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Assessing the Geometric Integrity of Cylindrical Storage Tanks: A Comparative Study Using Static Terrestrial Laser Scanning and Total Station

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Abstract: This study compares Static Terrestrial Laser Scanning (STLS) with the conventional Total Station (TS) method for the geometric assessment of cylindrical storage tanks. With the crucial need for maintaining tank integrity in the oil and gas industry, STLS and TS methods are evaluated for their efficacy in assessing tank deformations. Using STLS and TS, the roundness and verticality of two cylindrical tanks were examined. A deformation analysis based on American Petroleum Institute (API) standards was then provided. Key objectives included comparing the two methods according to API standards, evaluating the workflow for STLS point cloud processing, and presenting the pros and cons of the STLS method for tank geometric assessment. The study found that STLS, with its detailed and high-resolution data acquisition, offers a substantial advantage in having a comprehensive structural assessment over TS. However, STLS requires more processing time and prior knowledge about the data to tune certain parameters and achieve accurate assessment. The project outcomes intend to enhance industry professionals' understanding of applying STLS and TS to tank assessments, helping them choose the best method for their specific requirements.

Keywords: Geometric tanks assessment, STLS, TS, API standards

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1. Introduction

The geometric integrity of storage tanks, particularly those adhering to American Petroleum Institute (API) standards, has been a focal point of numerous studies due to their critical role in the safety and efficiency of industrial operations. API standards, like API 650 and API 653, provide comprehensive guidelines for designing, maintaining, and inspecting storage tanks, emphasizing their geometric stability and integrity (American Petroleum Institute, 2014; 2016).

In Geomatics Engineering, multiple studies are conducted to help inspectors and engineers evaluate the geometric condition of these storage tanks. For instance, Irughe et al. (2011) developed a method to determine the ovality of crude oil storage tanks using Total Station (TS) and Least Squares (LS), which is a standard method for such applications. The TS was utilized to perform angular and linear measurements through a method known as multiple intersections, which involved setting up the TS at various established monitoring stations around the tank. The field measurements were processed using an LS adjustment method to provide an unbiased estimation of the tank's most probable parameters. Through this methodological approach, the study was able to accurately determine the radius of the tanks and their ovality across different measurement epochs, offering valuable insights into the structural integrity and deformation patterns of the storage tanks over time.

Static Terrestrial Laser Scanning (STLS) is increasingly becoming an industry standard for structural geometric assessment due to its high precision, speed, and ability to produce dense point clouds that accurately represent complex geometries. Pukanská et al. (2014) utilized STLS to assess the deformation of an imploded oil tank at fine resolution. The study compared the point cloud against the tank's original 3D design to identify any changes in geometry. The comparative analysis was based on calculating the Euclidean distance between the point cloud and the original 3D design. By analyzing the Euclidean distance differences between the actual scanned surface and the original design, areas of deformation were identified and graphically interpreted as either bulges or dents.

Another study by Gumilar et al. (2021) used STLS to create a detailed 3D model of a water tank and assess its geometric condition as per API standards. The methodology included a manual extraction of the registered point cloud to remove irrelevant features and focus the analysis on the tank structure. A cross-sectional analysis was executed to evaluate the roundness and calculate the radius for each section. This was done by first determining the center point at the base of the tank, which was assumed to be the most stable and unaffected by the tank's contents. From this central reference point, the radius of the tank was measured at each section. Then, by comparing these radii measurements with the tank's design radius, the study could detect any significant deviations indicating deformations. This method provided a detailed quantitative analysis of the tank's structural integrity, showing that the variations in the tank's roundness were within the acceptable limits established by API.

Moreover, two studies by Truong-Hong et al. (2020) and Nurunnabi et al. (2019) focused on automating the process of tank deformation analysis by utilizing various segmentation algorithms. The major issue in using STLS for tank deformation analysis is to extract a point cloud of the cylindrical tank wall from massive data points of a complex structure consisting of the tank wall and its components (e.g., floor, floating roof, roof, columns, manways, etc.). The extraction of these cylindrical representations from the point cloud data is generally achieved through point cloud segmentation to determine descriptive parameters of the cylinder. The most common segmentation algorithms are based on Random Sample Consensus (RANSAC) and Hough Transform (Nurunnabi et al., 2019).

Among RANSAC-based methods, the algorithm by Schnabel et al. (2007) stands out for its widespread application in extracting cylindrical point clouds. This method calculates the cylinder's axis direction using the cross-product of the data points' normal vectors and identifies the cylinder's center and radius using the optimal fit circle on the plane orthogonal to the axis direction. A significant benefit of this approach is its capacity to process large datasets. However, it necessitates the adjustment of several input parameters by users, such as the minimum number of points for the estimated cylinder, the maximum distance from a point to the cylinder, and the normal vectors' angular deviation at the points to accurately define the cylinder.

STLS was found to be superior in efficiency and detail compared to TS, which is preferred for high-accuracy measurements in traditional methods. STLS is particularly useful in time-critical situations and provides a comprehensive visualization of structures, which is not as feasible with TS (Deruyter et al., 2013). For large cylindrical storage tanks, traditional TS methods are accurate but less efficient. Lv and Li (2022) have shown that STLS can achieve comparable accuracy with much higher measurement efficiency. They used only the maximum values of protrusion/ (bulge) and intrusion (dent) at each cross-section, along with the ovality values, to compare between STLS and TS data. The differences were found to be within the range of deformation limits according to GB 50128-2014 Code for Construction of Vertical Cylindrical Steel Welded Storage Tank.

This study seeks to explore STLS in evaluating the tank geometric condition and comparing it against the conventional TS method. The TS method is an industrial standard at this moment as it has data collection guidelines specified in API standards, which is why it's imperative to compare the relatively new approach against this established benchmark. The aforementioned studies have individually demonstrated the effectiveness of STLS and TS in assessing the geometric integrity of the storage tanks. However, a direct comparison of their geometric results is lacking. To address this gap, STLS and TS were deployed to evaluate the roundness and verticality conditions of two vertical cylindrical tanks as per API standards. The primary objective of this study is to deepen professionals' understanding of the practical application of STLS and TS in the geometric assessment of storage cylindrical tanks, thereby equipping them with the knowledge to select the most appropriate equipment for their unique tank conditions.

