TECHNOTE

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Pocket Lidar for Assessing Mechanically Stabilized Earth (MSE) Retaining Wall for Bridge Abutments

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This document is a technical summary of a case study for the Federal Highway Administration report *Leveraging Pocket Lidar for Construction Inspection and Digital As-Builts—Phase 1* (Forthcoming).

OVERVIEW

Mechanically stabilized earth (MSE) walls contain earth for embankments and support bridge abutments to ensure their structural integrity.(1) Inspection of the MSE wall systems is necessary during and after construction so that improper placement or damage on the retaining walls can be detected in a timely manner.(2) However, most of the specified inspection procedures, especially postconstruction, rely on qualitative assessment. Although key features such as vertical alignment can be measured during construction with tools such as hand held levels, these measurements are arbitrarily sampled and not rigorously recorded in a systematic way with location information. Capturing the MSE walls during and after construction with traditional survey equipment can potentially align all measurements into the same coordinate system. Nonetheless, it can be time consuming and require expertise to operate these devices for the data collection. More advanced remote sensing technologies, such as lidar, can also be leveraged for three-dimensional (3D) reconstruction of the MSE walls given their accuracy, efficiency, and resolution. However, the accessibility of lidar equipment is still limited, and processing the point cloud data acquired by the laser scanner can be labor intensive and require specialized software and associated expertise.

Fortunately, several smart phone models are now equipped with pocket lidar (PL) sensors. Inspectors can easily gain access to these devices and use them to perform 3D documentation with a variety of easy-to-use apps. As the performance of these PL has not been explored in the context of assessing MSE walls for bridge abutments, the research team collaborated with Florida Department of Transportation (FDOT) to conduct a case study to do the following:

- Assess the ability and associated data quality of PL to capture the geometry of the MSE walls and other pertinent dimensions.
- Evaluate the accuracy of the metrics extracted from the PL point cloud data.
- Explore other opportunities of leveraging PL in inspections related to bridges.

Figure 1. Screenshot. Google® Maps™, Google Street View™, and closeup photograph of the case study site.[3]

DATA COLLECTION AND FIELD SITE

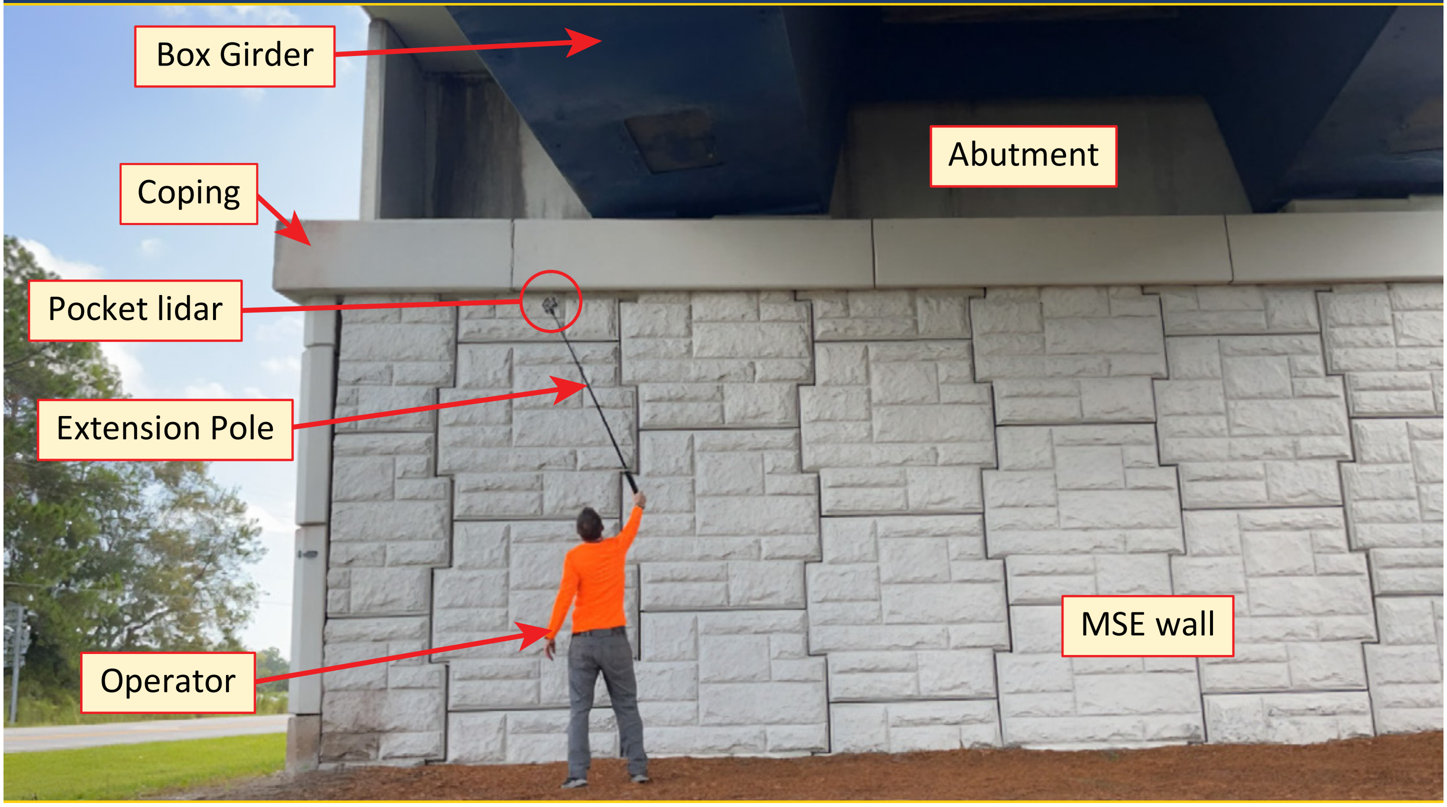
The research team coordinated with FDOT before the field deployment to identify candidate highway and bridges that were suitable for this case study. Several factors, including safety, traffic, traffic control, size of the bridge, locations, and so forth, were taken into consideration to ensure a representative case study. The location selected for this study was a bridge on Highway 102 at its intersection with Highway 243 in Jacksonville, FL (figure 1). This bridge is a steel box girder bridge with abutments supported by MSE retaining walls. Before data collection commenced for this case study, the research team gave an oral presentation on the key findings from the lab and field testing of PL conducted in the overall project for the Federal Highway Administration (FHWA). The team also provided an onsite demonstration of utilizing a PL to collect 3D point cloud data for several participants from FDOT.

