspections at various intervals in its design life are considered standard practice at most sites. These day-to-day inspections are often designed to maximise efficiency in order to meet rigorous production scheduling targets and reduce personnel exposure at the face. In some cases, these are only visual inspections, with some sites adopting additional support monitoring instrumentation and wall-mounted or tripod survey-grade scanning equipment to monitor ground deformation. Visual cues of support decay (Figure 1), such as rockbolt plate deflection, support damage or corrosion are often not sufficient to characterise the condition of ground support over time.



(a) (b) (c)

Figure 1 Examples of visual cues of ground support decay in an underground setting at Glencore's Sudbury operations. (a) Rockbolt plate deflection; (b) Bolt plate deflection and mesh bagging where all material was held by the ground support; (c) Ground support corrosion

In addition to visual assessments, ground deformation measurements can be used as robust indicators in support-capacity decay (Kaiser & Moss 2022). Although this is generally accepted in theory, many practitioners lack the data required to implement a deformation-based support-design approach. While these systems have only recently become more popular in underground construction and in mining environments, using LiDAR or radar technologies for displacement monitoring is considered standard practice in slope or open pit engineering (Kaiser & Moss 2022).

LiDAR technology, in particular, offers opportunities to utilise displacement monitoring for support-design verification and optimisation, safety assessment and preventative maintenance. Many mines, including Glencore's Sudbury operations in Northern Ontario, Canada, use miner-operated survey systems that pick up a 2D profile of the face and back as part of their regular development cycle. Full 3D LiDAR scans can be completed with a similar amount of effort; however, they often introduce large data storage and processing requirements.

Much of the scope of work for this project was inspired by the geotechnical issues experienced by the Sudbury mining operations and by other sites within the region. It is known from past experience in the Sudbury area that underground development mining can experience severe rock bursting conditions, often with little to no visual ground change or obvious ground support loading ahead of the event since the displacements are smaller than what can be reliably detected by visual cues or by many current portable LiDAR scanning systems.

The purpose of this testing was to determine if a handheld flash LiDAR approach can be used to reliably detect small ground displacements less than 0.01 m (which would likely be required for the pre-loading conditions at Sudbury and similar operations) and to develop a set of practical recommendations based on the empirical relationship between scanning distance and intended model comparison results that can be used as guidance for site geotechnical engineers.

2 Background

Typical ground displacements experienced by underground excavations vary at each mine site, and are heavily influenced by depth, local and regional stress conditions, rock mass characteristics, prevalent failure mechanisms etc. The emerging popularity of mobile and handheld LiDAR methods to capture detailed models of underground excavations efficiently offers geotechnical engineers the opportunity to integrate 3D ground displacement data into their support-design and performance-assessment process. The success of deformation-based support depends on the quality of data used to design it.

2.1 Deformation-based support design

The deformation-based support-design (DBSD) approach, as described by Kaiser & Moss (2022), identifies the reduction in capacity of an integrated support system as a function of imposed displacements and renders excavations more vulnerable if they are located within the influence of active mining and seismic activity. Available support-capacity substantially decreases over time since installation, and emerging technologies offer an opportunity to utilise displacement monitoring methods for support-design verification and operational decision-making.

In a field setting, the displacements experienced by an underground excavation throughout its operational lifespan are not limited to only bulking systems, so change monitoring equipment must be able to accommodate and model a variety of different displacement mechanisms at a variety of scales. Rockbolts, for example, can experience displacements every time a fracture dilates or shears; so in reality, a single bolt could displace significantly over multiple fractures. Smart cables or instrumented bolts are one approach to modelling these displacements, but they can often be very expensive and are only locally deployed. LiDAR solutions, such as the one presented in this paper, create an accessible, empirical link between displacement measurements via 3D scanning and real ground change experienced in the field.

For example, in the context of deep mining in very high-quality rock masses such as those in Sudbury, many typical displacement monitoring tools are often not able to detect the small ground changes that would be typical in a pre-loading scenario before a rockburst. As opportunities in the technological availability of remote sensing solutions continue, there is, therefore, a case to be made for mapping small ground changes in localised areas in addition to using other common measurement methods.