2. Materials and Methods

2.1. Study Area

The dataset utilized in this study consists of 3D data (XYZ) of slurry tanks located at the Animal Sciences Research and

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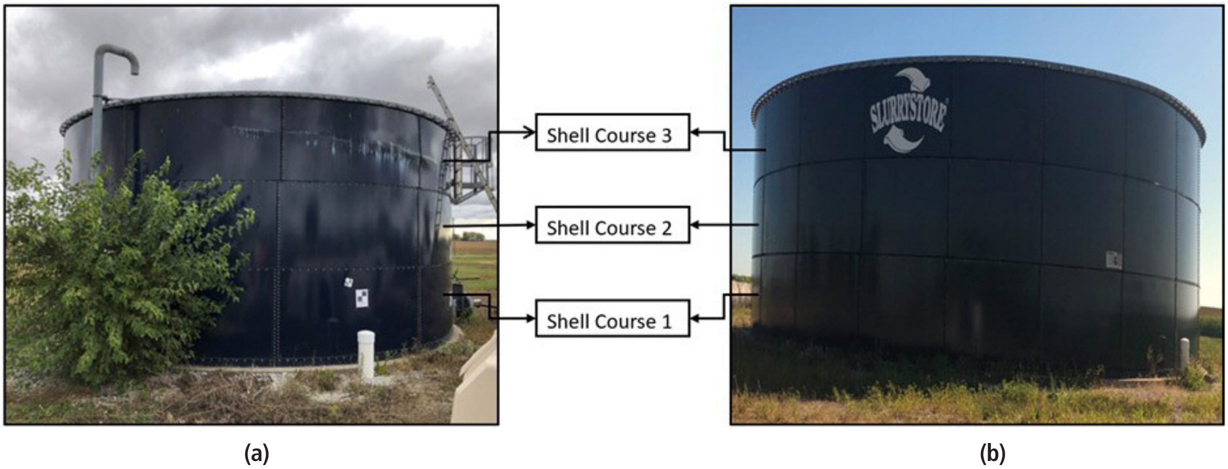

Fig. 1. Tank structures consisting of three shell courses. (a) Tank-1 structure. (b) Tank-2 structure.

Education Center (ASREC) of Purdue University in West Lafayette, Indiana. The data collection was performed using TS and STLS techniques on two distinct slurry tanks that were close to each other. The first tank, referred to as the Purdue Dairy Slurry Tank (Tank-1), has a height of approximately 4.3 m and a diameter of 8.5 m. The second tank, known as the ASREC Beef Unit Slurry Tank (Tank-2), shares the same height of 4.3 m but has a larger diameter of about 18.8 m. Both tanks have three shell courses, and the first shell course is mounted on a ring wall concrete foundation. The tank shell courses are made from rolled steel plates and rise vertically to contain the product. Each shell is welded and bolted with its neighboring shells, and the bolts are arranged uniformly. When welding, each shell course is welded separately, maintaining a gap between it and the course above to ensure proper alignment and structural integrity. These slurry tanks are used in the management of agricultural waste at ASREC, providing a means for storing and processing waste products from dairy and beef units.

For this study, both tanks were selected to exemplify a typical vertical cylindrical storage tank in order to conduct the geometric assessments in accordance with API standards. These tanks have been chosen to simulate, to some degree, the conditions and characteristics of small oil storage tanks found in the Petroleum industry. Fig. 1 illustrates their structures.

2.2. Survey Method

The Trimble S7 TS was used to conduct the TS survey and Faro Focus 3D X330 is the scanner used for STLS point cloud. To measure TS roundness and plumbness observations around the two tanks, a closed-loop traverse was conducted for each tank. Roundness and plumbness observations were collected from each station setup, using the welding joints as reference lines to

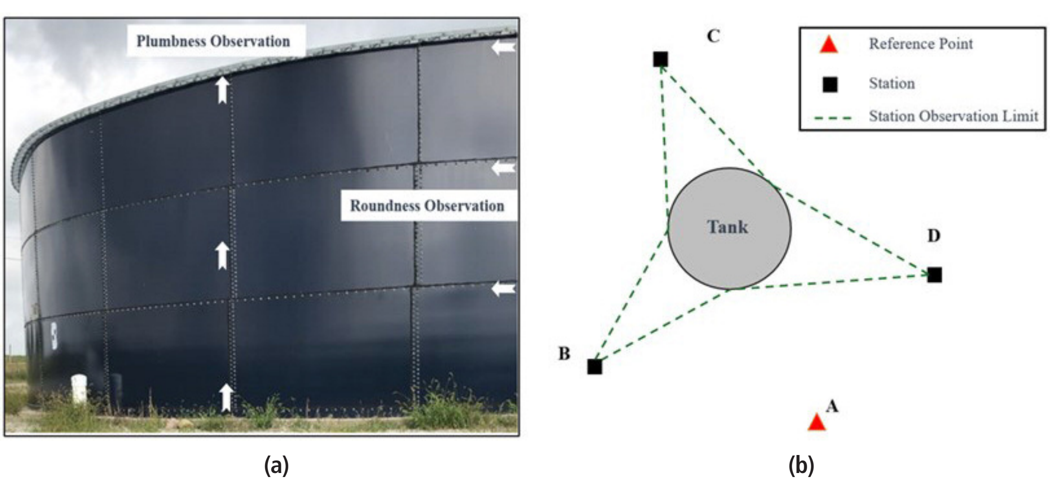

Fig. 2. TS survey method. (a) Approximate location of roundness and plumbness observations. (b) TS station setups.

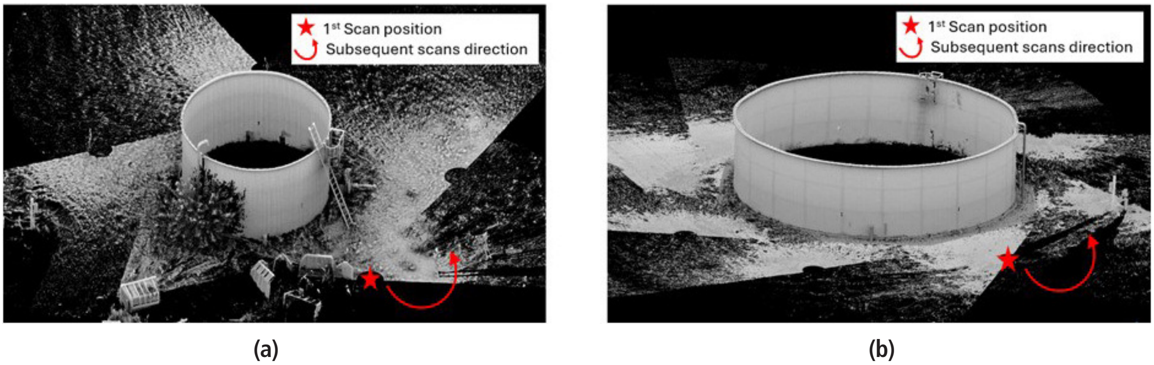

Fig. 3. Registered scans. (a) Tank-1 aligned scans. (b) Tank-2 aligned scans.

ensure roughly aligned observations as illustrated in Fig. 2(a). The layout of the closed loop traverse is displayed in Fig. 2(b).