The data collection took place on October 1 and 2, 2023 with the necessary traffic control provided by FDOT. The PL device used in this case study is an iPhone® 13 Pro Max. Because the lidar sensor's maximum range is 5 m in an ideal situation (e.g., proper lighting, sufficient contrast, minimal incidence angle, etc.), an extension pole was used to enhance PL device's coverage given the height of the MSE wall (over 4 m, figure 2). Many apps are available in the Apple® App Store® that utilize the lidar sensor to achieve 3D reconstruction and provide point cloud data. Previously, the team rigorously tested many apps and identified two promising apps for construction inspection: Scaniverse℠ (Toolbox AI) and 3D Scanner App℠ (Laan Labs).[4,5] The optimized settings determined in this testing for capturing larger objects identified in the prior lab and field testing were used in both apps. Each session lasted about 1 to 2 min and covered about 13 m wide, which is on par with the width of the bridge deck. In addition to the MSE wall, the research team also captured part of the box girder and ground surface to provide some context of the target objects for further processing (e.g., to improve the registration) and analysis, such as determining vertical clearances. For comparison and analysis, the reference data was collected by a Leica BLK360 terrestrial laser scanner. A total of three scans were collected in front of the MSE wall and captured the surface at high (subcentimeter) accuracy and resolution.

DATA PROCESSING

The BLK360 terrestrial laser scans were registered in Leica Cyclone software such that the data from all three scans were aligned in the same local coordinate system.[6]

Figure 2. Illustration. Data collection procedure with a PL unit on an extension pole.



Source: FWHA.

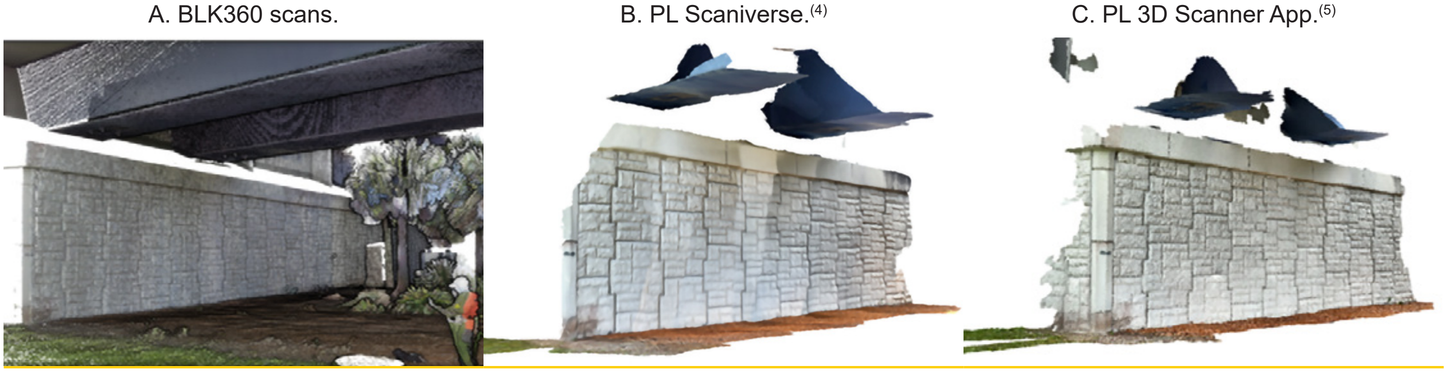
The combined point cloud was then exported in ASTM E57 format and converted to ASPRS LAZ format using EZDataMD EZPC tools (figure 3).[7]

The PL data was collected via two apps, Scaniverse and 3D Scanner App and exported in LAZ and E57 format, respectively.[4,5] To produce consistent comparison results, it is necessary to align the data from both apps to the reference data into the same coordinate system. This registration was performed in CloudCompare software.[8]

First, all point clouds were imported to the software, and the PL scans were manually moved (in X, Y, Z) and rotated (Z axis) to match the reference data. Next, researchers completed a fine registration utilizing the iterative closest point (ICP) algorithm to minimize the distance between the PL scans and the reference scans. It is worth noting that while determining the optimal transformation parameters (translation and rotation) of the PL, only the bearing (Z) angles were adjusted to preserve the original tilting measurements, which can be used to

Figure 3. Screenshots. Point cloud data of bridge wall.

A. BLK360 scans. B. PL Scaniverse.[4] C. PL 3D Scanner App.[5]



Source: FHWA. Created with data from the Leica BLK360 G1 visualized in CloudCompare version 2.13 software.[8]

Source: FHWA. Created with data from Scaniverse App visualized in CloudCompare version 2.13 software.[4,8]

Source: FWHA. Created with data from 3D Scanner App visualized in CloudCompare version 2.13 software.[5,8]

evaluate the PL's performance in conducting vertical alignment assessments. Lastly, all the point cloud data were cropped to the region on the MSE wall with other objects and noise removed.