2.2 Integrated sensor system

Mine sites looking to monitor small ground displacements require very high-resolution point clouds to see results in a model-to-model point cloud comparison. This tends to limit the applicable LiDAR options to tripod or wall-mounted solutions, as opposed to portable options. A typical LiDAR scanner generates a 3D model of its surrounding space by projecting a series of multi-directional laser pulses. Those pulses bounce off an object and return to the sensor, which then can be used to calculate a distance. This results in a 3D point cloud of the object. Point cloud resolution using this method can vary from scanner to scanner but can often range from the millimetre scale to a multi-centimetre scale. Mobile LiDAR scanners, in particular, can generate detailed scans of large areas very efficiently, but their substantial file sizes can make them very difficult to implement at some operations.

This study uses a handheld flash LiDAR scanner which operates by illuminating the entire field of view with a wide diverging laser beam within a single pulse of light (Figure 2). Though it is still considered a static solution, the scanner can capture very high-resolution results in a matter of seconds and, therefore, can be handheld without the use of a tripod. The structured light from the single pulse uses a near-infrared pattern projected across the space in front of the sensor and captures the reflected light pattern. The reflected pattern is deformed by the relative depth of the objects in front of the sensor and generates a 3D model. This approach allows the resulting point clouds to be captured within a matter of seconds, and to maintain a consistent point-to-point spacing throughout most of the scan, where the resolution of the point cloud depends on the distance from the rock mass, as shown in Figure 3.

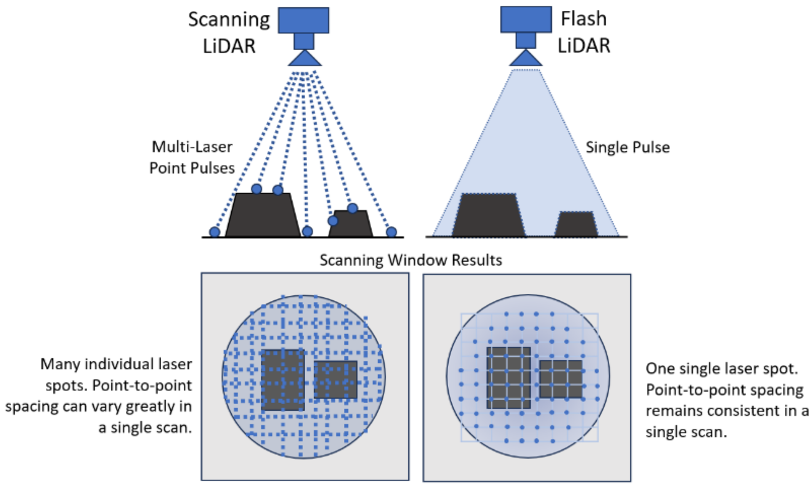


Figure 2 Scanning LiDAR versus flash LiDAR (adapted from Lohani et al. 2013)

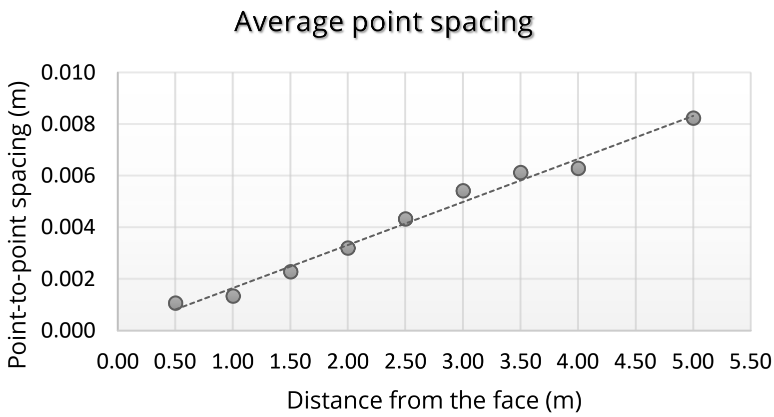


Figure 3 Chart showing the relationship between average point cloud point spacing in metres and scanning distance from the face in metres

In addition, the device used in this study contains an integrated onboard attitude and heading reference system (AHRS), which acts as a motion sensor. The AHRS system contains an inertial measurement unit (IMU) which consists of multiple gyroscopes, accelerometers and magnetometers. This system, in combination with an integrated rangefinder, is used to identify the scanner position relative to underground survey control and track its orientation in 3D space, i.e. enabling the device to track its location in terms of northing, easting and elevation relative to a known survey marker in the mine. Some of the unit's key hardware components and additional features are outlined in Figure 4. The combination of infrared LiDAR and AHRS allows for the capture of georeferenced scans in seconds in GPS-denied environments, which increases the efficiency of the data capture underground and subsequent downstream analysis processes (Gallant & Marshall 2016; Smith & Yee 2020; www.rockmasstech.com).