Additionally, readings of checkerboard paper targets were taken, each tank has 5 of these paper targets, which were utilized later for the georeferencing process to transform STLS point cloud to TS reference frame. The achieved horizontal and vertical misclosure errors were less than 2 mm for both tanks. Since the horizontal and vertical misclosure errors were very small, the traverse adjustment was deemed unnecessary.

After predefining Faro scanning parameters and placing the necessary checkerboard targets that were used for registering the overlapped scans, a series of scans to ensure full structure coverage for both tanks. For Tank-1, five scans were collected at a short range, with the farthest scan station approximately 7 m from the tank structure and an overlap between adjacent scans of about 40–50%. For the larger Tank-2, the number of scans increased to nine. The farthest scan station for Tank-2 was positioned roughly 10 m away from the tank structure, employing a similar scan overlap ratio as Tank-1. The subsequent scans for each tank were conducted in a counterclockwise direction around the tank. Then, Faro Scene software was utilized to register the overlapped scans using the scanned checkerboard paper targets, aligning and merging the overlapped scans into a cohesive 3D model for each tank.

Table 1 summarizes the registration maximum and mean errors in millimeters. Fig. 3(a) demonstrates the results of the registered scans for Tank-1, with the location of the first scan station indicated by a red star and a red arrow for the counterclockwise direction of the subsequent scans. Similarly, Fig. 3(b) depicts the registered scans for Tank-2.

After that, the georeferencing process was conducted to transform the registered scans from the global registration frame to the external frame which is TS coordinate system frame using

Table 1. Summary of registration errors

Error	Tank-1		Tank-2	
	Maximum (mm)	Mean (mm)	Maximum (mm)	Mean (mm)
Distance	3.9	1.4	3.6	1.5
Horizontal	3.9	1.2	3.3	1.1
Vertical	1.6	0.5	2.5	0.8

the rigid body transformation. This transformation is expressed mathematically as:

$$X_e = \Delta X_{ge} + \lambda \, R_{ge} \, X_g \tag{1}$$

where X_e represents the transformed points into the external frame (TS data frame), ΔX_{ge} correspond to the 3 translations along the 3 coordinate axes of the external frame (ΔX, ΔY, ΔZ), R_{ge} represents the 3 rotations around the 3 coordinate axes of the external frame (ω, φ, κ), λ is the scale factor, and X_g denotes the point cloud in its original (global) frame as explained by Reshetyuk (2009). As previously indicated, each tank has a total

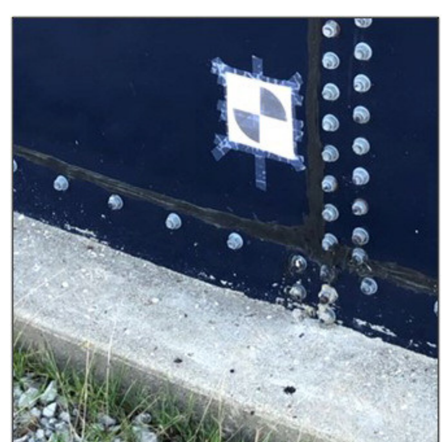

Fig. 4. A georeferencing checkerboard paper target on Tank-2 structure.

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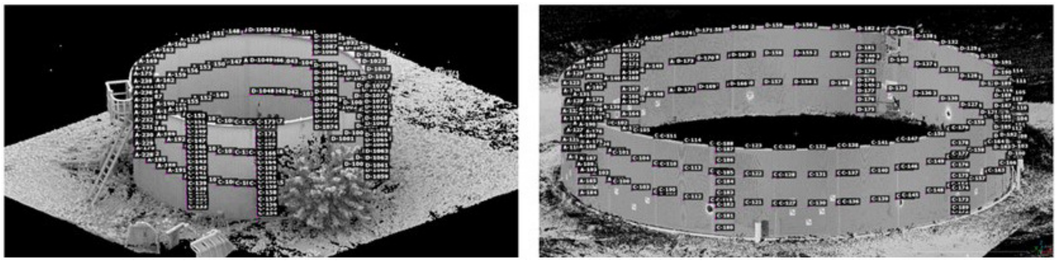

(a) (b)

Fig. 5. Georeferenced scans. (a) Tank-1 georeferenced point cloud. (b) Tank-2 georeferenced point cloud.

Table 2. Georeferencing transformation matrix RMSE

Tank-1		Tank-2	
Conjugate Point	Error (mm)	Conjugate Point	Error (mm)
Ref 1	3.4	Ref 1	7.3
Ref 2	4.6	Ref 2	3.2
Ref 3	3.0	Ref 3	6.0
Ref 4	1.5	Ref 4	2.5
Ref 5	8.8	Ref 5	6.8
RMSE = 4 mm		RMSE = 6 mm	

of 5 conjugate checkerboard paper targets, observed by both TS and STLS. These targets were strategically placed around the two tank structures at various elevations to ensure an accurate georeferencing process.

Fig. 4 shows an example of the georeferencing checkerboard paper target used for Tank-2. These conjugate targets/points were utilized to estimate the transformation matrix used in the georeferencing process. To estimate this transformation, Least Squares were utilized to minimize the Root Mean Square Errors (RMSE) of the differences between transformed points and the goal points in the TS data frame. The final RMSE and the conjugate points errors of the estimated transformation matrix are tabulated in Table 2. Figs. 5(a, b) show the georeferenced point cloud along with TS-labeled observations for both tanks.

2.3. Corresponding Observations Extraction

A K-dimensional tree (KDTree) structure was created to organize the georeferenced point cloud. This structure was then used to find and extract the closest points (nearest neighboring points) in the georeferenced point cloud to the reference points (TS observations). The purpose of extracting these points is to facilitate their use in a subsequent comparative analysis, specifically aimed at evaluating the discrepancies of the tank geometric assessments based on TS and STLS corresponding points.