ANALYSES

Linear measurement evaluation

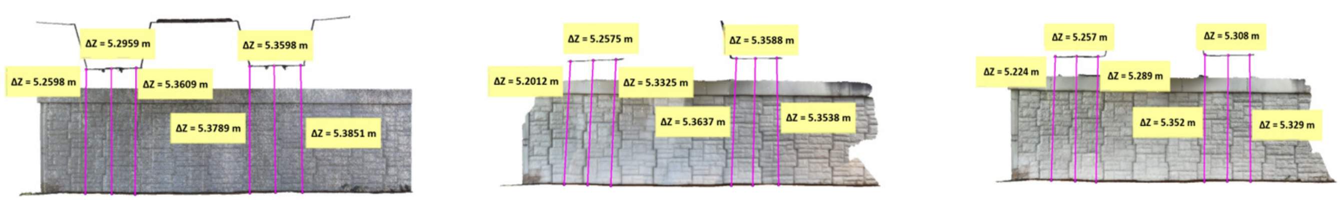
Before assessing the PL's feasibility and performance in inspecting the MSE retaining walls, the linear measurement accuracy was first evaluated to ensure that there was no noticeable bias or scaling issue in measuring the dimensions of an object. In this case, the vertical clearances from the ground surface to the bottom of the box girders were taken as an example (figure 4). The research team obtained 20 vertical measurements from each dataset and calculated several statistical metrics including the minimum, maximum, median, mean, and standard deviation of the observations (table 1). All the metrics measured in the PL data are within a few centimeters from the reference scans. In general, Scaniverse showed better performance than the 3D Scanner App in this comparison, most likely because the former is more aggressive in smoothing and filtering the point cloud data to remove noise.[4,5] It is also worth noting that both apps underestimate the minimum height of the box girder by a few centimeters. This suggests that the PL has the potential for some preliminary measurements for vertical clearances as it provided a more conservative assessment. Nonetheless, a more rigorous assessment is needed to determine if that finding is consistent under a variety of circumstances.

Cloud-to-Mesh Comparison

To perform an accuracy assessment for the PL point cloud data, the research team first generated a triangular mesh from the terrestrial lidar scanner (TLS) reference scans

Figure 4. Screenshots. Example vertical clearance measurements in the point cloud data from BLK360, Scaniverse, and 3D Scanner App.

A. BLK360 reference data. B. PL Scaniverse data.[4] C. PL 3D Scanner App data.[5]



Source: FHWA. Created with data from the BLK360 G1 visualized in CloudCompare version 2.13 software.[8]

Source: FHWA. Created with data from the Scaniverse visualized in CloudCompare version 2.13 software.[4,8]

Source: FWHA. Created with data from the 3D Scanner App. visualized in CloudCompare version 2.13 software.[5,8]

Table 1. Comparison of the vertical clearance measurements from terrestrial lidar and PL.

Statistics (m)	BLK360	Scaniverse[4]	Difference	3D Scanner App[5]	Difference
Difference	3D Scanner App[5]	5.201	Difference	5.207	−0.053
Difference	5.389	5.391	0.002	5.352	−0.037
Median	5.360	5.338	−0.021	5.299	−0.061
Mean	5.341	5.315	−0.026	5.286	−0.054
Std. dev.	0.046	0.058	0.011	0.038	−0.008

Std. dev. = standard deviation.

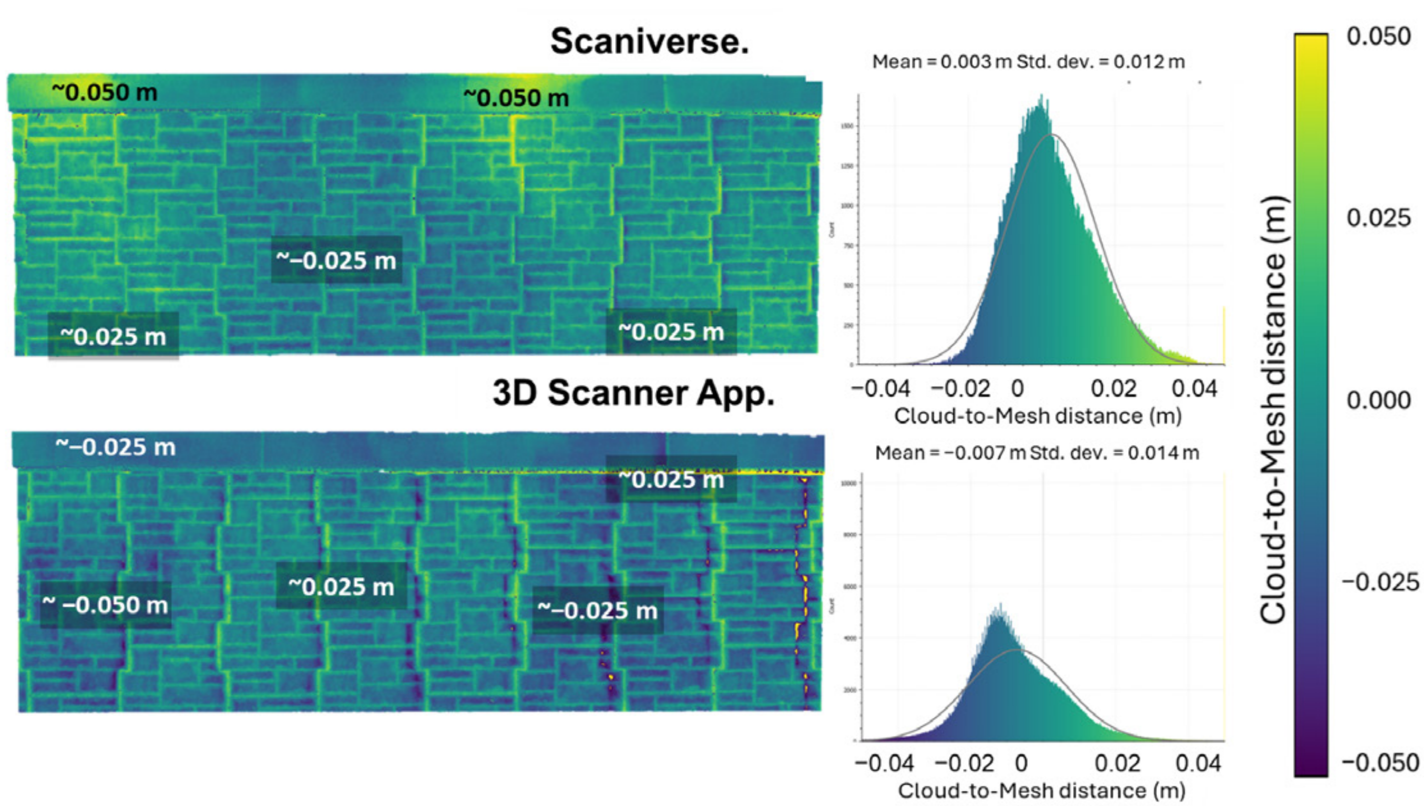
against the best fitting plane of the MSE wall section in CloudCompare.[8] Next, the researchers computed the distance from each point in the PL point cloud to the triangular mesh. The results can be visualized in CloudCompare for qualitative and quantitative assessment (figure 5).[8] The statistical analysis was conducted by fitting a Gaussian distribution to the cloud-to-mesh distance of all the points from each PL app. The mean distances (0.003 m and -0.007 m for Scaniverse and 3D Scanner App, respectively) validate the registration process used in this study as there was no significant bias from either PL dataset to the reference data.[4,5]

