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PROPOSED APPROACH FOR ASSESSING THE DEFORMATION OF LARGE-SCALE RETAINING WALLS IMPLEMENTING TERRESTRIAL LASER SCANNER

Moomen A. Mohamed[1], Ibrahim F. Shaker[1], Ayman F. Ragab[1], Mohamed Ramadan[1] and A. M. Abdel-Wahab[2]
[1]Department of Public Works, Civil Engineering, Faculty of Engineering, Ain Shams University, Cairo, Egypt
[2]Department of Civil Engineering, National Research Centre, Engineering and Renewable Energy Research Institute, Cairo, Egypt
E-Mail: Moamen.aly@eng.asu.edu.eg

ABSTRACT

New constructions in landfill zones have caused movement and cracks in large-scale retaining walls that are characterized by their high elevations and long lengths, necessitating unusual measurements for geotechnical experts to find a solution. A terrestrial laser scanner is one of the best ways to create a detailed 3D model. Laser scanning reduces the time required for on-site data collection by 50-70%, compared to traditional surveying. Laser scanning improves processes, accuracy, and cost, making it a viable tool for structural monitoring and deformation research. Coordinate transformation equations were used to align the X-axis with the wall's length, the Z-axis with the wall height, and the Y-axis perpendicular to the wall, creating a cross-section and contour map that shows how the wall has moved and cracked relative to the initial case. Geotechnical specialists can readily assess deformation and determine permanent solutions with these sections and contour maps. Vertical sections were generated every 5.0 m along the length of the retaining wall, accompanied by contour maps with a contour interval of 1 cm. The maximum movement is about 45 cm. One articulates the distinction as a swift and precise observation of deformation compared to conventional surveying methods.

Keywords: terrestrial laser scanner, well deformations measurement, transformation coordinate system, and land fill.

1. INTRODUCTION

In the past 30 years, surveying technologies have fundamentally transformed traditional methods, improved precision, dependability, and operational productivity while reducing the steps required by operators. 3D surface analysis, heritage documentation, archaeological excavation, artefact preservation, and volumetric mapping have greatly benefited from innovations in 3D data acquisition [1]. The application of new methods like laser scanning has increased the rate of data collection along with the quality, volume, and reliability of spatial information, aiding multi-disciplinary decision-making that requires high precision [2], [3]. Laser scanning reduces labor costs and increases efficiency, provides a quicker turnaround on projects, and allows contractors to add greater value to construction completion [4]. With unparalleled speed, laser scanning technology captures, stores, and processes spatial data with exceptional accuracy, making it one of the most sophisticated surveying tools. Such capabilities result in tremendous savings in time and costs, particularly in civil engineering activities like road surveying, deformation monitoring, pavement evaluation, and mapping hydraulic connections [5].

Laser scanning reduces manual data collection efforts, improves accuracy, gives engineers valuable insight to automate workflows, and enhances primary working results, which fortifies the importance of laser scanning in infrastructure development and upkeep[6]. Retaining walls undertake the role of critical infrastructure because they offer support and hold back soil in various engineering works. Their protection is critical for the dependable and effective upkeep of transport networks, urban systems, and geo-information systems. Their condition is traditionally assessed using qualitative evaluations coupled with visual inspections, a practice that, although common, is fraught with subjectivity and oversights. These constraints highlight the need for more advanced data-driven techniques, such as laser scanning and other forms of precise monitoring, to enhance objectivity, precision, and efficiency in design [7], [8].

The vertical retaining wall nailing process involves the use of wall-facing panels. They act as a protective measure for the soil on the exposed surface of a retaining wall. Panel facings are rigidly connected with soil reinforcements for stability and to protect against structural movement. To avoid soil erosion or sediment build-up as well as assist in draining, the joints in between panels serve as outlets, in most cases filled with geotextile filter fabric, which traps soil particles but permits the flow of water. Furthermore, the type of facing material used impacts the control of vertical or horizontal deformation and differential settlement, which in turn impacts the system's longevity and dependability significantly [9]. Precast concrete panels are the most common type of facing because they are cheap, easy to install, and can be finished in many ways. The panels must not be less than 140 mm thick and can be produced in various forms, including cruciform, square, rectangular, diamond, or hexagonal [10].