2.4. Cylinder Extraction

The extraction of the point cloud that represents only the tank's cylindrical structure is crucial before starting the tank geometric assessment using the point cloud data. This process consists of several steps based on the geometric features found in the collected point cloud data. Fig. 6 demonstrates the adopted extraction workflow that ensures the geometric assessment is based on refined data that represents only the cylindrical portions of the tank structure. The workflow involves identifying the point cloud that best fits the cylinder model using the RANSAC approach proposed by Schnabel et al. (2007).

Then, Density-Based Spatial Clustering of Applications with Noise (DBSCAN) was used to separate isolated outliers found within the points representing the cylinder. These outliers are structural components attached to the tank shell, such as a ladder, top curb angle, etc. After that, Statistical Outlier Removal (SOR) was applied to the cylinder point cloud (DBSCAN large cluster) to remove low-dense sparse outliers, mostly found at the cylinder's edges or remnants of tank bolts. The aforementioned 3 steps are based on different parameters that can be tuned based on prior knowledge about the point cloud data. The optimal parameters

Fig. 6. Cylinder extraction workflow.

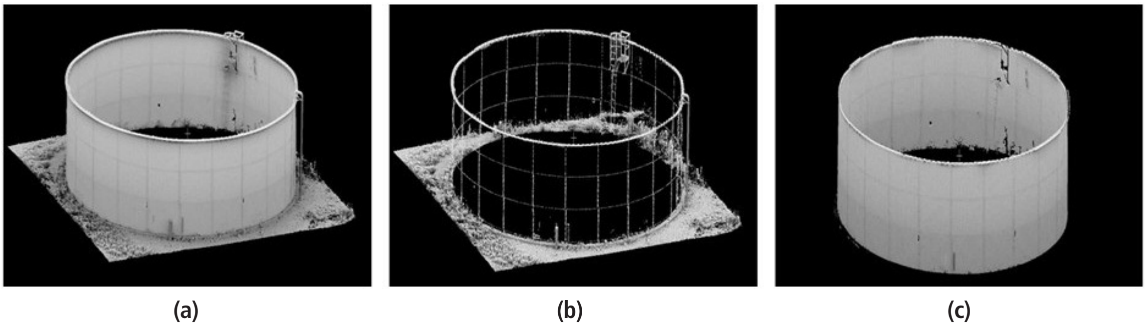

Fig. 7. Tank-2 cylinder extraction. (a) Complete point cloud. (b) Non-cylinder point cloud. (c) Cylinder point cloud.

were established empirically, following several experimental iterations and fine-tuning. Fig. 7(a) shows an example of a Tank-2 complete point cloud dataset. Figs. 7(b, c) illustrate the resultant non-cylinder and cylinder point cloud of Tank-2 after applying RANSAC, DBSCAN, and SOR.

Afterward, a voxel thinning process was applied to the point cloud data to reduce its density. The voxel size was set to 1 cm, which facilitated the subsequent processes of data extraction and geometric assessment by reducing the computational load, without compromising the tank structure details. Finally, thinner and more manageable point cloud slices were extracted for a precise geometric assessment of the tank structure. The extraction of horizontal sections was based on consistent intervals along the tank height, and vertical sections were extracted at specific angular intervals around the tank center.

2.5. Geometric Assessment Method

The roundness assessment is based on the radii deviation, which refers to the difference between the measured radius from the observed roundness point on the tank shell to the calculated radius of the best-fit circle. Therefore, Least Squares were used to estimate the best-fit circle for every horizontal section from TS and STLS data. For the assessment of plumbness deviations, a vertical reference line from the tank's lowest point was used to determine the deviation from this line.

2.6. Geometric API Standards

API 653 roundness and plumbness tolerances were applied in this study because our tanks are not new; they are existing tanks. Also, given the different diameters of the two tanks, different roundness tolerances were applied to each tank as per API 653 standards. A tolerance of ± 13 mm for Tank-1, which has a diameter of less than 12 m, and a tolerance of ± 19 mm for Tank-2, whose diameter is bigger than 12 m and less than 45 m (American Petroleum Institute, 2014). On the other hand, a plumbness tolerance of ± 42 mm was used, as per API 653, for both tanks since they share a roughly similar height of 4.24 m.

3. Results

3.1. TS Geometric Assessment

The best-fit circle parameters of the shell courses (horizontal sections) 2 and 3 of each tank are close to those from respective shell course 1. The parameters for Tank-1 and Tank-2, detailed in Table 3, show small variations in circle centers and radii, the variations are in millimeters for each tank.

Fig. 8 illustrates the Tank-1 roundness assessment of the deviations in the three shell courses from their best-fit circles. The tolerance limit is ± 13 mm based on the tank's diameter as explained earlier. Shell course 2 exhibits the highest compliance, with 87.80% of its observations within the tolerance, followed by shell course 1 with 70.73%, and shell course 3 with the least, at 51.22%. Similarly, Fig. 9 depicts Tank-2 roundness assessment of the deviations in the three shell courses from their best-fit circles. The tolerance limit is ± 19 mm based on the tank's diameter. Shell course 1 has 91.43% of the observations within the acceptable

Table 3. Best fit circle deltas from shell course 1

Shell Course	Tank-1		Tank-2	
	Center Distance	Radii Difference	Center Distance	Radii Difference
Shell Course 2	1 mm	1 mm	1 mm	1 mm
Shell Course 3	3 mm	5 mm	3 mm	5 mm

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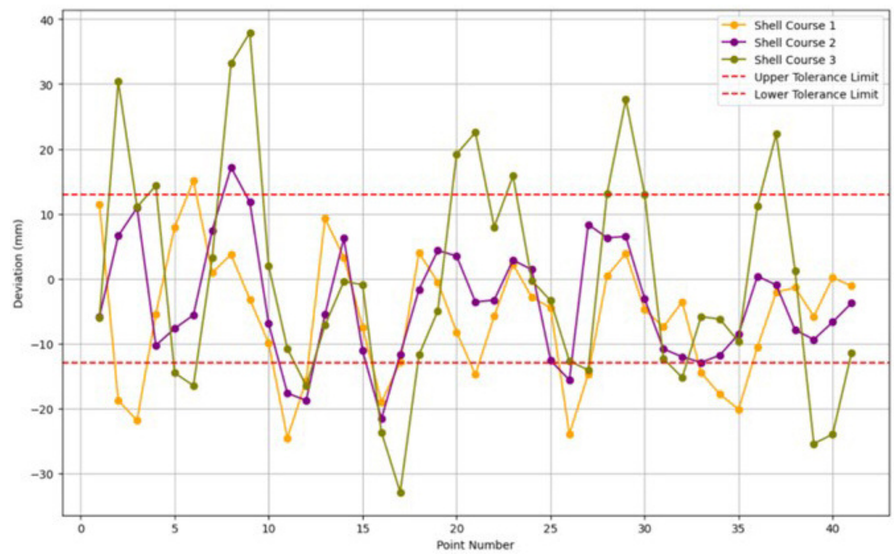


Fig. 8. Tank-1 TS roundness deviation, tolerance: ± 13 mm.

