Abstract: Mechanically stabilized earth (MSE) walls rely on its weight to resist the destabilizing earth forces acting at the back of the reinforced soil area. MSE walls are a common infrastructure along national and international transportation corridors as they are low-cost and have easy-to-install precast concrete panels. The usability of such transportation corridors depends on the safety and condition of the MSE wall system. Consequently, MSE walls have to be periodically monitored according to prevailing transportation asset management criteria during the construction and serviceability life stages to ensure that their predictable performance measures are met. To date, MSE walls are monitored using qualitative approaches such as visual inspection, which provide limited information. Aside from being time-consuming, visual inspection is susceptible to bias due to human subjectivity. Manual and visual inspection in the field has been traditionally based on the use of a total station, geotechnical field instrumentation, and/or static terrestrial laser scanning (TLS). These instruments can provide highly accurate and reliable performance measures; however, their underlying data acquisition and processing strategies are time-consuming and not scalable. The proposed strategy in this research provides several global and local serviceability measures through efficient processing of point cloud data acquired by a mobile LiDAR system (MLS) for MSE walls with smooth panels without the need for installing any targets. An ultra-high-accuracy vehicle-based LiDAR data acquisition system has been used for the data acquisition. To check the viability of the proposed methodology, a case study has been conducted to evaluate the similarity of the derived serviceability measures from TLS and MLS technologies. The results of that comparison verified that the MLS-based serviceability measures are within 1 cm and 0.3° of those obtained using TLS and thus confirmed the potential for using MLS to efficiently acquire point clouds while facilitating economical, scalable, and reliable monitoring of MSE walls.

Keywords: MSE walls; smooth precast concrete panels; mobile mapping systems; mobile LiDAR; static LiDAR; performance/serviceability measures; quality control; direct geo-referencing; transportation infrastructure; registration; segmentation; in-plane/out-of-plane deformations

1. Introduction

Mechanically stabilized earth (MSE) walls are low-cost and have easy-to-install precast concrete panels. This type of infrastructure is used extensively as it resists destabilizing earth forces acting on
reinforced soil areas [1]. MSE walls are often found along transportation corridors. Just as an example, there are roughly more than 1500 MSE walls in the state of Indiana, USA, apart from those on local public agency routes [2]. An MSE wall has multiple components to ensure its efficacy including a precast paneled façade and backfill layers that have been compacted and strengthened through a metallic or geosynthetic reinforcement material [3]. Modular facing blocks, which make up the façade, can be either smooth or textured—with the former constituting the majority of existing MSE walls [4,5]. The primary purpose of these panels is to prevent the backfill material from spilling out yet allowing excess water to seep and escape through the joints. Collapse of an MSE wall will have a high repair price tag in addition to endangerment to corridor users. Therefore, an accurate yet scalable inspection methodology is important.

Governing bodies—e.g., the U.S. Department of Transportation (DOT)—relies heavily on the long-term efficacy of the MSE walls and therefore looks to organizations such as the American Association of State Highway and Transportation Officials (AASHTO) for a standard set of serviceability measures. AASHTO utilizes longitudinal angular distortion ($\alpha_L$) and transversal angular distortion ($\alpha_T$) as part of their standard serviceability measures (AASHTO 2014). The $\alpha_L$ is described as the differential settlement between two points along an MSE wall row of panels divided by the lateral distance between these points. The $\alpha_T$ is the differential normal-to-plane displacement of the MSE wall along a vertical profile divided by its height.

The acceptable $\alpha_L$ values for an MSE wall with precast concrete panels depend on the panel area and joint width. For example, for a 19 mm joint width and panel area in the range from 2.8 m\(^2\) to 7 m\(^2\), the tolerable $\alpha_L$ is 1/200 [6]. During construction, the tolerable $\alpha_T$ values for an MSE wall must be less than 1/160 while using a 3.048 m straight edge. Post construction, $\alpha_T$ should be less than 1/240 when measured using a vertical line [6]. The U.S. Federal Highway Administration (FHWA) has additional specifications for tolerable out-of-plane displacements between neighboring panels [7]. Such specification dictates that out-of-plane displacement at a joint must not exceed 9.53 mm (3/8 in.) throughout the construction stage. These standard serviceability measures, excluding the out-of-plane displacement, are considered global measures that concentrate on the vertical settlement and lateral deflection of an MSE wall. In spite of the common acceptance of these standard measures, most MSE wall failures start with local deformations. Just as an example, Figure 1 shows a local deformation where failure resulted from an excessive angular tilt between neighboring panels. Therefore, any type of effective monitoring should deliver measures that assesses the deformation pattern for each panel individually within an MSE wall. Lin et al. [5] provide examples of proposed measures that fit these criteria.

![Figure 1. An illustration of (a) Mechanically stabilized earth (MSE) wall failure that could have started with (b) an excessive bulging at the joint between neighboring panels (images sourced from Jensen [8]).](image-url)
A monitoring approach needs to take into consideration the ease of its implementation and scalability. Traditional surveying instruments, e.g., a total station; geotechnical field instrumentation, e.g., an inclinometer; and terrestrial laser scanning (TLS) are commonly used data acquisition modalities. These data acquisition tools are time-consuming and require direct access to the MSE wall site. Since most MSE walls are located at the vicinity of traffic flow, collecting the needed data subjects field workers to dangerous conditions. Therefore, a practical, scalable monitoring strategy has to address such safety concerns. The monitoring strategy should also be capable of deriving serviceability measures for planar and non-planar MSE walls—i.e., an MSE wall façade has a set of individual planar faces as shown in Figure 2a or a curved façade, which could be considered as piece-wise planar, as shown in Figure 2b. To date, current research has only addressed planar MSE walls (e.g., Lin et al. [5])—Figure 2a. To deal with the aforementioned MSE wall monitoring challenges, this research aims to achieve the following objectives:

1. Develop a monitoring strategy that delivers both standard (global) and newly-developed (local) serviceability measures.
2. Provide a reliable, target-less, scalable monitoring strategy using mobile LiDAR mapping system (MLS).
3. Introduce a methodology that can tackle MSE walls comprised of smooth precast concrete panels along either planar or piece-wise planar façades.

**Figure 2.** An illustration of (a) MSE wall with multi-face planar façade and (b) MSE wall with piece-wise planar façade (image sourced from Pinnacle Design/Build Group, Inc. [9]).
This research work starts by providing a coverage of existing strategies for MSE wall monitoring, while emphasizing those employing LiDAR point clouds, in Section 2. The used MLS in this study is introduced in Section 3, which also covers the data acquisition for the case study conducted to illustrate the comparative performance of MLS and TLS. The proposed methodology is then presented in Section 4. Experimental results from the data processing/reduction strategy for the case study are discussed in Section 5. Lastly, Section 6 presents the conclusions and suggestions for future research direction.

2. Literature Review

The far majority of MSE wall monitoring techniques are based on manual and visual inspection in the field with the help of basic tools such as measuring tapes, profile contour gauges, inclinometers, and plumb lines. These strategies can lead to irregularities arising from human subjectivity [10]. Moreover, they require physical contact with the MSE wall, which might not always be possible and/or safe to field inspectors. Laefer and Lennon [11] proposed an approach for monitoring retaining walls with precast concrete panels using TLS, whereby multiple temporal scans were collected and analyzed to discern movements within a column of panels along the MSE wall. In their research, three or more spherical static targets in each scan are used as tie points for establishing the coarse registration between the scans. The authors suggest that the targets remain on site throughout the monitoring process. Oskouie et al. [1] employed TLS for point cloud acquisition and derivation of performance measures for MSE walls. Unwanted objects, such as brackets and scaffolds, were removed from point cloud data and then a random sample consensus (RANSAC) algorithm [12] was used to fit a planar model through the wall. The points representing joints between the panels were isolated as outliers when checking the normal distances between the point cloud and the fitted wall-plane. The joint distances are then used as the serviceability measure.