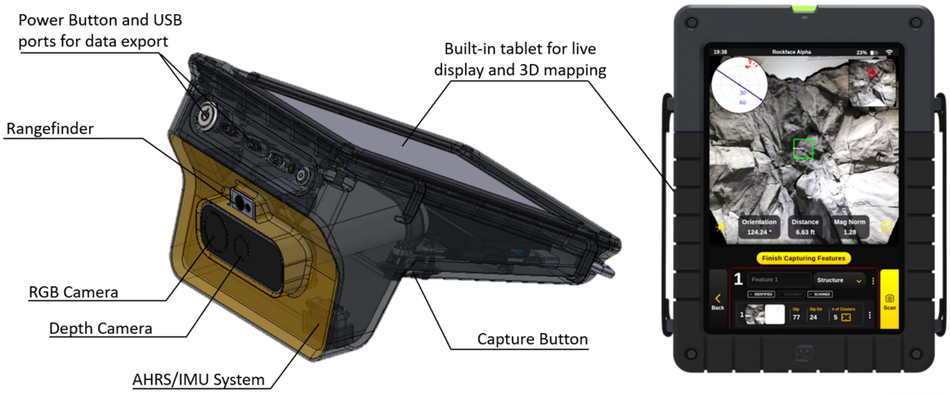


Figure 4 Diagram showing some of the key hardware components of the LiDAR tool used in this study, as well as a sample workflow screen using the system's built-in tablet

3 Digital data collection

3.1 Experimental setup

Initial testing using the handheld scanner was performed in an experimental environment in accordance with Technology Readiness Level 4 as described in ISO 16290:2013 (International Organization for Standardization 2018). The purpose of this testing was to establish a baseline recommendation guide based on scanner performance in ideal conditions without the interference of the environmental factors that are typically experienced in an underground setting. Future work will assess the performance of this approach in an operational environment.

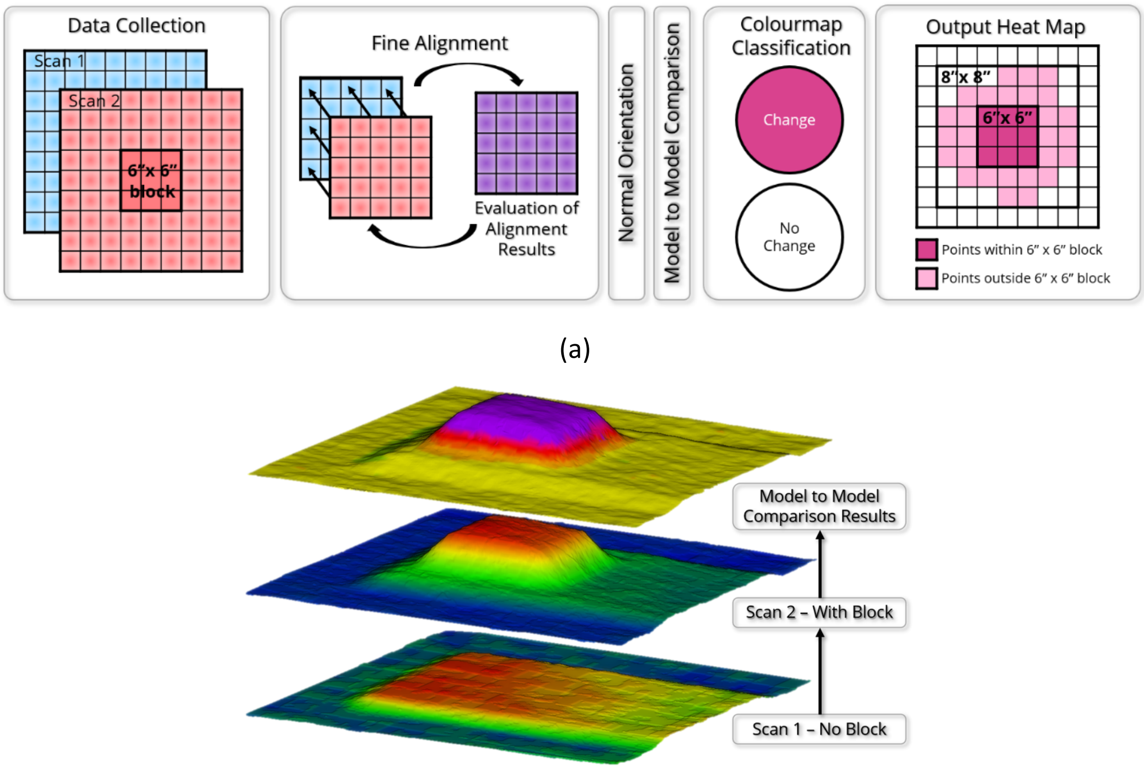
This study used scans of foam blocks of variable controlled thicknesses to investigate the change detection threshold for the handheld scanner in relation to the unit's distance from the scanned face. The foam blocks used for the experimental testing were 0.15 × 0.15 m (6 × 6”) in size and were mounted to a wall to simulate ground displacements less than 0.025 m, at face distances that ranged from 0.5 to 5 m, as this is the recommended range for the unit's scanner. Scans were taken with and without the foam blocks at the same distance and compared using the M3C2 plugin in CloudCompare (James et al. 2017; CloudCompare 2023).