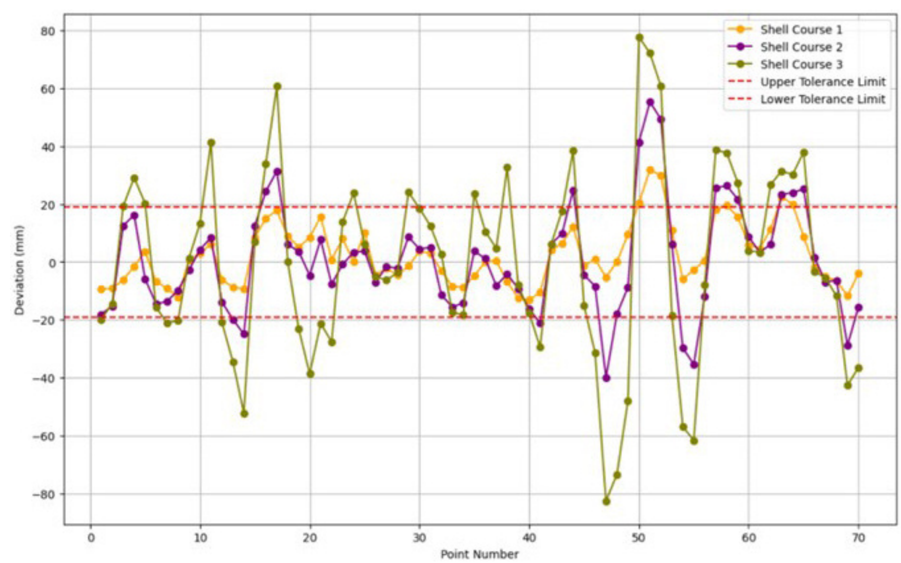


Fig. 9. Tank-2 TS roundness deviation, tolerance: ± 19 mm.

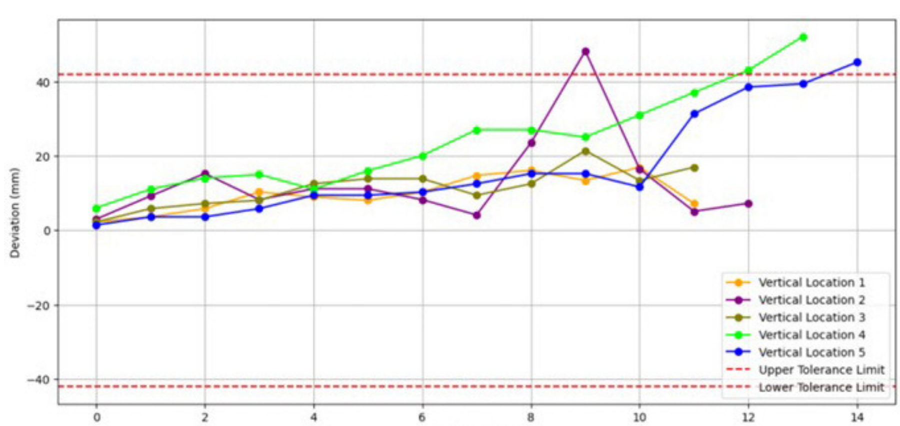


Fig. 10. Tank-1 TS plumbness deviation, tolerance: ± 42 mm.

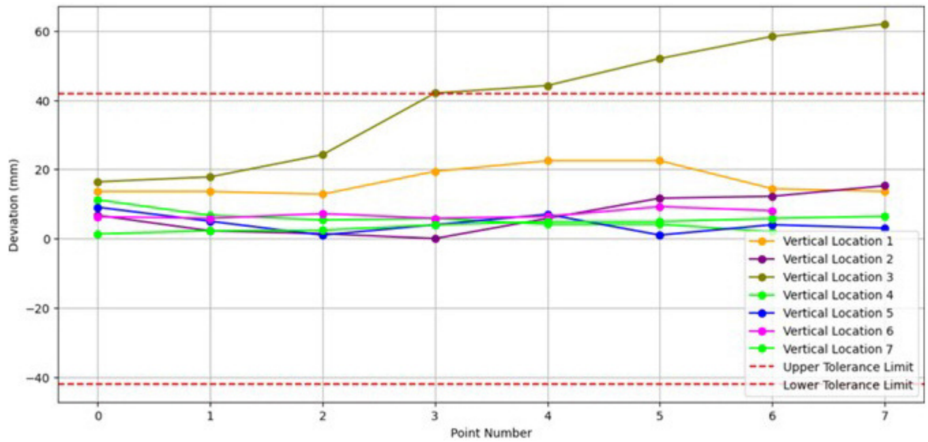


Fig. 11. Tank-2 TS plumbness deviation, tolerance: ± 42 mm.

tolerance range. Moving upward, shell course 2 displays a lower compliance of 72.86%. However, shell course 3 deviates from this pattern more dramatically with a low percentage of 42.86%.

Figs. 10 and 11 present the plumbness assessment of Tank-1 and Tank-2, respectively. The deviations are from the designated vertical reference line at each vertical position. The tolerance limit is set at ± 42 mm, as per API 653 standards. The Point numbers shown in the figures are arranged from the bottom to the top of the tank, corresponding to increasing elevation levels starting from 0 near the base and moving upwards. Particularly for Tank-1, additional measurements were deemed necessary based on preliminary visual inspections. These inspections suggested the presence of deviations near the top of the tank's shell structure, specifically at shell course 3, prompting more detailed observations. This is why there are more plumbness points in Tank-1 than in Tank-2. Overall, the plumbness conditions of both tanks are satisfactory, with a few observations being outside the acceptable tolerance range. Most of the vertical locations' deviations fall within the range of 20 mm.

3.2. STLS and TS Corresponding Observations Assessment

The purpose of extracting STLS points that correspond to TS points is to compare the closeness of STLS geometric assessment results to those of the TS assessment. TS points were utilized to extract their georeferenced STLS nearest neighboring points. It has been found that the majority of the extracted corresponding points between STLS and TS points are within a distance of 10 mm with a mean equal to 7 mm and a standard deviation equal to 5 mm.