The standard deviations in the cloud-to-mesh comparisons (0.012 m and 0.014 m) are very similar, indicating that the data products generated from Scaniverse and 3D Scanner App are on par with each other. The number of points from Scaniverse (192,265) is substantially less than 3D Scanner App (1,461,090) due to its more aggressive noise filtering and downsampling, while BLK360 provided the highest point density with 1,630,604 points.[4,5] While some distortions occurred in some local areas (e.g., the bulging yellow regions in the point cloud from Scaniverse in figure 5), there was no noticeable drifting observed in either PL dataset. This finding demonstrates that the PL devices are generally suitable for capturing a 10 m section of an MSE wall with some buffers on both ends of the target section for initialization, agreeing with the findings from the previous testing conducted for this project.

Surface Characteristics

The research team further evaluated the surface characteristics of the models derived from the PL point clouds. To assess the overall geometry of the MSE wall, a best-fitting plane was generated from the point cloud with the coping on top of the wall cropped out (table 2). The plane fitting root-mean-squared (RMS) deviation represents the fitting quality. The results show that there is no significant difference in the fitting quality between the two PL scans conducted with the apps (0.011 m versus 0.009 m). This finding is in line with the prior analysis in cloud-to-mesh comparison, which once again demonstrates the consistency of the PL in capturing a surface. The plane fitting RMS in the BLK360 data (0.016 m) is noticeably higher than those in PL data, despite it being a more accurate, robust laser scanner. The reason for this discrepancy is mostly that the PL is not able to capture the surface in the same level of detail as the terrestrial lidar due to downsampling and smoothing. As a result, the PL does not capture some of the surface roughness and texture. This discrepancy will be further demonstrated and analyzed in the following analysis of surface characteristics.

Figure 5. Illustration. Cloud-to-mesh comparison between the PL and the TLS reference scans.



Source: FWHA. Created with data from the Scaniverse, 3D Scanner App, and BLK360 G1 visualized in CloudCompare version 2.13 software.[4,5,8]

Table 2. Summary of plane fitting results in terrestrial lidar and PL data.

Parameter	BLK360	PL (Scaniverse)[4]	PL (3D Scanner App)[5]
Number of points for plane fitting	1,394,492	159,300	1,217,421
Plane fitting RMS (m)	0.0159	0.0106	0.0091
Best-fitting plane normal X	−0.725975	−0.726026	−0.726234
Best-fitting plane normal Y	0.687712	0.687648	0.687430
Best-fitting plane normal Z	0.015881	0.010576	0.009100

Next, the research team used surface normal vectors to characterize the best-fitting planes. Specifically, the z component of a normal vector (Normal Z) can be used to assess the verticality of the surface, which is an important characteristic for inspectors to measure for an MSE wall both in construction and monitoring. In this case, the tilting angles derived from the BLK360, Scaniverse, and 3D Scanner App are 0.200 degrees, 0.296 degrees, and 0.284 degrees, respectively. The accuracy of the inclination sensor in the BLK360 is 0.05 degrees, while a typical handheld digital level used in construction can be as accurate as 0.1 degrees (in ideal situation).[9] These tilting measurements from the PL data show promise to assess the vertical alignment of the retaining walls. It is worth noting that a reliable assessment from a handheld tool requires an inspector to take sufficient samples across the surface and place the device properly. In contrast, the PL can provide a very efficient way of capturing the MSE wall to conduct a preliminary assessment of its vertical alignment without physical contact and enable more systematic measurement procedures.