Optical surveying of individual point targets using total stations, on the other hand, requires a labor-intensive procedure and restricts the data obtained to the surveyed points. This process's constraints make it useless for gathering spatially precise information about lengthy retaining walls with considerable length and height, since scanning each point is both wasteful and impractical. Consequently, innovative techniques such as terrestrial laser scanning provide a superior approach to generating high-density, high-resolution data over extensive areas for a very short duration, significantly minimizing the work required for field measurements [11], [12]. Moreover, accurate and thorough modelling of reinforced soil structures is essential for analyzing and forecasting their behavior; such analysis relies on the collection of extensive data points scattered throughout the structure. Comprehensive and rapid data collection with full geographical coverage and precision is required. Additionally, using automated tools to measure movement will improve how we monitor these structures by removing the need for people to be involved and allowing us to continuously check how well the structure is performing and staying stable, especially for large retaining walls that are very tall and long[13].

It is very difficult to identify good benchmark features on which to measure changes in a target structure over time, since modifications are likely to manifest along several different dimensions, i.e., geometry, material properties, and environment. Most detection techniques available today are typically founded on the manual input of highly precise parameters, which adds subjectivity and increases the likelihood of inconsistency between long-term measurements. For enhanced accuracy and efficiency, there is a need for an automated means of change detection that can mechanically detect and quantify structural changes with minimal human input. Such an approach would enhance reliability in reinforced soil structure and retaining wall monitoring, allowing for better-informed decisions in maintenance and stability analysis [14]. When it comes to the building and maintenance of retaining walls on highways, wall movement is a major reason for worry. This is because excessive wall movement may result in damage to the structure, such as cracking in the facade, fractures in the pavement, and breaking of the face panel. The current research suggests evaluating whether or not it is possible to use terrestrial laser scanning (TLS) for the purpose of monitoring the deformation of retaining walls to find solutions to these problems. By comparing many scans and developing a registered, three-dimensional model, the research endeavours to provide a comprehensive evaluation of TLS accuracy, efficiency, and prospective improvements in structural health monitoring. This objective may be regarded as the primary reason for the present work [1].

2. PRINCIPLES OF MONITORING METHODS

Using terrestrial laser scanners (TLS) for monitoring retaining wall deformations is a cutting-edge approach in structural engineering. Here are some key principles and applications:

- **High-Resolution Data Collection**

Terrestrial Laser Scanning (TLS) provides extremely accurate 3D point clouds of retaining walls, allowing accurate monitoring of even slight deformations. Lateral displacements, settlements, and tilts can be tracked by engineers using this technology with millimeter accuracy, greatly improving structural health monitoring. [15].

- **Non-Contact and Rapid Scanning**

One of the strong advantages of TLS is that it is non-contact, allowing rapid data gathering without disrupting the structure. It is particularly beneficial in remote or hazardous retaining walls. Research has indicated that TLS can be used effectively to monitor retaining walls in real time and provide vital information on maintenance [16].

- **Integration with Structural Health Monitoring (SHM)**

TLS can be used in extended SHM systems to enable continuous monitoring of retaining walls. By comparing successive scans, engineers can see trends in deformation and forecast future failure. Research has proven the capability of TLS to increase the accuracy and reliability of SHM for retaining walls [17]

- **Producing Cross Sections and 3D Contour Maps**

Data from a ground-based laser scanner can be used to create 3D contour maps and cross sections after adjusting the axes and orientations of the coordinate systems. This approach enables geotechnical experts to effectively analyses and evaluate wall displacements and cracks in various sections of these walls [18].[19], [20]

3. STUDY AREA AND METHODOLOGY

Large-scale retaining walls that are defined by their high heights and extensive lengths have been affected by movement and fractures as a result of new development in landfill zones. To identify a solution, geotechnical specialists have had to take unique measurements. In most cases, the horizontal movements (lateral displacements) of the wall are brought about by the internal stability.

These movements are brought about by the soil's reinforcement pushing away from the wall. Moqatam Square, October, and El-Ain El-Sokhna are only a few of the locations in Egypt where retaining walls are being used to restrict the implementation of several projects. The elevation of the retaining wall on the site is shown in Figure-1 as a sample of the retaining wall in this study, along with the equipment that was used.

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Figure-1. Sample of the retaining wall in this study.