Lienhart et al. [13] used a mobile mapping system (MMS) for a scalable inspection of earth walls along Austrian highways. In their work, a practical approach was proposed using an MMS composed of two laser profilers, a differential global navigation satellite system (GNSS) receiver, an inertial measurement unit (IMU), and multiple cameras, which provided true colors for the derived point clouds. Vertical profiles at 5-cm intervals were created from the captured point clouds along the retaining wall by intersecting planes orthogonal to the vehicle’s trajectory with the wall surface. A regression along the vertical profile derived the tilt angle of the MSE wall façade. Their research was able to identify tilt angles with an accuracy of ±0.1°. However, the inspection measure was restricted to evaluating the transversal tilt angle. Lin et al. [5] employed TLS to evaluate the standard measures (i.e., \( \alpha_L \) and \( \alpha_T \)) of MSE walls with smooth panels. Lin et al. [5] also defined measures that represent in-plane and out-of-plane angular tilts and movements of the individual panels relative to the encompassing MSE wall faces. In this process, Lin et al. [5] introduced two coordinate systems, which are referred to as the Leveled Face \( (LF_{cs}) \) and Panel \( (P_{cs}) \) coordinate systems for the individual faces and panels, respectively. The \( LF_{cs} \) considers the local horizontal/vertical directions within the site and utilizes a fitted plane through a manually cropped MSE wall face. The \( P_{cs} \) definition starts by identifying individual panels through a segmentation process, where the local point spacing and normal distance between the points and the best fitting plane through that face are determined and used as the segmentation criteria. After panel segmentation, \( P_{cs} \) was defined using the bounding box for each panel—i.e., the minimum bounding rectangle—MBR [14]. The translational and rotational relationships between the \( LF_{cs} \) and \( P_{cs} \) were used to establish new serviceability measures. Aldosari et al. [15] introduced a procedure for monitoring MSE walls with textured precast concrete panels to evaluate standard serviceability measures as well as those proposed by Lin et al. [5]. This preliminary work has shown the possibility of using mobile LiDAR for deriving reliable serviceability measures for textured walls. However, the ability of handling smooth MSE walls still need to be addressed. Moreover, evaluating the potential of this technology in handling large MSE wall sites needs more investigation.
The proposed monitoring strategy in this work expands the work of Aldosari et al., [15] by taking advantage of LiDAR-based MLS, which collects highly accurate, high-resolution point clouds while driving along the transportation corridor. This research tackles larger MSE Walls with smooth panels, which has not been previously addressed in other studies. It also introduces a strategy for panel identification for smooth MSE walls and establishes extensive quality control measures through the comparison with interactive measurements of displacement in the point cloud and in-situ profiler gauge measurements. The robust performance of the proposed strategy was verified even when some intermittent access to the GNSS signal (when driving under the bridge) was present. This research also addresses the performance of the registration procedure in the alignment of a multi-sensor/multi-drive run/multi-modal scanning system and showcases the quality of the system calibration and trajectory information.

3. Data Acquisition System and Case Study Specifications

The key goal of this study is to demonstrate the viability of using a vehicle-based MLS for point cloud acquisition to derive a wide range of serviceability measures for large MSE walls. An in-house-developed MLS, which is shown in Figure 3, was used for the case study conducted. The MLS has two laser scanners (VUX-1HA, Riegl, Horn, Austria and ZF Profiler 9012, ZF, Wangen, Germany). These two scanners have been specifically chosen to provide long range scanning and high ranging accuracy through the Riegl VUX-1HA and ZF profile 9012, respectively. The Riegl VUX-1HA operates at a maximum range of 150 m (with an accuracy of ±5 mm) while the ZF Profiler 9012 operates at a maximum range of 120 m (with an accuracy of ±2 mm). Each scanner captures roughly one million points per second [16,17]. The Riegl and ZF units are 2D ranging systems (i.e., they are equipped with a single laser beam that rotates in a single plane). As a result of this scanning mechanism, a given object point will be scanned only once by a single scanner from a given drive run. Therefore, having two scanners onboard the MLS is recommended to increase point density (i.e., number of points per unit surface area) and increase the extent of the covered area. Scanners type, using either two Riegl or two ZF scanners for example, would not make a difference on the quantitative inspection outcome.

![Figure 3. The mobile LiDAR mapping system used for the MSE wall data acquisition. (Aldosari et al. [15]).](image)

Derivation of the point cloud data requires a geo-referencing procedure, which aims at establishing the position and orientation of the individual sensors relative to a user-defined mapping coordinate system. The used position and orientation system in this study comprises a NovAtel ProPak6 GNSS...
receiver and ISA-100C near-navigation grade IMU (NovAtel, Calgary, AB, Canada) to directly provide the geo-referencing parameters for the imaging and ranging sensors. Inertial Explorer with Differential GNSS post-processing from NovAtel is used for the integration of the raw GNSS/INS data. Following post-processing, the accuracy of the derived GNSS/INS attitude is 0.003° and 0.004° for the pitch/roll and heading (yaw), respectively [18]. The positional accuracy, on the other hand, is in the range between 0.01 to 0.02 m [18]. The derivation of high-quality point cloud from the directly-geo-referenced scanners is contingent on the accuracy of the position and orientation of the vehicle frame and precise estimation of the spatial and rotational offset (collectively known as the mounting parameters) between the GNSS/INS unit and ranging sensors. Using a high quality GNSS/INS unit would ensure reliable evaluation of the vehicle’s position and orientation. In this study, a thorough system calibration procedure by Ravi et al. [19] was used for estimating the mounting parameters between the laser scanning units and GNSS/INS position and orientation system. The system calibration parameters were estimated by minimizing misalignments between conjugate linear features, planar features, and points that have been captured by different scanners in multiple drive runs. According to the used calibration procedure, the expected alignment between point clouds from different scanners in a given drive run and/or different drive runs should be in the range of 1–2 cm. Using a dual scanner system equipped with high quality GNSS/INS unit, which has undergone a rigorous calibration procedure, would ensure the availability of dense point clouds along the surveyed MSE walls that are conducive to the evaluation of a reliable set of serviceability measures.

A smooth MSE wall in the U.S. State of Indiana was selected as a case study in this research to test the capability of the MLS used as well as the feasibility of the proposed processing strategy in deriving the $\alpha_L$ and $\alpha_T$ angular distortions as well as the performance measures introduced by Lin et al. [5]. The overall capability of mobile LiDAR in examining an MSE wall is evaluated by comparing the measures derived with those based on data collected by a TLS. For the TLS data acquisition process, a Faro Focus x330 (Faro, Mary, Florida, USA) with a range accuracy of ±2 mm at an object distance of 25 m was used [20]. This scanner emits close to one million pulses per second with a maximum range of 330 m and produces a color-coded point cloud (i.e., the scanner is equipped with a camera and a scene is scanned twice to collect the ranging and RGB data). Figure 4 depicts a portion of the MSE wall that has piece-wise planar façades (i.e., where the façades cannot be modeled as a single planar surface).