Next, the research team utilized EZDataMD RAMBO software to perform more advanced and detailed surface morphology analysis.[7] The software projected the point cloud to the best-fitting plane and created a two-dimensional (2D) grid with a given cell size to compute surface characteristics including slope, aspect, roughness, and curvature locally at each grid point with a given window size. The cell size in this case was set to be 0.03 m based on the point density of the PL data, such that more detailed information can be extracted while minimizing the data gaps in the 2D grid. To evaluate the results both quantitatively and qualitatively, the statistical summary (table 3) and visualization of the results (figure 6, figure 7, figure 8, and figure 9) were produced for the comparison and discussion.

The slope and aspect describe how the facets in the search window (0.09 m × 0.09 m) on the MSE wall surface are oriented. While the mean slope and aspect extracted from the PL data are very close to the reference data, the standard deviations of the slope and aspect from both apps are significantly smaller than the reference values. Such phenomena can also be observed in the visualization of the results (figure 6 and figure 7). In the reference data result, the cruciform panel shape as well as the pattern of the finish stone panel can be clearly identified with consistent readings in both slope and aspect. Nonetheless, in the results from PL data, while the cruciform panel shape can be recognized with less consistency in the actual values, the geometric details on the finish stone panel are missing.

This pattern effect is also reflected in the roughness and curvature calculations, where a larger window size (0.15 m) is used due to the minimum sample size required to compute these metrics. Roughness is defined as the slope's standard deviation and is affected by bumps from poor concrete finishing or other surface deviations. Only some of the rough areas on the finish stone panel are highlighted in the PL data where the 3D Scanner App shows a slightly better performance than Scaniverse in this regard (figure 8).[4,5] It is also worth noting that the boundary between the upper coping and MSE wall is captured well in the roughness map created from the PL data. The 3D Scanner App has more consistent roughness readings along the extruded area of the coping on top of the wall compared with Scaniverse.[4,5] Given the same hardware device and APIs used by both apps,

Table 3. Summary of surface characterization results in terrestrial lidar and PL data.

Parameter	BLK360	PL (Scaniverse)[4]	PL (3D Scanner App)[5]
Number of points	1,630,604	192,265	1,461,090
Mean slope (degrees)	89.643	89.668	89.873
Slope std. dev. (degrees)	10.240	3.826	4.374
Mean aspect (degrees)	313.451	313.455	313.472
Aspect std. dev. (degrees)	8.572	3.851	4.241
Roughness Alpha (Weibull Distribution)[10]	1.128	0.789	0.819
Roughness Beta (Weibull Distribution)[10]	9.101	2.020	2.688
Roughness Shift (Weibull Distribution)[10]	0.079	0.045	0.063
Mean curvature (m-1)	−2.165	−2.314	−0.903
Curvature std. dev. (m-1)	1203.195	666.429	708.615

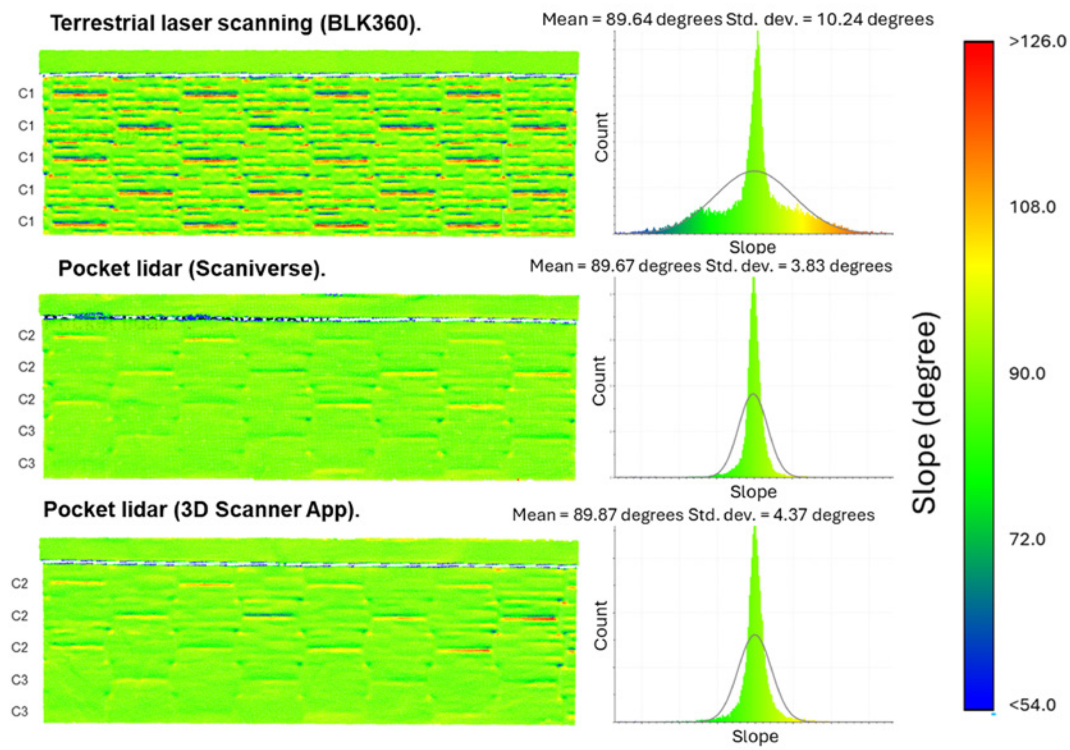
the reason for such differences is primarily due to the implementation of the internal data processing. Scaniverse is more aggressive in filtering and downsampling the data to remove the noise and reduce the data volume. This filtering helps improve localized plane fitting and dimensional analysis; however, the tradeoff is detailed texture information is often lost. By contrast, the 3D Scanner App produces a denser point cloud and can capture more detail on the geometric features, resulting in more noise and larger data volumes. Similar observations can also be made from the curvature calculation results (figure 9).[5]

Point Cloud Segmentation

Segmentation is a process that clusters the point cloud into groups based on geometric or other attributes. Taking the MSE wall as an example, an ideal segmentation process would divide the millions of points into the individual wall-facing panels. Next, the surface characterization, such as the aforementioned analysis, can take place to assess each wall-facing panel. In this study, the research team performed automated segmentation using EZDataMD Vo Norvana software.[7] The Vo-Norvana algorithm used in this software defines segments by extracting edges and smooth surfaces in the point cloud data.[11] One of the key thresholds in distinguishing an edge and surface point is the maximum normal gradient in a local area. The team varied this tolerance (5.0, 3.0, and 1.5 degrees) to highlight the difference between reference TLS data and PL data in terms of their sensitivity to data processing algorithm settings (figure 10 and table 4).