Following construction, an as-built survey of the retaining wall was conducted, subsequently using a terrestrial laser scanner to create a 3D model for comparison between the as-built condition and the current state. After the construction was finished, the retaining wall was surveyed as-built. Then, a 3D model was created using a terrestrial laser scanner so that we could compare the present status to the as-built condition. According to the plan of the retaining wall design in Figure-2, the retaining wall in the study area is 895 meters long, with a height varying from 4.4 to 11 meters and a width of 30 centimeters. During the wall's georeferencing phase, two control locations were surveyed on-site using GPS.
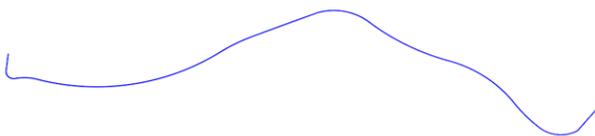

Figure-2. The plan of the retaining wall.

To monitor the retaining wall, central reference points were strategically installed along its surface, establishing fixed benchmarks. Using a 3D laser scanner, the entire wall was scanned to capture millions of data points, generating a highly detailed digital replica of its surface. These data points were processed into a three-dimensional model, enabling comprehensive analysis of the wall's geometry.

The 3D model revealed measurable deformations and displacements in the wall's structure. By comparing the initial reference points with the scanned data, one can identify the exact magnitude and direction of movements. The high-resolution analysis exposed subtle changes that might otherwise go undetected, offering critical insights into the stress distribution and potential structural weaknesses of the wall. The position of the laser scanner was chosen so that the entire area of the retaining wall is covered. The laser scanner used was a Trimble TX8Extended, [21] as shown in Figure-3.

Figure-3. The used 3-D laser scanner trimble TX8 [22].

Active sensors with the ability to release electromagnetic energy on their own are laser scanners. To determine the distances to the studied features, they release laser beams. As shown in Figure-4, TLS samples the studied features by a large number of points that rely on determining the slope distance (r), vertical angle (θ), and horizontal angle (φ). Then, it computes the Cartesian coordinates (X, Y, Z) of the surveyed points, as shown in equation 1. Terrestrial laser scanners pre-processing: Registration[23], [24].
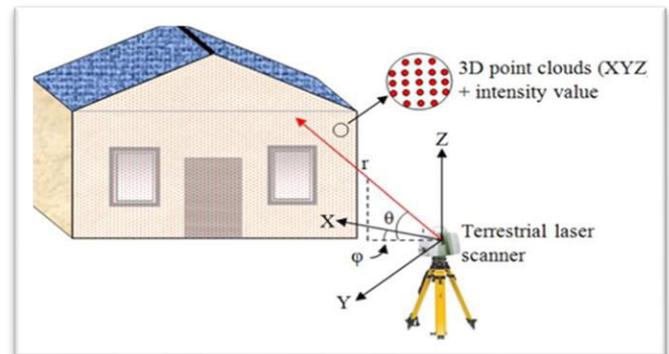

Figure-4. The principle of TLS measurement [20].

$$\begin{bmatrix} Xj \\ Yj \\ Zj \end{bmatrix} = \begin{bmatrix} r_j\cos\theta_j\cos\varphi_j \\ r_j\cos\theta_j\sin\varphi_j \\ r_j\sin\theta_j \end{bmatrix} \qquad \text{Eq. 1.}$$

Coordinate transformation equations (2) were used to align the TLS axis to the new axis to produce cross sections and a contour map for the deformation of the wall which will discuss in the following sections which let the final axis will be as the following the X-axis with the wall's length, the Z-axis with the wall height, and the Y-axis perpendicular [25]

$$\begin{bmatrix} X_{new} \\ Y_{new} \\ Z_{new} \end{bmatrix} = SR \begin{bmatrix} X_{TLS} \\ Y_{TLS} \\ Z_{TLS} \end{bmatrix} \qquad \text{Eq. 2.}$$

Where:

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X_{new}, Y_{new}, Z_{new} are the new coordinate system as mentioned above paragraph.
S scale factor = 1
R rotation angles about the X-axis, Z-axis, and the Y-axis.
X_{TLS}, Y_{TLS}, and Z_{TLS} are the TLS coordinate systems.

4. DATA REGISTRATION

The registration of data was conducted using Trimble Real Works software, employing the cloud-to-cloud registration method to integrate multiple datasets effectively. This approach eliminates the need for physical reference points by relying on advanced algorithms to align and merge point clouds captured from various positions [26].