![Figure 4. An image covering a portion of the MSE wall with smooth panels (the boundaries of the different panels are highlighted by red rectangles).](image)

The MSE wall at the site was constructed in 2014 and consists of 11 piece-wise planar faces along six façades (see Figure 5). The length of the MSE wall is approximately 345 m with an average height of 7 m. This study focuses on approximately 160 panels (i.e., fully covered and not occluded) of
the MSE wall covering façades 1, 2, and 5 (façades 3, 4, and 6 are excluded as they are out of the range of the LiDAR units). The individual panels are approximately 1.5 m by 3 m with 19 mm joint width, which meets Indiana's Department of Transportation standard specifications [21]. Three TLS scans were collected to avoid occlusions caused by road features or vegetation. Figure 5 shows four drive runs in opposite directions that have been conducted by the MLS, with each run completed in under 30 s at an average driving speed of 15 mph. A sample of the collected point cloud can be seen in Figure 6.

![Figure 5. Illustrations of (a) drive run configuration for the MLS data acquisition and (b) 3D point cloud colored by height of the MSE wall faces covered by the MLS.](image)

![Figure 6. Point cloud at the MSE wall site location collected by the MLS (colored by height).](image)

4. Methodology

4.1. Proposed Framework of the Suggested Methodology

The overall framework for the data collection/processing, and estimation of the serviceability measures is illustrated in Figure 7. In this framework, the standard serviceability measures, as specified by AASHTO [6], include the $\alpha_L$ and $\alpha_T$ angular distortions. In addition, the serviceability measures introduced by Lin et al. [5] including the differential displacements and rotations of the individual panels relative to a $LF_{cs}$ are also evaluated.
To derive the serviceability measures, the point clouds acquired by the scanners onboard the MLS from different drive runs are registered to a single reference frame. In theory, one can argue that this registration step is redundant for point clouds acquired by an MLS equipped with a direct geo-referencing GNSS/INS unit. In other words, the position and orientation of the laser scanners relative to the mapping frame are available through the combination of the GNSS/INS trajectory with the system calibration parameters—e.g., the horizontal and vertical point cloud coordinates could be defined relative to a Universal Transverse Mercator coordinate system (UTM) with the WGS84 as the datum and the National American Vertical Datum of 1988 (NAVD 88), respectively. Thus, acquired point clouds from neighboring drive runs should be well-aligned provided that accurate system calibration parameters and reliable trajectory data are available. However, the GNSS/INS trajectory might be compromised due to GNSS signal loss of lock when traveling in tunnels and/or under overhead bridges, canopy cover, multipath interference from nearby traffic, and platform speed. Such issues together with residual artifacts in the system calibration parameters can lead to discrepancies between conjugate features in overlapping point clouds from the onboard two scanners and neighboring drive runs. Before taking advantage of the complementary point cloud data from dual scanners and multiple drive runs (e.g., point clouds with higher point density and less occlusions), alignment of such data must be ensured. Considering the accuracy of the alignment procedure, registration strategies can be categorized into coarse and fine approaches [22,23]. As the name suggests, coarse registration strategies are suited for point clouds that are given relative to reference frames with significant translational and rotational offsets. Fine strategies, on the other hand, are used for coarsely-registered point clouds to ensure better alignment of corresponding features. It is worth noting that this study is focusing on MLS point cloud data, which should be relatively well-aligned through the onboard GNSS/INS unit coupled with the system calibration procedure. Therefore, this research will implement a fine registration strategy, which is discussed in detail in Section 4.2.

For both standard and newly-available serviceability measures, one needs to partition an MSE wall façade into planar sections, denoted here forward as MSE wall faces. The identification of individual planar sections within the wall façade starts with the finely-registered point cloud. Thus, if an MSE wall has a multi-face façade with individual planar faces, as shown in Figure 2a, or piece-wise planar
 façade, as shown in Figure 2b, it needs to be partitioned into sections that are believed to be perfectly planar. In this study, the MSE wall façades are manually partitioned. The partitioning procedure is based on the Root Mean Square Error (RMSE) of the normal distances between the points along a partitioned face from the corresponding best-fitting plane through that face. If the RMSE value is greater than the expected noise level in the point cloud data—which is in the range of 1–2 cm for the used MLS in this research—the partitioning is revised.

Defining the coordinate systems for the MSE wall face in question ($LF_{cs}$) and the enclosed individual panels ($P_{cs}$) is the next step. These coordinate systems, which are shown in Figure 8, are used for determining both global and local serviceability measures. The $LF_{cs}$ is defined by the best-fitting plane through the face in question and the local horizontal/vertical directions at the MSE wall site. More specifically, the $y$-axis of the $LF_{cs}$ is defined along MSE wall face (as defined by the fitted plane parameters) and is parallel to the horizontal plane of the mapping coordinate system at the study area. The z-axis of the $LF_{cs}$ is established to be parallel to the plumb line at the MSE wall site. Finally, the x-axis of the $LF_{cs}$ is derived to define a right-handed coordinate system. To enable straightforward derivation of the $LF_{cs}$, the geo-referencing parameters from the MLS are established in a local mapping coordinate system with the z-axis pointing in the local level (plumb line) direction at the MSE wall site location. The $P_{cs}$ is needed for deriving the panel-to-leveled face differential rotation and translation as well as the panel-to-panel displacement. As can be seen Figure 8, the panel coordinate system is defined with its $y$- and $z$-axes aligned along the bottom and left sides of the bounding rectangle enclosing the panel in question. Finally, the x-axis of the $P_{cs}$ is derived to define a right-handed coordinate system (i.e., it is defined by the normal to the panel surface). A key prerequisite for a reliable derivation of the local serviceability measures is to ensure that the $P_{cs}$ is defined in a similar manner for all the panels within a particular face. For this purpose, this study utilizes a region-growing segmentation procedure to identify the points constituting the individual panels (these points are then used to define the panel coordinate systems by deriving the MBRs that enclose them). For the panel segmentation, the Local Point Spacing (LPS) and normal distance ($n_d$) from the best-fitting plane to the MSE wall face are used as the region-growing criteria. The fundamental assumption for the segmentation using such criteria is that points with large normal distances from the best-fitting plane correspond to the joints between neighboring panels. The details of MSE wall face partitioning and panel identification are included in Section 4.3. The aforementioned performance measures can be derived once the coordinate systems are defined and the individual panels are isolated from the point cloud along a partitioned face. Section 4.4 describes the derivation of global and local performance measures for MSE walls with smooth panels.

Figure 8. Graphical representation of the relationship between $LF_{cs}$ and $P_{cs}$ for deriving the panel-to-leveled face position and orientation serviceability measures

4.2. Point Cloud Registration

Several procedures have been introduced in recent literature for the fine registration of point cloud data. According to Habib and Al-Ruzouq [24], an automated registration approach should
address the following four components: (1) the parameters describing the transformation between
the reference frames of the respective datasets, (2) the primitives used for the evaluation of the
transformation parameters, (3) the mathematical conditions ensuring the alignment of corresponding
primitives following the registration, and (4) the matching strategy for the automated identification of
corresponding primitives and derivation of transformation parameters. A six-parameter transformation
(three shifts and three rotation angles denoted here forwards as XT, YT, ZT, Ω, Φ, and K, respectively)
can be used for relating the reference frames of acquired point clouds from different drive runs
considering the short acquisition period—mainly under 30 s each. In spite of the fact that there is no
point-to-point correspondence between overlapping drive runs, point primitives are recommended
for the fine registration. This is mainly attributed to the huge redundancy, which will still assure
the highest accuracy for the estimated transformation parameters. The similarity metric is based on
ensuring that the distance between a point in one drive run and its corresponding point in another drive
run is zero. As for the matching strategy, the well-known iterative closest point (ICP) algorithm [25,26]
can be used to establish the correspondences through iterative minimization of the squared sum
of point-to-point distances in the common area between neighboring drive runs. Grant et al. [27]
proposed an alternative strategy to avoid the underlying assumption of the ICP—i.e., point-to-point
correspondence in overlapping point clouds—where the estimation of the transformation parameters
is based on a point-to-plane minimization metric. This strategy suffers from computational inefficiency.
The iterative closest patch (ICPatch) algorithm [28], which is a variant of ICP, is an alternative strategy
that mitigates the point-to-point correspondence assumption. The ICPatch strategy derives point–patch
pairs in two overlapping point clouds through an iterative minimization of the squared sum of the
normal distances between such pairs (e.g., the points in a drive run are matched to the triangular
patches, which are established through a triangular irregular network procedure, in another drive run).
In order to avoid the key shortcoming of a TIN generation procedure (namely, inability to represent
vertical surfaces), the iterative closest projected point (ICPP) algorithm was developed by Al-Durgham
and Habib [22]. In the ICPP approach, the triangular patch is defined by the closest three points in the
point cloud from another drive run to a transformed point from the first one using the current estimate
of the transformation parameters.