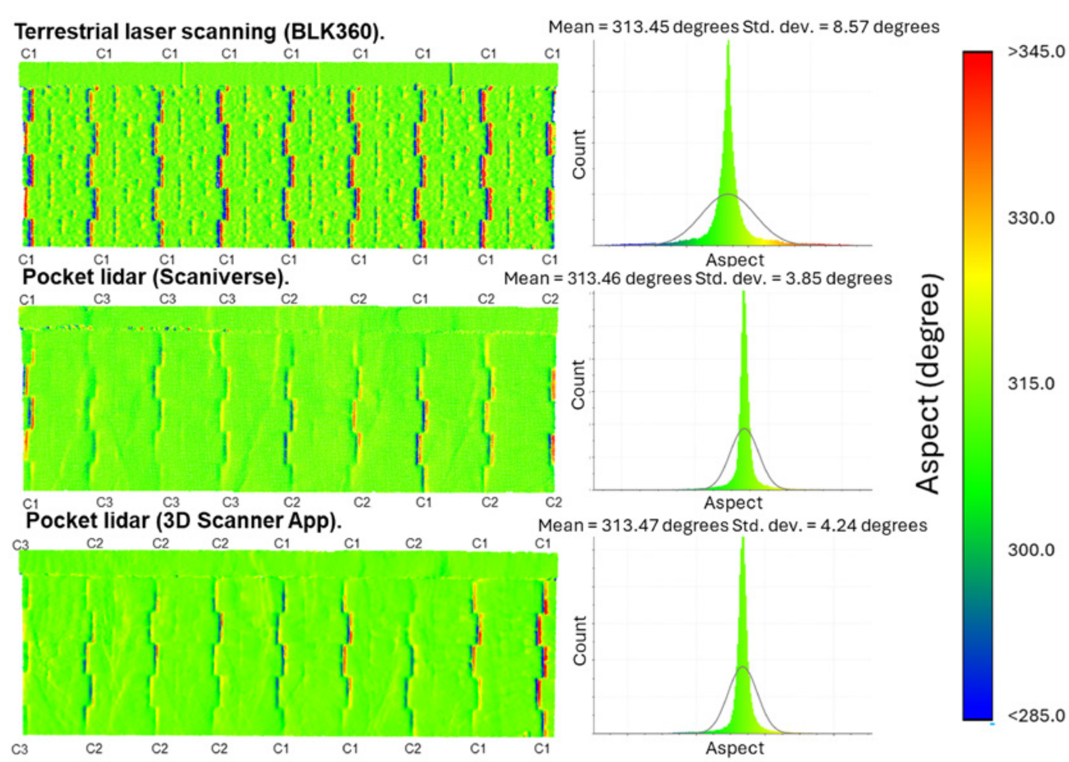
As the normal gradient tolerance decreased, more and more segments were rejected for the reference scans. This segment loss occurs because smooth surfaces do not exist at those smaller gradient tolerances as the surface texture is rough. The PL data, on the other hand, tends to divide cruciform panels better with lower normal gradient tolerance. Without downsampling or smoothing for preprocessing, the reference data can suffer from over-segmentation (more segments than desired), given the roughness of the finish stone. In other words, for MSE

Figure 6. Illustration. Slope calculation results from the point cloud data (window size: 0.09 m).



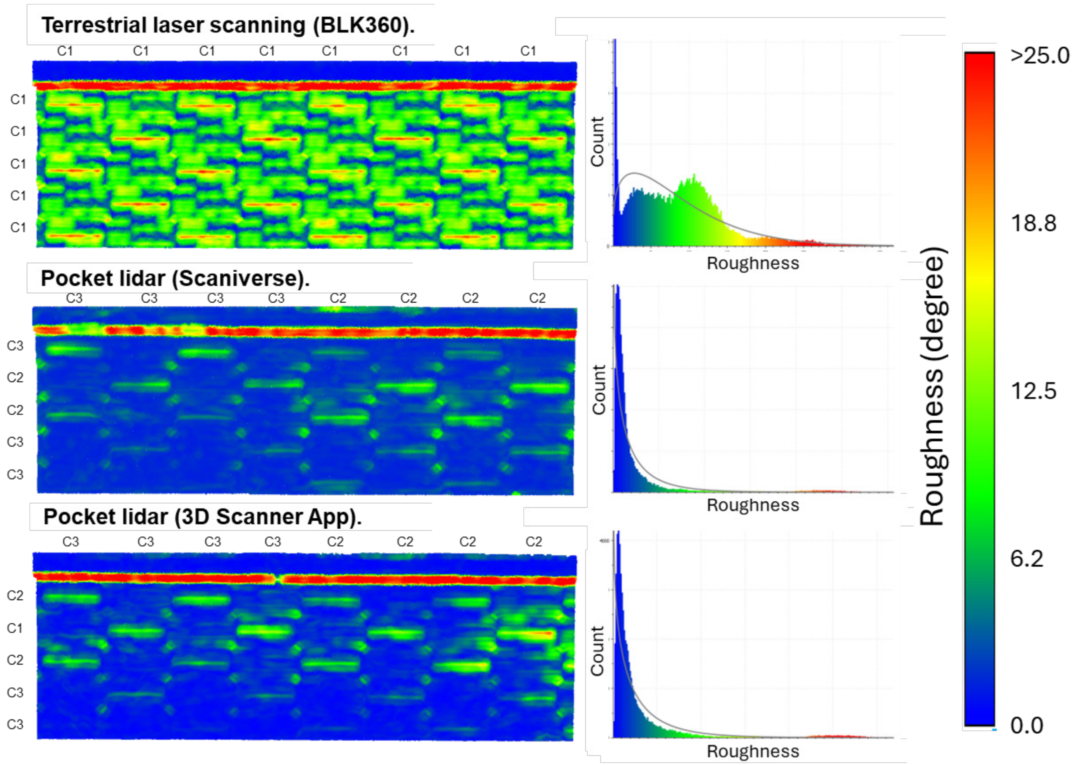
Source: FWHA. Created with data from the BLK360 G1, Scaniverse, and 3D Scanner App visualized in CloudCompare version 2.13 software.[4,5,8]
C = change in slope; 1 = clearly detected change; 2 = partially detected change; 3 = minimally detected change.