The cloud-to-cloud technique ensures high precision in matching overlapping areas of the datasets, resulting in a unified and accurate 3D model [7]. The consolidated data provides a comprehensive basis for analyzing deformations and structural changes, which facilitates detailed assessments of the retaining wall's condition. The Trimble Real Works platform proved instrumental in streamlining this process, enabling efficient handling of large-scale 3D laser scanning datasets. Figure-5 shows the 3D model of the registered scans for the retaining wall.

Figure-5. The registered 3D model for the retaining wall.

The site coordinate system generates a three-dimensional model of the wall. Figure-6, shown below, depicts a segment of the spatial representation of the wall. Trimble Real Works, a 3D scanning program, was utilized and displayed on Autodesk Recap.

Figure-6. The 3D model for the retaining wall is presented on autodesk recap.

5. DATA ANALYSIS

In this phase, subsequent to modifying the final coordinates, 1,740 vertical segments were excised from the wall at intervals of 5 meters to assess the extent of alterations from the original condition to the final state. A slope of 2° 1' 19" is evident in the vertical portion of the wall, as seen in many vertical profiles in Figure-7. The deformation in each segment will be ascertained by averaging a contour map of the wall, the current survey, and the as-built survey.
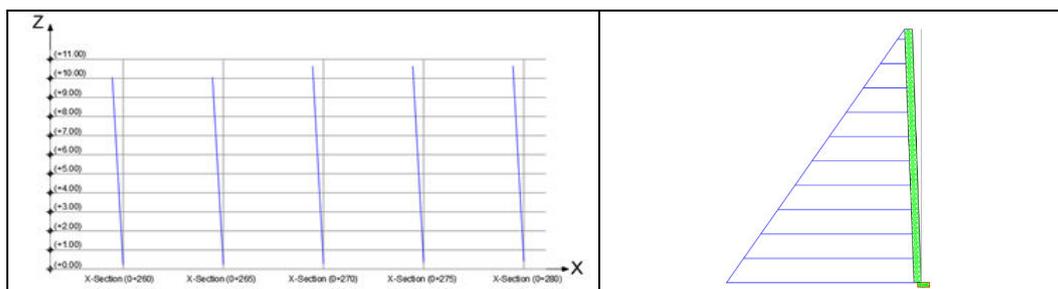

Figure-7. The 3D model for the retaining wall is presented on autodesk recap.

6. FINDING

According to Figure-8, the blue line represents the first survey of the as-built scenario, whereas the red line represents the final situation. At station 270, the wall has a height of 10.0 meters, and it displays a bulge with a displacement of 44.8 centimeters at level 7.0 meters. This displacement diminishes to 30.0 centimeters at the top of the vertical portion as we proceed higher. It displays a displacement of 41.9 centimeters at station 265, which is

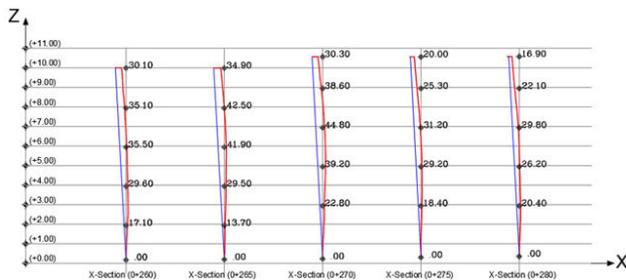located at a level of 6.0m. To a large extent, this pattern is consistent throughout all vertical parts.

Figure-8. The difference between the state just after construction (blue) and the current state of the retaining wall now as a displacement in (cm).

Because the x-axis is parallel to the direction of the retaining wall, the z-axis indicates its height, and the contour lines reflect the change in the y-axis (movement direction), which is perpendicular to the wall plane. The contour lines are spaced 1 cm apart. Figure-9 shows how thick the contour lines are at the bottom of the retaining wall. This is owing to the high pressure in that area, which causes rapid changes in contour lines.
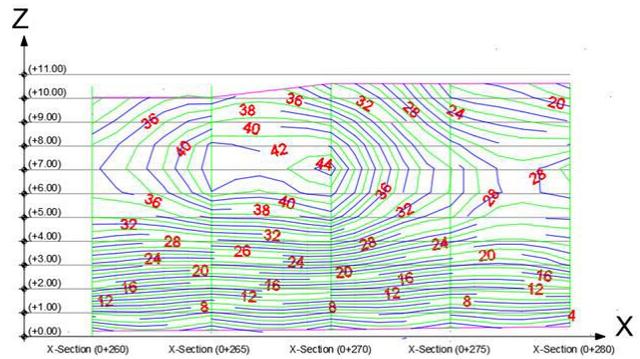

Figure-9. The difference between the state just after construction and the status of the retaining wall now as a contour map in cm.