STLS extracted points were utilized to estimate the best-fit circle parameters for the three shell courses of each tank, and then

Table 4. Best fit circle parameters STLS vs. TS of Tank-1

Shell Course	Circle Center	Radius
Shell Course 1	1 mm	−4 mm
Shell Course 2	2 mm	−3 mm
Shell Course 3	2 mm	−3 mm

Table 5. Best fit circle parameters STLS vs. TS of Tank-2

Shell Course	Circle Center	Radius
Shell Course 1	1 mm	−4 mm
Shell Course 2	1 mm	−6 mm
Shell Course 3	1 mm	−3 mm

these parameters were compared against the TS best fit circle parameters. Tables 4 and 5 present a comparison of the best fit circle parameters between STLS and TS points for the two tanks. For Tank-1, the circle center points differences are within 2 mm, while the radii exhibit a slight variation, with differences ranging from −3 to −4 mm. Tank-2 shows a uniform deviation of 1 millimeter for the circle center points, but a more varied difference in the radii, ranging from −3 to −6 mm. These small discrepancies indicate that the estimated best-fit circle parameters of STLS and TS data are almost the same.

Given the stringent roundness tolerances of ± 13 mm for Tank-1 and ± 19 mm for Tank-2, compared to the ± 42 mm tolerance for plumbness for both tanks, the roundness deviations between the TS and STLS observations were evaluated to find how closely STLS observations are aligned with TS observations.

Tables 6 and 7 summarize the differences in roundness deviation between STLS and TS observations for the two tanks. For Tank-1, the maximum deviation difference observed is 14.67 mm, and there is only one point where the deviation difference

Table 6. Comparative deviation analysis of STLS and TS roundness deviations for Tank-1

Shell Course	Max. Value (mm)	Min. Value (mm)	Points > 10 mm	Points < –10 mm
Shell Course 1	9.83	–9.98	0	0
Shell Course 2	8	–7.60	0	0
Shell Course 3	14.67	–7.41	1	0

Table 7. Comparative deviation analysis of STLS and TS roundness deviations for Tank-2

Shell Course	Max. Value (mm)	Min. Value (mm)	Points > 10 mm	Points < –10 mm
Shell Course 1	6.8	–12.73	0	5
Shell Course 2	8.18	–11.01	0	2
Shell Course 3	23.52	–10.17	5	1

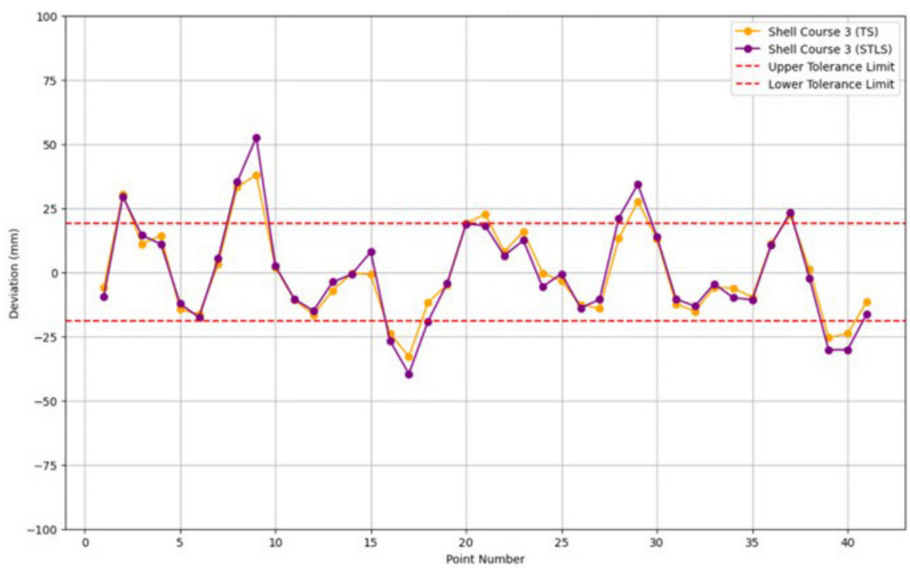


Fig. 12. Visual comparison of deviation in shell course 3 of Tank-1: STLS versus TS roundness deviations.

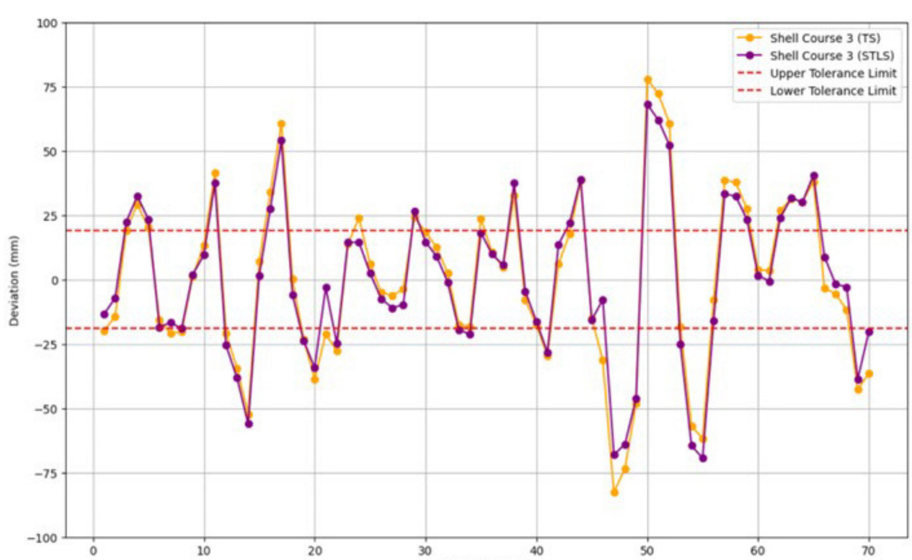


Fig. 13. Visual comparison of deviation in shell course 3 of Tank-2: STLS versus TS roundness deviations.

exceeds 10 mm in shell course 3. In Tank-2, the maximum deviation difference is 23.52 mm in shell course 3, with a few points—five exceeding 10 mm and eight falling below –10 mm. Overall, STLS roundness deviation of both tanks closely mirrors the roundness deviation patterns from TS data, with minor variations predominantly within the 10 mm range. Figs. 12 and 13 are examples of the highest deviations found at shell course 3 of Tank-1 and Tank-2.

Tank-1 exhibits a marginally more consistent alignment, which could be attributed to slightly precise registration and a slightly better georeferencing RMSE compared to Tank-2. Additionally, the number of scans may be a contributing factor, as Tank-2 consists of 9 scans, whereas Tank-1 comprises only 5.