Figure 7. Illustration. Aspect calculation results from the point cloud data (window size: 0.09 m).



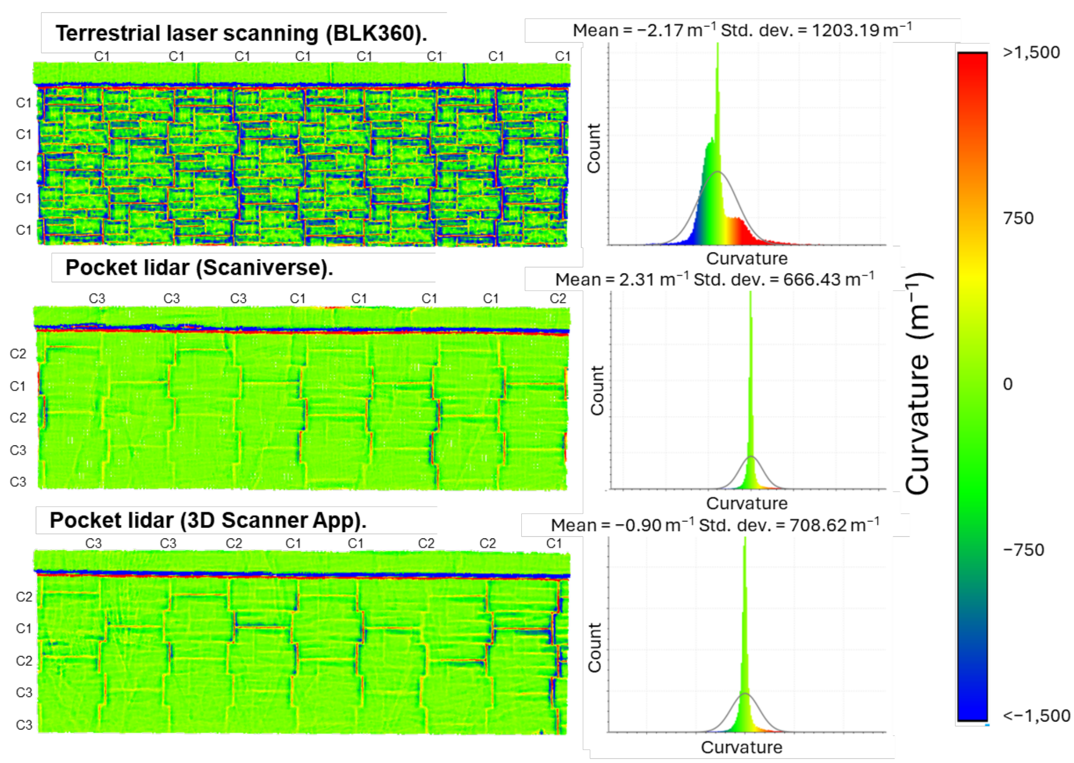
Source: FWHA. Created with data from the BLK360 G1, Scaniverse, and 3D Scanner App visualized in CloudCompare version 2.13 software.[4,5,8]

Figure 8. Illustration. Roughness calculation results from the point cloud data (window size: 0.15 m).