The Trimble Real Works tool made orthophotos of the curved parts of the retaining wall to project its length and find cracks. Figure-10(a) shows that the cracks at the top of the retaining wall are 3.8 cm wide. As you can see in Figure-10(b), the supporting wall has cracks that can be seen.
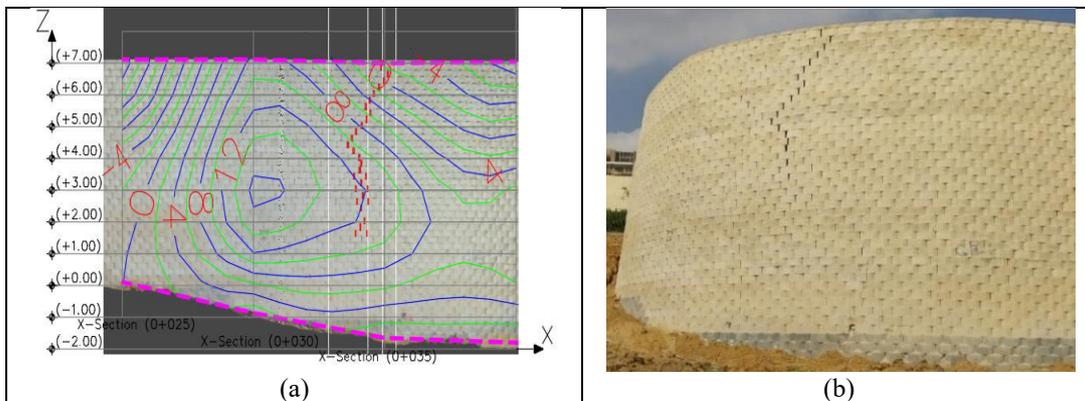

Figure-10. The Cracks (a) is the orthophoto for the wall showing the cracks and contour (b) Is the original photo on the wall.

Finally, Figure-11 illustrates the longitudinal section of the wall for deformation at levels 4.0m, 6.0m, and 8.0m. The x-axis shows the station, and the y-axis shows the deformation in cm. The displacement was highest at station 0+270, measuring 43.8 cm, and lowest at station 400 m, measuring 2.3 cm.
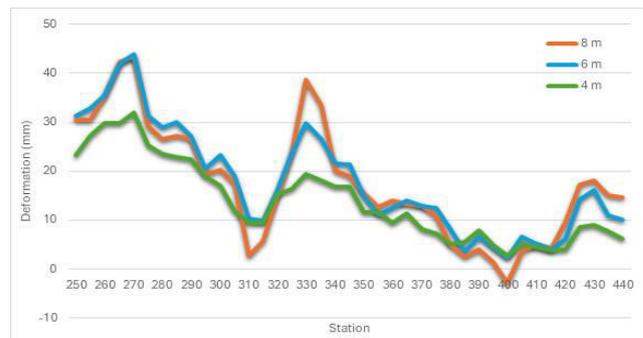

Figure-11. Illustrates a longitudinal section for the deformation at level 137.0m, showing the station as the x-axis and the deformation in mm on the y-axis.

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7. CONCLUSIONS

Using a laser scanner is very accurate in the monitoring of retaining walls because the instrument, Trimble TX8, can create cloud points of 7 mm x 7 mm, and it gives about less than 1cm in depth distance, and there is a furrow in the wall at the middle of the height of the wall.

3D laser scanning technology is a transformative tool in structural engineering, providing precise, real-time data for evaluating deformations for geotechnical specialists, who can readily assess distortion and determine permanent solutions with these sections and contour maps. Vertical sections were generated every 5.0 m along the length of the retaining wall, accompanied by contour maps with a contour interval of 1 cm. The maximum movement is 45 cm. One articulates the distinction as a swift and precise observation of deformation compared to conventional surveying methods.

This methodology enables engineers to make informed decisions regarding remediation and stabilization. The integration of automated scanning systems for continuous monitoring holds promising potential for future research and applications.

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