3.3. STLS and TS Corresponding Observations Assessment

Given the STLS data's demonstrated accuracy in line with TS data for assessing the geometric structure of both tanks, it's feasible to proceed with more detailed analyses, such as horizontal and vertical section extraction. By sectioning the point cloud into thin, regular slices, we can conduct a precise and more continuous geometric assessment of the tank structure. In this study, the horizontal sections were extracted at consistent height intervals, and vertical sections were extracted at specified angular intervals around the tank's central axis. Fig. 14 illustrates an example of the extracted sections from the full point cloud of the Tank-2 cylinder point cloud. The horizontal sections were extracted at every 50 cm and the vertical sections were extracted at every 50 degrees.

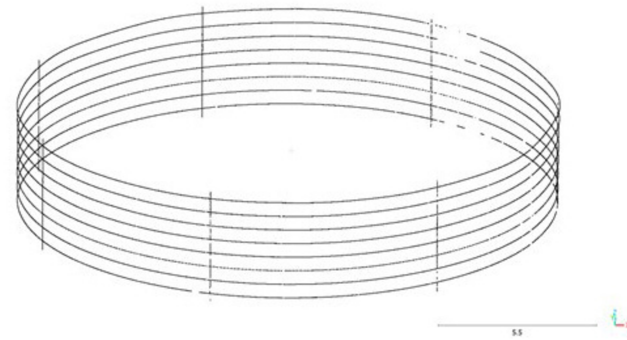
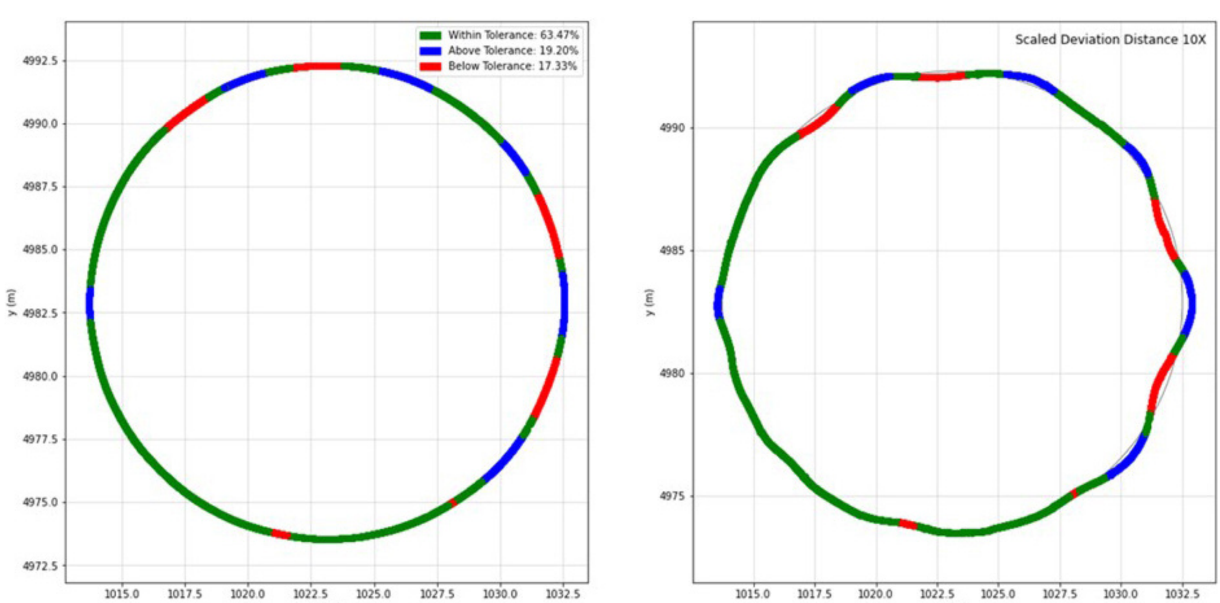


Fig. 14. Extracted horizontal and vertical sections from Tank-2 cylinder point cloud.

After that, a best-fit circle estimation was conducted for every horizontal section to assess their roundness deviations, plumbness was evaluated by measuring the deviation of vertical sections from the vertical reference line, established from the cylinder's lowest points. This method mirrors the geometric assessment techniques applied to TS data. The forthcoming figures (Figs. 15 and 16) exemplify the roundness and verticality assessment with scaled/exaggerated deviation, offering a glimpse into the comprehensive evaluation of the extracted sections.



(a) (b)

Fig. 15. Roundness deviations at horizontal section 3, 1.5 m above Tank-2 base. (a) True scale deviations. (b) Scaled deviations by 10X.

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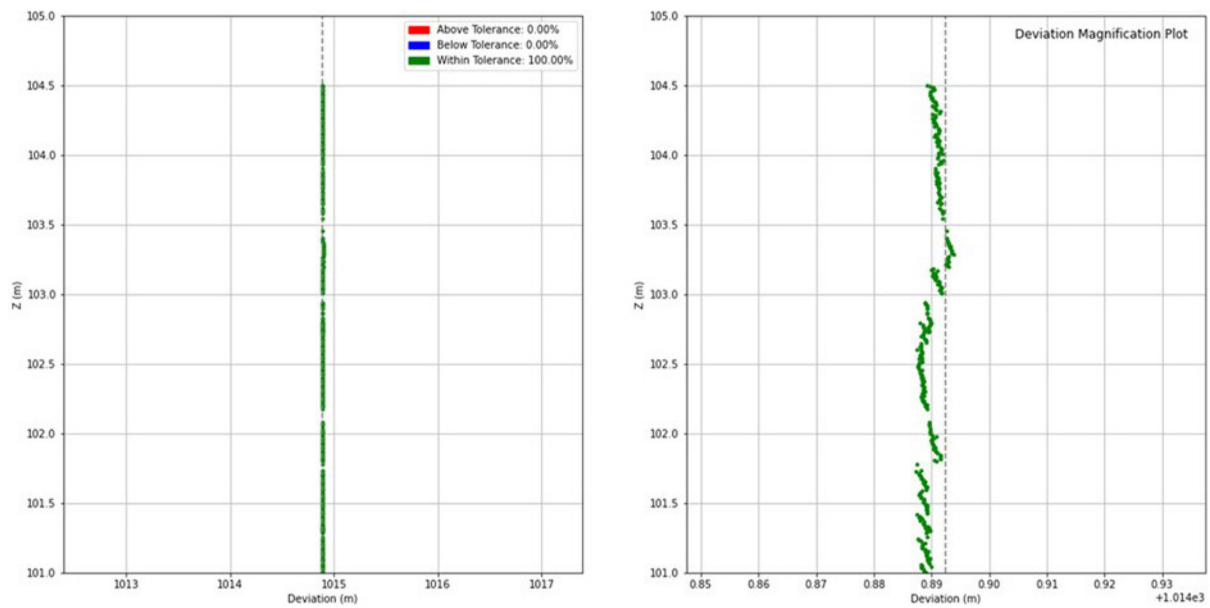

Fig. 16. Plumbness deviations at angle 150° for Tank-2. (a) True scale deviations. (b) Magnified deviations plot.