3.2 Model-to-model comparison

Relative ground displacement can be measured underground using a LiDAR model-to-model comparison between two scans taken at the same location but at different points in time. For both practical field use and experimental testing, the general workflow will follow the same key steps that are described in Figure 5.

To simulate ground change in an experimental environment, the first and second scans were collected in the same location, both without and with the block, respectively. The scans were then imported into the CloudCompare software and underwent a series of rough and fine alignment iterations using the software's built-in automatic fine registration tool. This process ensures a good dataset ‘fit’ between the scans and reduces the opportunity for alignment errors in the M3C2 comparison process.

The comparison used a multi-scale distance computation to calculate the relative change between the two scans and generated a 3D heat map based on the results. The plugin's main parameters are fully customisable to meet the comparison resolution requirements, as well as the upper limit, lower limit and step interval in the heat map results. It also requires users to set the ‘normal’ orientation, which can be a scan trajectory file, survey topographic line, or, in this case, the point position of the scanner upon capture. Although the flash LiDAR point-to-point spacing remained mostly consistent across most of the scan, the distance to the face plays a significant role in the resolution of results, and subsequently, the displacement detection threshold.



(b)

Figure 5 (a) M3C2 model-to-model comparison workflow summary used in this report; (b) Figure using sample data examples to outline basic data-collection requirements to generate model comparison results

Many Canadian mine sites, including Glencore's Sudbury operations, often operate with development round lengths of approximately 4 m. This was considered when defining the upper distance limit for scanner performance testing in this report, as this distance would ensure the scan operator could capture the required dataset from a safe location.

4 Results

The results for each iteration of testing were evaluated using an original rating scale based on the percentage of coloured ('change') points within the 0.15 × 0.15 m (6 × 6") original block boundaries, compared to the percentage of coloured points outside of the block boundaries (also referred to as 'point seepage' in this document). Equation 1 describes this comparison and was used to define the final rating scale listed in Table 1.

$$\frac{\#\ of\ coloured\ points\ inside\ block}{Total\ \#\ of\ points\ inside\ block} - \frac{\#\ of\ coloured\ points\ outside\ block}{Total\ \#\ of\ points\ outside\ block} \quad (1)$$

Table 1 List of criteria and example result for each of the rating scale intervals used to evaluate the quality of comparison results in this study

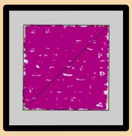
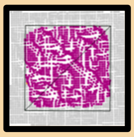
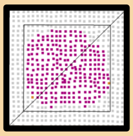
Example result	List of evaluation criteria
	**Excellent (>94%)** Block shape is still maintained in its exact form Little to no point seepage beyond block boundaries Excellent fit within block boundaries
	**Good (90–93%)** Coloured points still resemble block-like shape Minimal point seepage beyond block boundaries Good fit within block boundaries
	**Fair (86–89%)** Coloured points resemble somewhat block-like shape Some point seepage beyond block boundaries Somewhat of a good fit within block boundaries
	**Poor (<85%)** Coloured points do not resemble block-like shape Significant point seepage beyond block boundaries Poor fit within block boundaries

Table 1 above demonstrates that a dataset's point density, which is controlled by the scanner's distance from the face, plays a key role in the quality of results. As the user's distance from the face increases, the scanner's field of view, which remains constant, must compensate for the larger scan area by increasing the spacing between individual points. Using a flash LiDAR system, where the point-to-point spacing in a single point cloud is mostly constant across the entire dataset, as shown in Figure 3, the relationship between average point density in the scan and distance from the face is linear.