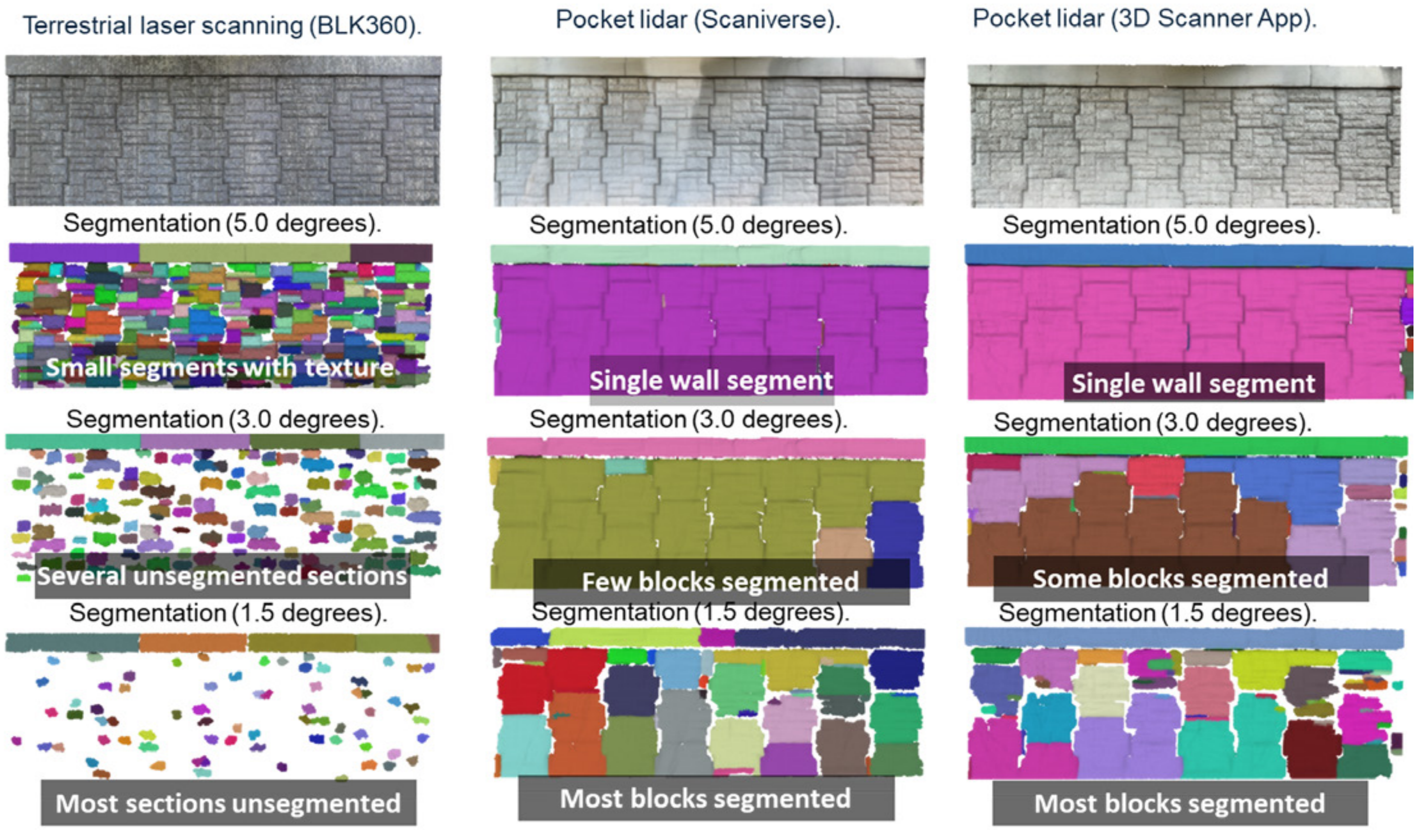
Source: FWHA. Created with data from the BLK360 G1, Scaniverse, and 3D Scanner App visualized in CloudCompare version 2.13 software.(4,5,8)

Figure 9. Illustration. Curvature calculation results from the point cloud data (window size: 0.15 m).



Source: FWHA. Created with data from the BLK360 G1, Scaniverse, and 3D Scanner App visualized in CloudCompare version 2.13 software.(4,5,8)

Figure 10. Illustration. Vo-Norvana point cloud segmentation results with different normal gradient tolerance settings where each segment is randomly assigned with a color.[11]



Source: FWHA.

Table 4. Number of segments in the Vo-Norvana segmentation results with different normal gradient tolerances.[11]

Maximum Normal Gradient (degrees)	BLK360	PL (Scaniverse)[4]	PL (3D Scanner App)[5]
5.0	296	16	20
3.0	148	7	30
1.5	75	45	55

wall inspection purposes, the filtering and downsampling in the apps help simplify the data processing necessary for segmenting the wall-facing panels to support a more detailed analysis of each panel.

KEY FINDINGS/FUTURE OPPORTUNITIES

The research team learned several lessons during the process of scanning and analyzing the MSE walls with PL:

- The PL apps are intuitive to use, with real-time coverage displayed on the screen, which is helpful for tight spaces under a bridge to ensure all appropriate areas were captured before leaving the site.
- The entire face of the MSE wall can be captured in minutes.
- An extension pole can be very helpful to make sure that the inspector can capture the higher part of the

wall in a consistent range and angle of incidence due to the limited range of the PL sensor (5 m). Some extension poles can be as long as 3 m.

- The PL has the benefit of being a remote sensing technique that can capture the object without physical contact.
- The recommendation of the research team is to scan the wall in vertical stripe pattern and move sideways in a single pass for improved data quality. For a single data collection session, the length of the focus area should be less than 10 m with some buffer on both ends to provide overlap to match with adjacent scans.
- The point cloud created from the PL can be used to evaluate global surface characteristics such as vertical and horizontal alignment (e.g., tilting) of the entire wall.
- The PL can be limited based on its local accuracy and point density for local surface characterization to detect effects, such as bulging.
- The objects or features less than 0.05 m cannot always be effectively distinguished in the point cloud. Certain features, such as cracks, can be potentially captured in the texture map, which can still be helpful even without accurate geometric information. The advantage of the scan compared to a photograph is that the location of the cracks on the wall is known, so observations can be made in context with the entire wall to evaluate patterns or the severity of the cracking.
- A detailed analysis can potentially be performed on each individual wall-facing panel to extract similar metrics of tilting, roughness, etc. for each panel individually when paired with an effective data processing pipeline (e.g., point cloud segmentation).
- The GNSS capabilities of the PL means that the scan can be georeferenced for integration with asset management databases.

ACKNOWLEDGEMENTS

The map in figure 1 was modified by the authors to show the location of the bridge. The original map is the copyright property of Google® My Maps™ and can be accessed at https://www.google.com/maps/@30.484916,-81.664142,18z?entry=ttu.

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Source: FWHA.

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