A modified matching strategy was introduced in this research, where a hybrid implementation
of ICPatch and ICPP is utilized [29]. Similar to any fine registration procedure, one needs to start by
setting approximate estimates for the transformation parameters between the collected point clouds
from different drive runs. Since the available point clouds are assumed to be in good alignment
through the system calibration and onboard GNSS/INS direct geo-referencing unit, zero shifts and
zero rotation angles can be employed as the starting estimates for the transformation parameters.
These values are applied to transform a point from one drive run, which is designated as the source
surface, to the reference frame of another drive run, which is referred to as the reference surface.
Given the system calibration, zero shifts and zero rotations could be also used when registering two
point clouds captured by two scanners in a given drive run. The transformed point (Pt) is then utilized
to identify the three closest points in the reference surface. If (Pt) belongs to a bi-pyramid created
by these points and two vertices that belong to the orthogonal to the triangle, which is defined by
these three points, through its centroid given a predefined normal distance threshold (n), then the
closest three points are accepted as a possible match (Figure 9). It is worth noting that the predefined
normal distance threshold is defined according to the noise level within the data in question as well as
the quality of the current estimate of the transformation parameters. Therefore, the normal distance
threshold would reduce as we proceed with the iterations as the quality of transformation parameters
improves. Instead of minimizing the squared sum of the distances between the transformed point
and its projection onto the corresponding patch (which is implemented in ICPP), this study utilized
a modified weight function proposed by Habib et al. [28]. Through this weight modification, one
can use non-conjugate points from a point–patch pair while minimizing the squared sum of normal
distances between transformed points from the source surface and the corresponding patches in the reference surface.

\[ \text{Figure 9. (a) source to reference point cloud transformation for a given point, and (b) condition for accepting point-to-patch correspondence for a transformed point (Al-Rawabdeh et al. \[29\]).} \]

The key advantages of the proposed hybrid approach, when compared to either the original ICPatch or ICPP strategies, include less sensitivity to the existence of erroneous points (i.e., outliers), higher computational efficiency, and ability to incorporate vertical patches \[29\]. The first two advantages are attributed to the use of a simpler similarity constraint using pseudo-conjugate points for a point–patch pair. A similar registration procedure could be also used for the registration of multiple TLS scans as well as TLS and MLS point clouds. Just as an example, Figure 10 illustrates the registration outcome of three TLS point clouds together with MLS scans from neighboring drive runs.

\[ \text{Figure 10. Registration outcome of TLS scans colored by RGB and MLS point clouds from different drive runs in different colors.} \]

4.3. MSE Wall Façade Partitioning and Panel Identification

A semi-automated procedure is developed in this study to isolate the faces and the panels of the MSE wall. This is done by partitioning the MSE wall façade into individual faces that can be deemed planar (Figure 11). The sectioning process is manually accomplished while fitting a plane to the constituent points to evaluate the planarity of the derived partitions. A sectioning is considered acceptable if the RMSE values of the normal distances of the points from the best-fitting plane through the different sections are below a threshold, which is defined according to the noise level in the data. If the derived RMSE values are larger than the inherent noise level in the point cloud data (which is in the order of 1.5 cm), the partitioning process is revised. The \( LF_{cs} \) is defined, as discussed in Section 4.1, once the individual faces are finalized. A region-growing segmentation technique is then applied
for each face to cluster points comprising the individual panels, as described by Habib and Lin [30]. The similarity criteria for the region growing process includes the local point spacing (LPS) and normal distance ($n_d$) between the points and the fitted plane through the face. More specifically, a point is augmented into a segmented region if it is within a multiplication factor of the LPS and a normal distance threshold. For the involved point clouds in this work, the multiplication factor is in the range of 2.0–2.5 and the normal distance threshold is in the range of 0.01–0.03 m. The segmentation result for one face is shown in Figure 12. Following the panel segmentation technique, the $P_{cs}$ for a given panel is simply established by deriving the MBR enclosing that panel, as proposed by Lin et al. [5]. More specifically, the $x$-axis of the $P_{cs}$ is oriented along the normal to the best-fitting plane through the points covering that panel. The $y$- and $z$-axes of the $P_{cs}$ are aligned along the bottom and left sides, respectively, of the MBR enclosing the panel in question, as can be seen in Figure 8. Having defined the $LF_{cs}$ and $P_{cs}$, the different serviceability measures can be established.

![Figure 11](image1)

**Figure 11.** An illustration of three manually established faces along an MSE wall with piece-wise planar façade.

![Figure 12](image2)

**Figure 12.** An illustration of segmented panels along an MSE wall face with different panels shown in distinct colors.

### 4.4. Evaluating Global and Local Serviceability Measures

The global serviceability measures comprise the $\alpha_L$ and $\alpha_T$ angular distortions. To arrive at these measures, longitudinal and transversal lines are established along the MSE wall face. A fitting technique establishes the longitudinal lines through the corners of the horizontal sides of the MBRs enclosing the panels along the above and below rows adjacent to these lines. Once the 3D line parameters have been derived, the $\alpha_L$ value is defined through the dot product between the directional line parameters and the $y$-axis components of the $LF_{cs}$. The transversal line for a column of panels is determined using the centers of the horizontal sides of the MBRs enclosing the uppermost and lowermost panels for that column. To derive the $\alpha_T$ value, a dot product of the transversal line and $z$-axis components of the $LF_{cs}$ is then performed. An example of the defined longitudinal and transversal lines for a planar MSE Wall face is shown in Figure 13.
In contrast to the standard/global serviceability measures, the recently-developed local measures by Lin et al. [5] are used to evaluate the differential rotations and displacements for a given panel relative to the $LF_{cs}$ of its enclosing face. The translational and rotational relationships between the $LF_{cs}$ and $P_{cs}$, as seen in Figure 8, are used to derive these serviceability measures. Thus, the location of the origin of the Pcs relative to the $LF_{cs}$ (denoted as Xo, Yo, and Zo) defines the panel position. On the other hand, the rotation angles (denoted as $\theta_x$, $\theta_y$, and $\theta_z$) that need to be applied to the $LF_{cs}$ to make it parallel to the $P_{cs}$ are used to define the panel orientation. The last serviceability measure is the normal displacement between the corners of each panel and the fitted planes through neighboring panels. These normal distances are established using the derived MBR corners as shown in Figure 14, where a total of eight normal distance estimates (shown by the black lines) from the four corners of a given panel to its adjoining panels is evaluated.

**Figure 13.** Established longitudinal and transversal lines for the evaluation of the angular distortions for an MSE wall face.