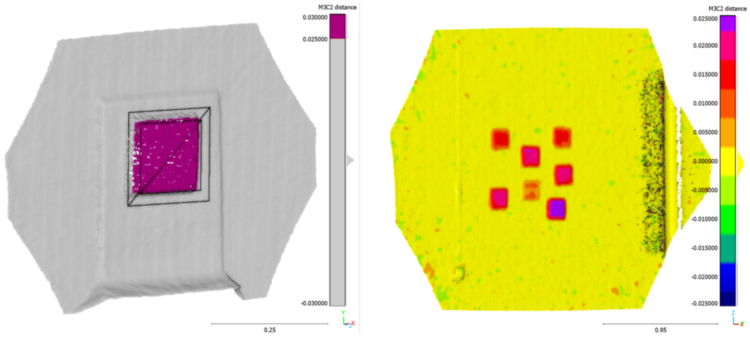
This relationship between average point spacing and face distance was also observed as a driver of the key trends in the final testing results that are summarised in Figure 6. Although the upper and lower limits of each variable used in this testing were chosen based on scanner performance and general user feedback, it is reasonable to assume that this linear trend will be consistent beyond the limits of this study.

Distance from Face (m)	Displacement (m)				
	0.005	0.010	0.015	0.020	0.025
0.5	Excellent	Excellent	Excellent	Excellent	Excellent
1.0	Good	Excellent	Excellent	Excellent	Excellent
1.5	Good	Excellent	Excellent	Excellent	Excellent
2.0	Fair	Good	Good	Excellent	Excellent
2.5	Poor	Fair	Fair	Good	Good
3.0	Poor	Fair	Fair	Fair	Fair
3.5	Poor	Poor	Poor	Fair	Fair
4.0	Poor	Poor	Poor	Poor	Poor
5.0	Poor	Poor	Poor	Poor	Poor

Figure 6 Chart showing a summary of testing results using the defined rating scale described above

By using the summary of results below and observations from the experimental results, a few key observations were made:

- For best results, users looking to scan ground displacements less than 1 cm (0.01 m), should scan at distances less than 1.5 m; however, displacements at this scale can still be detected by the scanner up to 5 m away from the face.
- Higher ground displacements, such as 0.020 and 0.025 m, begin to show signs of a smoothing or rounding effect of the block edges at distances greater than 2.5 m as a result of resolution loss in the scan. Due to this behaviour, the resulting area of coloured points was significantly reduced. This phenomenon appears to only be limited to parallel surfaces that are not visible to the scanner, so should not affect most results taken at a natural rock face.
- Although a two-bin colourmap and single-block approach was required in order to assess the quality of results in this study, a multi-bin colourmap and multi-block system is much more realistic in representing what real results would look like when this method is used in practice (Figure 7).



(a) (b)

Figure 7 (a) Example of model comparison results using a two-bin colourmap and single-block approach; (b) Model comparison example using a much more realistic, multi-bin gradational colourmap

The results from this study demonstrate that the flash LiDAR system was able to successfully detect very small model-to-model changes at distances up to 5 m. Scanning at this distance still maintains good scanner performance and allows underground users to capture high-resolution 3D datasets from a safe location. For sites looking to monitor low levels of ground displacement, the scanner was also able to detect displacements less than 0.01 m at this distance.

Additionally, because LiDAR data can be integrated with a variety of modelling and analysis software, there is an opportunity to model flash LiDAR systems as a high-resolution localised deformation mapping tool in combination with other LiDAR-based tools that may offer different data-collection capabilities.

5 Conclusion

Initial results from this study demonstrate that a handheld flash LiDAR solution can meet point cloud resolution requirements to efficiently capture and model small ground displacements. However, further testing is required to determine how environmental factors (dust and humidity) and surface conditions (dry or wet faces) impact the scanner's performance in the field.

As shown in this paper, LiDAR point cloud density plays a key role in determining the quality of the model comparison results. Since point density is directly related to its hardware specifications, it is safe to assume that in most scenarios, the flash LiDAR sensor would still be able to detect and model ground deformations less than 0.025 m under moderately variable conditions. Early testing shows that a handheld, high-resolution flash LiDAR approach can offer geotechnical engineers the opportunity to efficiently capture and integrate small ground displacement data into their daily visual inspections, support-design, and performance-assessment process, which leads them to make better long-term design decisions for their operation.

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