4. Discussion

The roundness assessment results from the STLS deviate by less than 10 mm when compared to those from the TS, demonstrating a successful georeferencing process and confirming the high level of accuracy achievable with STLS. While Tank-2 shows a minor increase in deviation, this is still within acceptable bounds, especially when considering its georeferencing RMSE is 2 mm greater than that of Tank-1. Additionally, the four more scans of Tank-2 compared to Tank-1 could contribute to this slight deviation due to the possibility of error accumulation throughout the registration process.

The full point cloud roundness assessment based on the extracted horizontal sections reveals that the deviations increase from the bottom to the top of the tank structure because the structure is more robust near the tank base. This confirms API's expected assessment. Typically, in storage tank design, the most robust shell course is at the bottom—shell course 1—due to its attachment to the foundation and its higher shell thickness (American Petroleum Institute, 2014).

According to the findings of this study, STLS can be an optimal solution for the geometric assessment of storage vertical cylindrical tanks, offering data that is both dense and relatively as accurate as that obtained from the traditional TS method. Although it requires more amount time for data processing, approximately three times the duration spent in the field based on this study. However, with the established methods in this study, data processing can be streamlined, and less time can be achieved when processing the point cloud. In addition, the study showed that the data acquisition time for STLS was considerably less compared to TS. For instance, scanning the entire surface of Tank-1 with STLS took approximately 45 minutes, while the same task using TS required over four hours due to the need for multiple setups and manual measurements.

Furthermore, the labor involved in the TS method is more intensive, requiring a skilled surveyor to operate the equipment and record the measurements accurately. This method involves meticulous setup procedures, including the establishment of backsight and foresight points, and manual data collection at each station setup. STLS, on the other hand, can be operated with less specialized labor. The process is faster in data collection, as it automates the scanning measurement, significantly reducing the time and complexity compared to the manual setup and measurement steps required in the TS method.

Another significant advantage of STLS is its flexibility in adjusting the spacing of sections. Unlike TS, where the spacing of sections for measurements is fixed and determined by the physical setup of the equipment, STLS allows for dynamic adjustment of section spacing during data processing as needed when processing the data. This capability enables the creation of very detailed reports, such as measurements every 5 cm or more frequent measurements in areas where surface deviations are

Table 8. Comparison of efficiency and operational characteristics between TS and STLS

Aspect		Total Station (TS)	Static Terrestrial Laser Scanning (STLS)
Data Acquisition Time	Tank-1 (Height: 4.3 m, Diameter: 8.5 m)	~4 hr	~45 min
	Tank-2 (Height: 4.3 m, Diameter: 18.8 m)	~5 hr	~60 min
Number of Operators		2 Skilled surveyors	1 Operator (Less specialized)
Manual Measurements		Required	Not required
Flexibility in Section Spacing		Fixed	Adjustable; very detailed (e.g., every 5 cm) or more frequent in areas with deviations
Error Potential		Higher (Human error)	Lower (Automated process)

more prominent. Such detailed and customized sectioning ensures a comprehensive understanding of the tank's geometric integrity.

Moreover, the process from data acquisition to processing and analysis can be fully automated with appropriate processing workflow. This reduces human error and increases the overall efficiency and reliability of the assessment. The automated nature of STLS also allows for more frequent inspections, ensuring that any deformations or issues are detected and addressed promptly, thus enhancing the safety and maintenance of storage tanks. Table 8. tabulates the comparative efficiency and operational characteristics between the TS and STLS methods for geometric assessments of cylindrical storage tanks.

Overall, for internal tank data collection, we think STLS is highly recommended as it can assess roundness, verticality, and tank floor settlement efficiently from potentially a single setup without the need for an extensive registration process. This approach can significantly enhance accuracy by minimizing error propagation associated with scan registration. For external tank surveys, similar to the survey of this study, we think STLS is effective for roundness and verticality assessments, particularly for large-diameter tanks where long-range STLS can capture more details of the tank structure from one scan position.

Some scanners offer survey-style scanning that allows for the creation of a relative coordinate system directly in the field (e.g., resection survey method) thereby eliminating the time-consuming tasks of target placement and scan registration. However, we think STLS may not be the most efficient method for evaluating external settlement of tank concrete foundations. The method's precision could be compromised by the laser's incident angle at ground-level scans. Additionally, the extensive foundation might necessitate multiple scanner setups due to the proximity required for comprehensive coverage, increasing the complexity of ensuring no critical areas are overlooked.

5. Conclusions

The study thoroughly investigated the geometric integrity of vertical cylindrical storage tanks by comparing the capabilities of STLS against the industry standard TS method. The study focused on roundness and verticality assessments as per API standards to ensure structural integrity, which is crucial for the safety, environmental protection, and efficiency of storage tanks in the oil and gas industry. The study noted that deviations tend to increase from the bottom to the top of the tank.

Also, the study found that the results obtained from STLS were nearly equivalent to those from TS measurements, despite the inherent uncertainties associated with STLS equipment, the registration process, georeferencing process, and point cloud data such as dealing with outliers and tuning segmentation parameters. The study concluded that STLS provides a detailed and efficient approach for the geometric assessment of tanks. It offers high-density data and proves to be relatively as accurate as TS. The established methods and the streamlined data processing could lead to a more efficient workflow in future applications, with STLS showing potential for both internal and external survey tank assessments.

Looking ahead, the methodologies adopted in this project pave the way for broader applications, including internal tank assessments. This could be particularly useful for the assessment of other structural components, such as tank roofs. Moreover, STLS offers a promising alternative for evaluating tank settlement issues, providing results that could match data obtained from digital leveling instruments. As the industry moves towards more technologically integrated assessment methods, STLS stands out as a valuable tool for both current and future applications in the geometric analysis of storage tanks.

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Conflict of Interest

No potential conflict of interest relevant to this article was reported.

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