**Figure 14.** Using the panel four corners and their neighboring panels for panel-to-panel out-of-plane displacement evaluation.

### 5. Experimental Results

To assess the capability of the developed MLS as well as the feasibility of the data processing/reduction strategy in providing a comprehensive set of serviceability measures for large MSE walls with smooth precast concrete panels, a case study was conducted in the State of Indiana, USA. In this study, a comparison of TLS and MLS-based serviceability measures is also provided. The key objectives of the experimental results include: (1) illustrating the quality of the direct geo-referencing and system calibration of the used MLS by investigating the estimated transformation parameters
from the hybrid registration procedure; (2) verifying the feasibility of using MLS point clouds to
derive comparable serviceability measures to those based on TLS scans; and (3) highlighting the
capability of MLS to survey large MSE wall sites in a short time while providing a wide range of
serviceability measures.

5.1. Point Cloud Registration and Quality Control of System Calibration and Direct Geo-Referencing

Point cloud registration was sequentially executed to align: (1) MLS point clouds captured by the
onboard two scanners for each drive run, (2) MLS point clouds from neighboring drive runs, (3) TLS
point clouds from three scan stations, and (4) MLS and TLS point clouds. The estimated transformation
parameters for the alignment of the point clouds from the two scanners in a given drive run were used
to assess the quality of the system calibration procedure (major deviations from zero shifts/rotation
angles would be an indication of inaccurate system calibration procedure). To quantitatively assess
the quality of the GNSS/INS trajectory, the evaluated transformation parameters when aligning point
clouds from different drive runs are used (i.e., significant deviations from zero shifts/rotation angles
is an indication of less than optimal GNSS/INS trajectory). In this regard, one should note that the
registration of the TLS and MLS point clouds was only performed to ensure that there were uniquely
defined local vertical and horizontal directions within the study site (i.e., there is not quality control
aspect associated with the derived estimates of the transformation parameters in this case). To evaluate
the comparative performance of TLS and MLS-based inspection strategies, the results for three faces
(with a total of 76 panels) along façade 2 of the MSE wall (i.e., the façade covering faces 2, 3, and 4) are examined. Two MLS drive runs in opposite directions at the vicinity of the MSE wall were used for
this comparative test. Six registration steps were performed. Registration of the Riegl and ZF scans in
each drive run was conducted in the first and second steps of the analysis. In the third step, alignment
between the combined/registered scans from the two drive runs was achieved. Then, three TLS scans
were registered to a unified coordinate system in two successive steps. Finally, the TLS and MLS
point clouds were registered to the MLS reference frame. For qualitative evaluation, Figures 15–18
illustrate four vertical profiles—which were manually extracted to highlight the alignment quality of
point clouds from the two scanners (i.e., Riegl and ZF) in a given drive run, point clouds from two
drive runs in opposite directions, point clouds from the TLS scan stations, and point clouds from the
TLS and MLS units. The profiles in these figures verify the good alignment among the different point
clouds following the proposed registration process.

![Figure 15. Vertical profiles illustrating post-registration alignment quality of Riegl and ZF scans Figures 1–4 along façades 1 and 2 of the MSE wall.](image-url)
Figure 16. Vertical profiles illustrating post-registration alignment quality of point clouds from two MLS drive runs covering faces 1, 2, 3, and 4 along façades 1 and 2 of the MSE wall.

Figure 17. Vertical profiles illustrating post-registration alignment quality of two TLS scans covering faces 2, 3, and 4 along façade 2 of the MSE wall.

Figure 18. Vertical profiles illustrating post-registration alignment quality of TLS and MLS point clouds covering faces 2, 3, and 4 along façade 2 of the MSE wall.
Table 1 reports the corresponding transformation parameters, square root of a posteriori variance factor ($\hat{\sigma}$), and average RMSE of the normal distances between the registered point clouds in Figures 15–18. The reported values in this table can be used to quantitatively evaluate various aspects related to the used MLS as well as the proposed processing framework. Close inspection of Figures 15–18 and Table 1 shows the following:

### Table 1. Post-registration transformation parameters between (a) Riegl and ZF scans in a given drive run (b) MLS point clouds from two different drive runs; (c) two TLS scans, and (d) MLS and TLS point clouds and quality control measures (square root of a posteriori variance factor, average normal distance among point–patch pairs, and RMSE of the normal displacement).

| $X_T$ (m ± mm) | $Y_T$ (m ± mm) | $Z_T$ (m ± mm) | $\Omega$ (deg ± sec) | $\Phi$ (deg ± sec) | $K$ (deg ± sec) | $\hat{\sigma}$ (m) | Average Normal Dist. (m) | RMSE (m) |
|----------------|----------------|----------------|----------------------|-------------------|----------------|-------------------|------------------------|----------|
| −0.003         | 0.023          | 0.002          | −0.104               | −0.008            | 0.014          | 0.016             | 0.0012                 | 0.0018   |
| ±0.02          | ±0.01          | ±0.02          | ±0.01                | ±0.00             | ±0.00         | 12.25             | 0.0005                 | 0.0016   |
| 0.028          | −0.108         | 0.012          | 0.064                | −0.039            | 0.018          | 0.034             | 0.0023                 | 0.0037   |
| ±0.01          | ±0.01          | ±0.01          | ±0.01                | ±0.00             | ±0.00         | 14.25             | 0.0005                 | 0.0016   |
| 6.73           | 18.98          | −2.44          | −0.005               | −0.018            | 0.018         | 14.25             | 0.0005                 | 0.0016   |
| ±0.01          | ±0.01          | ±0.02          | ±0.02                | ±0.00             | ±0.00         | 0.0012             | 0.0009                 | 0.002    |
| −4.33          | 16.01          | 2.26           | 0.07                 | 0.01              | −69.61        | −69.61             | 0.0027                 | 0.002    |
| ±0.00          | ±0.00          | ±0.01          | ±0.00                | ±0.00             | ±0.00         | ±0.00             | ±0.00                  | ±0.00    |

1. The magnitudes of the estimated transformation parameters for the alignment of the point clouds captured by the Riegl and ZF scanners in a given drive run—as indicated by the small values in Table 1a where the estimated parameters are in the range of 2 cm and 0.1°—confirm the high quality of the system calibration procedure.

2. The transformation parameters needed for the alignment of the MLS point clouds from various drive runs reflect discrepancies between these point clouds in the ranges of −11 to 2 cm and −0.04° to 0.06° as shown in Table 1b. These discrepancies are mainly caused by some environmental factors (GNSS signal loss and multipath from neighboring traffic).

3. The square root of a posteriori variance factor ($\hat{\sigma}$) and average RMSE of the normal distances between conjugate primitives for the different point clouds reflects the high quality of the registration process (i.e., in the range of 1 to 4 mm as can be seen in Table 1, these are well within the specifications of the used MLS). It is worth noting that the observed high precision is attributed to the high redundancy for the implemented hybrid ICPP/ICPatch procedure (i.e., thousands of conjugate point–patch pairs have been used for the estimation of such RMSE values).

### 5.2. Comparative Analysis of TLS and MLS Serviceability Measures

The $\alpha_L$ and $\alpha_T$ angular distortions for the MSE wall planar face depicted in Figure 13 and the recommended tolerable values (denoted by the red lines) are illustrated in Figure 19. The angular distortions were assessed using the longitudinal and transversal lines in Figure 13 (i.e., L1 to L9 and T1 to T6 for $\alpha_L$ and $\alpha_T$, respectively). The horizontal line in Figure 19a shows the tolerable $\alpha_L$ (1/200) for a joint width of 19 mm and panel area of 4.5 m$^2$. The horizontal line in Figure 19b, on the other hand, shows the post-construction tolerable and $\alpha_T$ (1/240), as suggested by AASHTO [6]. Figure 19 shows that both $\alpha_L$ and $\alpha_T$ derived from the MLS are closely similar to those obtained using the TLS point cloud. This similarity confirms the capability of MLS in achieving a reliable, high-quality assessment of standard serviceability measures. As far as the MSE wall evaluation is concerned, Figure 19a,b show that this wall meets the tolerable $\alpha_L$ measure. However, it does not meet the tolerable $\alpha_T$ measure.
These estimates are quite close to the expected 3 m by 1.5 m panel dimensions.

Recently-available, local serviceability measures include the position of the lower left corner of each panel (X₀, Y₀, and Z₀) and angular orientation of each panel (θₓ, θᵧ, and θᶻ) relating the P₀ and LF₀ coordinate systems. Table 2 shows a sample of the calculated values of such performance measures from the TLS and MLS point clouds for the 32 panels covering face 3 along façade 2 of the MSE wall. The X-coordinate of the origin of the P₀ relative to the LF₀ should be close to zero for a properly constructed MSE wall. Moreover, the YZ-coordinates of the origin of the P₀ reflect the joint width between the panels and the overall dimensions of the panels. Therefore, panel position, identified through repetitive scans over time, can identify potential relative movements among the panels of a given face. The second set of measures include the angular rotations representing the relationship between the LF₀ and P₀. The angles θᵧ and θᶻ define out-of-plane rotations of the panel relative to the LF₀, while θₓ signifies a rotation in the plane of the panel. For a well-constructed wall, these rotation angles should be close to zero. The evaluated dimensions of complete/non-occluded panels can be used as a supplementary measure for validating the proposed methodology by evaluating their similarity to previously known panel size. For example, panels 3, 4, 5, and 7 had an estimated width and height varying from 2.95 to 2.97 m and from 1.46 to 1.48 m, respectively, as presented in Table 2. These estimates are quite close to the expected 3 m by 1.5 m panel dimensions.
| ID | $X_o$ (m) TLS | $Y_o$ (m) TLS | $Z_o$ (m) MLS | $X_p$ (deg) TLS | $Z_p$ (deg) TLS | $X_p$ (deg) MLS | $Z_p$ (deg) MLS | $W$ (m) TLS | $H$ (m) MLS | $W$ (m) MLS | $H$ (m) MLS |
|----|-------------|-------------|-------------|----------------|----------------|----------------|----------------|-------------|-------------|-------------|-------------|
| 1  | 0.00        | 0.00        | 0.00        | -0.08          | -0.06          | -0.07          | -0.06          | 1.49         | 0.13        | 0.14        | 2.99        |
| 2  | -0.02       | -0.02       | 0.01        | 0.91           | 0.92           | -0.20          | -0.11          | -0.33        | 0.05        | 0.06        | 2.96        |
| 3  | -0.03       | -0.03       | 0.02        | 2.40           | 2.40           | 0.14           | 0.07           | -0.69        | 0.06        | 0.07        | 2.96        |
| 4  | -0.05       | -0.05       | 0.03        | 3.90           | 3.89           | -0.07          | 0.05           | -0.79        | 0.03        | 0.05        | 2.95        |
| 5  | -0.07       | -0.07       | 0.07        | 5.39           | 5.40           | -0.03          | -0.24          | 0.12         | 0.11        | 0.03        | 2.96        |
| 6  | -0.07       | -0.06       | 0.01        | 6.91           | 6.89           | -0.09          | -0.36          | 0.37         | 0.22        | -0.12       | -0.09       |
| 7  | -0.01       | -0.01       | 3.01        | 0.14           | 0.14           | 0.24           | 0.39           | -0.85        | -0.13       | -0.12       | 2.96        |
| 8  | -0.03       | -0.03       | 3.01        | 0.65           | 1.64           | -0.06          | 0.15           | -1.09        | -0.03       | -0.02       | 2.96        |
| 9  | -0.05       | -0.05       | 3.01        | 0.14           | 0.31           | -0.14          | -0.51          | -0.59        | 0.26        | 0.25        | 2.23        |
| 10 | -0.06       | -0.06       | 3.01        | 4.64           | 4.63           | 0.20           | 0.32           | -0.38        | 0.36        | 0.19        | 2.95        |
| 11 | -0.06       | -0.06       | 3.00        | 6.14           | 6.13           | -0.07          | -0.02          | 0.06         | 0.37        | 0.38        | 2.96        |
| 12 | 0.00        | 0.00        | 6.00        | -0.08          | 0.02           | 0.32           | 0.20           | -1.08        | -0.97       | -0.07       | -0.07       |
| 13 | -0.02       | -0.02       | 6.01        | 6.00           | 0.91           | 0.30           | 0.28           | -0.64        | -0.44       | -0.32       | -0.33       |
| 14 | -0.04       | -0.04       | 6.00        | 2.40           | 2.40           | 0.34           | 0.24           | -0.42        | 0.44        | -0.53       | -0.52       |
| 15 | -0.05       | -0.05       | 6.01        | 3.90           | 3.90           | 0.35           | 0.10           | -1.00        | -0.99       | -0.55       | -0.57       |
| 16 | -0.07       | -0.07       | 6.00        | 5.40           | 5.39           | 0.09           | 0.18           | -0.66        | -0.69       | -0.44       | -0.45       |
| 17 | -0.08       | -0.08       | 6.00        | 6.90           | 6.90           | -0.08          | 0.15           | 0.68         | 0.63        | -0.15       | -0.16       |
| 18 | 0.00        | 0.00        | 9.01        | 0.17           | 0.18           | -0.01          | 0.03           | -0.38        | -0.59       | 0.36        | 0.36        |
| 19 | -0.02       | -0.02       | 9.01        | 1.67           | 1.67           | 0.02           | -0.04          | -0.36        | -0.35       | 0.31        | 0.31        |
| 20 | -0.03       | -0.03       | 9.02        | 3.17           | 3.16           | -0.27          | 0.05           | -0.46        | 0.45        | 0.13        | 0.11        |
| 21 | -0.03       | -0.03       | 9.00        | 4.66           | 4.65           | -0.02          | 0.01           | -0.54        | 0.19        | 0.17        | 2.97        |
| 22 | -0.06       | -0.06       | 8.99        | 8.99           | 6.17           | 6.15           | -1.14          | -0.19        | 0.20        | 0.25        | 0.04        |
| 23 | -0.02       | -0.02       | 12.02       | 12.01          | -0.07          | -0.07          | -0.03          | 0.03         | -0.80       | 0.16        | 0.15        |
| 24 | -0.03       | -0.03       | 12.02       | 12.00          | 0.92           | 0.93           | -0.01          | -0.44        | -0.13       | -0.15       | 2.96        |
| 25 | -0.03       | -0.03       | 12.01       | 2.42           | 2.43           | -0.05          | 0.20           | -0.23        | 0.22        | 0.03        | 2.96        |
| 26 | -0.04       | -0.04       | 12.00       | 3.93           | 3.92           | -0.15          | -0.19          | -0.28        | -0.23       | 0.17        | -0.19       |
| 27 | -0.05       | -0.05       | 11.99       | 5.43           | 5.42           | -0.30          | 0.41           | 0.82         | -0.85       | -0.23       | -0.24       |
| 28 | -0.02       | -0.02       | 15.02       | 0.16           | 0.15           | 0.29           | -0.01          | -0.29        | -0.27       | 0.85        | 0.84        |
| 29 | -0.03       | -0.03       | 15.01       | 1.66           | 1.67           | 0.34           | 0.18           | -0.57        | -0.57       | 0.97        | 2.14        |
| 30 | -0.04       | -0.04       | 15.01       | 3.15           | 3.16           | 0.44           | 0.05           | -0.04        | -0.01       | 1.19        | 1.19        |
| 31 | -0.03       | -0.03       | 15.00       | 4.66           | 4.66           | 0.09           | -0.09          | -0.86        | 1.43        | 1.44        | 2.14        |
| 32 | -0.06       | -0.06       | 15.01       | 6.16           | 6.15           | -0.24          | 0.29           | -0.40        | 0.42        | 1.30        | 1.28        |

Table 2. TLS and MLS-based panel parametrization (position, angular tilts, as well as width and height of panels) for the panels covering face 3 along façade 2 of the MSE wall.
The overall statistics for the serviceability measures of the examined 76 panels covering faces 2, 3, and 4 along façade 2 using the TLS and MLS point clouds are provided in Table 3. The results in Table 3 show how the TLS-derived measures (i.e., angular orientation and panel-to-panel displacements) are quite similar to the performance measures derived using MLS. This similarity validates the capability of using an MLS system to obtain the serviceability measures for MSE walls. A graphical summary of the listed values for the statistics in Table 3 is provided in Figure 20, which shows the cumulative distribution functions (CDFs) for the three angular values (θ_{xp}, θ_{yp}, and θ_{zp}) and the panel-to-panel normal distance for the TLS and MLS datasets. As an overall comparison between TLS and MLS-based serviceability measures, Table 4 shows a statistical comparison of such measures, as well as the width and the height of the panels. It can be concluded from Table 4 that the MLS-based measures were within 1 cm and 0.3° for the recently available serviceability measures and within 0.3/1000 for the standard measures (i.e., α_l and α_T) when compared to those from TLS. In addition, the measures for the width and height of the panels that are complete in size, were similar compared to those derived from the TLS dataset within an RMSE range of 1 to 2 cm (which is again within the expected noise level for the used MLS).

Table 3. Summary statistics of TLS and MLS-based serviceability measures for 76 panels covering faces 2, 3, and 4 along façade 2 for the MSE wall.

|                  | θ_{xp} (deg.) | θ_{yp} (deg.) | θ_{zp} (deg.) | Panel-to-Panel Displacement (mm) | Panel-to-Panel Displacement (mm) |
|------------------|---------------|---------------|---------------|-------------------------------|-------------------------------|
|                  | TLS | MLS | TLS | MLS | TLS | MLS | TLS | MLS |
| Sample Size      | 76  | 76  | 76  | 76  | 76  | 76  | 454 | 454 |
| Minimum Value    | -1.14 | -0.48 | -1.61 | -1.49 | -0.77 | -0.77 | -14.10 | -16.00 |
| Maximum Value    | 0.47  | 0.38  | 0.68  | 0.63 | 1.43  | 1.44  | 13.50 | 18.10 |
| Range            | 1.60  | 0.86  | 2.29  | 2.11 | 2.21  | 2.21  | 27.60 | 34.10 |
| Average          | -0.03 | 0.00  | -0.46 | -0.45 | 0.06  | 0.07  | -0.30 | -0.21 |
| Standard Deviation | 0.26 | 0.19  | 0.4  | 0.39 | 0.48  | 0.48  | 4.97  | 5.19 |
| 5th Percentile   | -0.39 | -0.39 | -1.12 | -1.09 | -0.61 | -0.58 | -8.80 | -9.00 |
| 25th Percentile  | -0.11 | -0.12 | -0.72 | -0.73 | -0.20 | -0.22 | -3.70 | -3.70 |
| 50th Percentile (median) | -0.03 | 0.00 | -0.45 | -0.44 | 0.01  | 0.01  | -0.20 | -0.20 |
| 75th Percentile  | 0.09  | 0.14  | -0.21 | -0.20 | 0.18  | 0.18  | 3.10  | 3.20 |
| 95th Percentile  | 0.34  | 0.28  | 0.12  | 0.14 | 1.19  | 1.19  | 7.70  | 8.40 |
| Interquartile Range (IQR) | 0.20 | 0.26 | 0.52 | 0.53 | 0.39 | 0.40 | 6.80 | 6.90 |

Figure 20. Cumulative Distribution Functions (CDF) for panel-to-leveled face orientation angles and panel-to-panel displacement using TLS point cloud (in blue) and MLS point cloud (in red) for 76 panels constituting three faces along MSE wall façade 2.
Table 4. RMSE of evaluated differences between TLS and MLS-based serviceability measures for a total of 76 complete panels covering faces 2, 3, and 4 along façade 2 for the MSE wall.

| New-Available Serviceability Measures | Standard Serviceability Measures | Quality Control |
|---------------------------------------|----------------------------------|-----------------|
| \( X_0 \) (m)                         | \( Y_0 \) (m)                    | \( Z_0 \) (m)    |
| \( \theta_{xp} \) (deg.)             | \( \theta_{yp} \) (deg.)        | \( \theta_{zp} \) (deg.) |
| \( \alpha_L \) \((10^{-3})\)         | \( \alpha_T \) \((10^{-3})\)    | Panel-to-Panel Disp. (m) |
| RMSE                                  | \( 0.001 \)                      | \( 0.0027 \)     |
|                                      | \( 0.019 \)                      | \( 0.23 \)       |
|                                      | \( 0.30 \)                       | \( 0.048 \)      |
|                                      | \( 0.34 \)                       | \( 0.37 \)       |
|                                      | \( 0.0039 \)                     | \( 0.010 \)      |
|                                      | \( 0.022 \)                      |                 |

As mentioned earlier, one of the assumptions for a well-constructed MSE wall is that joints (i.e., gaps) between neighboring panels are within a tolerable range and have minimum offsets along the \( x \)-axis of the \( P_{cs} \) (i.e., along the face normal direction). To evaluate the accuracy of the automatically-derived panel-to-panel normal displacement between adjoining panels, such distances have been compared to interactive measurement of the displacement in the TLS point cloud, MLS point cloud, and on-site profiler gauge measurements derived at locations \( i, ii, \) and \( iii \)—refer to Figure 21. The individual checks of the panel-to-panel normal displacement are shown in Figure 22—where Figure 22a shows the manual measurements from the point cloud and Figure 22b shows the on-site profiler gauge measurements. In this regard, one should note that the on-site profiler gauge measurements are an independent evaluation of the absolute accuracy of derived normal distances. The estimated values for panel-to-panel normal displacements from the above approaches are shown in Figure 23. The results in Figure 23 indicate that the panel-to-panel normal displacements from the TLS and MLS data as evaluated by automated approach or interactive measurement of the displacement in the LiDAR point cloud as well as the on-site profiler gauge measurements were in good agreement (i.e., the reported numbers in Figure 23 are within the range of \( \pm 0.5 \) cm).

Figure 21. Overall out-of-plane displacement map for a face along the MSE wall façade (reported values along the scale bar are in meters) and locations \( (i, ii, \) and \( iii) \) for validating the automatically-derived displacement.
Figure 21. Overall out-of-plane displacement map for a face along the MSE wall façade (reported values along the scale bar are in meters) and locations (i, ii, and iii) for validating the automatically derived displacement (a) and (b).

Figure 22. Validation of panel-to-panel normal distance measurement: (a) interactive measurement from point cloud and, (b) on-site profiler gauge approach.

Figure 23. Validation of panel-to-panel out of-plane displacement (different colors in the interactive point cloud measurements columns represent different panels).

Now that we evaluated the comparative performance of TLS and MLS in reporting global and local serviceability measures, one can proceed with evaluating the measures for the MSE wall that has been surveyed by the MLS. Regarding the whole MLS dataset, Table 5 provides summary statistics of the proposed serviceability measures, derived using the MLS point clouds from different drive runs, for the complete and non-occluded panels of the smooth MSE wall (160 panels in total).

![Diagram](image_url)

| Location | Automated Measurement | Interactive Point Cloud Measurement | Independent Quality Control Measurements |
|----------|-----------------------|--------------------------------------|-----------------------------------------|
| i        | Normal distance of TLS derived from the proposed approach | Normal distance of MLS derived from the proposed approach | Profile view of TLS data measurement | Profile view of MLS data measurement | Profiler gauge measurement |
| 1 7      | 1.1 cm                | 0.97 cm                              | 1.07 cm                                 | 1.01 cm                               | 0.85 cm                   |
| ii       | North-East Corner of Panel 1 Relative to Panel 7 | North-East Corner of Panel 1 Relative to Panel 7 | 1.20 cm                                 | 1.22 cm                               | 1.06 cm                                 | 1.14 cm                               | 0.90 cm                   |
| 24 28    | 1.12 cm               | 1.08 cm                              | 0.96 cm                                 | 0.98 cm                               | 1.00 cm                                |

Table 5. Summary statistics of MLS-based serviceability measures for 160 panels constituting eight faces along façades 1, 2, and 5 of the MSE wall.
Now that we evaluated the comparative performance of TLS and MLS in reporting global and local serviceability measures, one can proceed with evaluating the measures for the MSE wall that has been surveyed by the MLS. Regarding the whole MLS dataset, Table 5 provides summary statistics of the proposed serviceability measures, derived using the MLS point clouds from different drive runs, for the complete and non-occluded panels of the smooth MSE wall (160 panels in total). Figure 24 shows the CDFs for the three angular values \(\theta_{xp}, \theta_{yp}, \text{ and } \theta_{zp}\) and panel-to-panel normal distance of the MLS dataset in this case study site. The graphical summary in Figure 24 is much easier to use for identifying trends and outliers than examining the values of each individual panel of the MSE wall. As can be seen in Table 5, the angular deviation values were less than 1° for the tilts around the \(x-, y-, \text{ and } z\)-axes. Table 5 also shows that 95% of the panels had an offset less than 1.00 cm, which indicates that the MSE wall meets the acceptable out-of-plane offset recommended by FHWA [7].

Table 5. Summary statistics of MLS-based serviceability measures for 160 panels constituting eight faces along façades 1, 2, and 5 of the MSE wall.

| Statistical Parameter | \(\theta_{xp}\) (deg.) | \(\theta_{yp}\) (deg.) | \(\theta_{zp}\) (deg.) | Panel-to-Panel Displacement (mm) |
|-----------------------|------------------------|------------------------|------------------------|---------------------------------|
| Sample Size           | 160                    | 160                    | 160                    | 911                             |
| Minimum Value         | -2.68                  | -1.43                  | -1.09                  | -32.30                          |
| Maximum Value         | 1.14                   | 1.45                   | 1.97                   | 30.50                           |
| Range                 | 3.82                   | 2.88                   | 3.05                   | 62.80                           |
| Average               | -0.35                  | 0.01                   | 0.05                   | -0.10                           |
| Standard Deviation    | 0.50                   | 0.50                   | 0.36                   | 6.73                            |
| 5th Percentile        | -1.15                  | -0.82                  | -0.50                  | -10.70                          |
| 25th Percentile       | -0.60                  | -0.26                  | -0.12                  | -3.80                           |
| 50th Percentile (median) | -0.33              | 0.00                   | 0.00                   | -0.10                           |
| 75th Percentile       | -0.04                  | 0.20                   | 0.22                   | 3.60                            |
| 95th Percentile       | 0.33                   | 0.98                   | 0.63                   | 9.80                            |
| Interquartile Range (IQR) | 0.57               | 0.46                   | 0.34                   | 7.40                            |

Figure 24. Cumulative Distribution Functions (CDF) of panel-to-leveled face orientation angles and panel-to-panel displacement using the MLS point cloud for 160 panels constituting eight faces along MSE wall façades 1, 2, and 5.
6. Conclusions and Potential Directions for Future Research

This study verified the ability of MLS for the procurement and generation of a wide range of serviceability measures for MSE walls with smooth precast concrete panels through a proposed monitoring strategy that expanded on the work of Aldosari et al. [15], which segmented the large textured MSE walls into isolated panels for serviceability measures. This study built on this and was able to tackle larger smooth paneled MSE walls and could be utilized in evaluating the long-term serviceability of MSE walls. It could also be used to create new acceptance criteria for new projects and evaluate the serviceability of MSE walls susceptible to natural disasters. A LiDAR-based MLS which can lower infrastructure management cost and enhance performance through better overall maintenance operations was utilized to collect highly accurate, high-resolution point clouds while driving along the transportation corridor. This research also introduced a strategy for panel identification for smooth MSE walls and established extensive quality control measures through the comparison with interactive measurements of displacement in the point cloud and in-situ profiler gauge measurements. The robust performance of the proposed strategy was verified even when some intermittent access to the GNSS signal (when driving under the bridge) was present. This research also addresses the performance of the registration procedure in the alignment of a multi-sensor/multi-drive run/multi-modal scanning system and showcases the quality of the system calibration and trajectory information.

The research objectives were tested through a case study in the State of Indiana where a comparative performance evaluation using TLS and MLS data acquisition modalities was conducted. The contributions/findings of the proposed strategy can be summarized as follows:

1. The study illustrated the capability of MLS in collecting point clouds with appropriate point density to derive global and local serviceability measures without the need for installing targets.
2. The study introduced a point-cloud processing framework, which includes a hybrid approach for the fine registration of scans derived from different sensors collected from single and multiple drive runs, segmentation, panel isolation, and derive both global and local serviceability measures evaluation.
3. Point clouds from different sensors and different drive runs can increase the level of detail in the gathered point clouds when using an MLS, with a high quality GNSS/INS direct geo-referencing unit, that has been accurately calibrated.
4. The potential of MLS was evaluated through a comparative evaluation against TLS. The derived serviceability measures from TLS and MLS were in close agreement within the range of $0.3/1000$ for the standard measures (i.e., $\alpha_L$ and $\alpha_T$) and $1\text{ cm}$ and $0.3^{\circ}$ for the recently-available serviceability measures (i.e., panel-to-panel differential displacements and angular deviations).
5. The derived panel-to-panel distance measure from TLS and MLS were quite similar (within the range of $0.5\text{ cm}$), thus providing additional validation for the MLS potential. Moreover, the comparison with on-site measurements (using profiler gauge) confirmed the absolute accuracy of such measures.
6. Extensive testing with a large real dataset demonstrated the feasibility of the different aspects of the proposed acquisition and processing framework.

Future work will focus on developing a completely automated process for MSE walls with piece-wise planar façades, improving system calibration, and GNSS/INS trajectory by considering observed discrepancies from multiple drive runs, as well as evaluating the impact of driving speed on the estimated serviceability measures. Moreover, the potential of using lower grade MLS to generate serviceability measures and expanding the strategy to handle non-identical and textured panels will also be investigated. Finally, the proposed procedure will be used for short-term (few months) and long-term (several years) evaluation of serviceability measures of MSE Walls. This study will be also used to evaluate the efficacy of different construction approaches.
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