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Robotic In-Service Tank Bottom Differential Elevation Survey

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Overview

Today's Aboveground Storage Tank (AST) owners face the ongoing need to monitor settlement of their site's tank bottoms in order to maintain superior operational integrity. Various tank foundation constructions are used in different geographical regions affecting settlement. However tank facilities are bound to experience settlement, may it be from soil erosion or the presence of moisture, so it is of the utmost importance to accurately locate and quantify the severity of the settlement before it becomes excessive. But what if tank owners could obtain all the required inspection results without taking the tank out-of-service and avoiding major disruption to operations? This paper describes Square Robot's submerged inspection robot and the pressure sensor method it uses to measure tank bottom elevation resulting in an accurate Differential Elevation Map of an In-Service AST. Included in this paper are details about how the depth is acquired and coupled with the robot's positional data then displayed with differential elevation plots and comprehensive tank bottom settlement evaluations in accordance with API 653. This process will be shown using a dataset from one of Square Robot's recent tank bottom inspections for a customer who approached Square Robot after observing severe inward distortion of the tank shell and suspected settlement to be present.

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Introduction to Tank Integrity

The best way to ensure longevity of Aboveground Storage Tank service life is dependent on quality control of its initial construction as well as the effectiveness of periodic inspections. *API Standard 653 Tank Inspection, Repair, Alteration, and Reconstruction* describes in detail the minimum requirements for upkeep and maintenance of an AST. These tank evaluations include items such as nozzle assessments, shell out-of-plane settlement, edge settlement, bottom settlement, and minimum remaining thickness (MRT) measurements. Square Robot's SR-1 Inspection Robot is capable of simultaneously running multiple survey types. This paper will highlight one of its many capabilities, elevation measurements, and focus on settlement evaluations.

Figure 1 - SR-1 Inspection Robot being Hoisted to Tank Roof

To date, manual tank bottom settlement surveys that include internal elevation measurements require taking the tank out-of-service (OOS). Preparing an above-ground storage tank for internal inspection by humans requires the tank to be drained, opened, and cleaned, as well as have its waste processed. All of these common tasks lead to operational downtime. Due to the time consuming, costly, and highly disruptive nature of out-of-service inspections there is an undeniable advantage to keeping a tank on-line and gathering data with the product still in the tank. Nevertheless, it is imperative that these bottom inspections are thoroughly completed to ensure the integrity of an AST. Through automation, settlement monitoring can be safer, faster, and cheaper.

Settlement Monitoring

Ideally a settlement monitoring program begins during construction and continues during hydrostatic testing and throughout operations. Settlement is generally caused by soil moving and creating voids which can not support the combined load of the tank bottom, shell, roof and product. Initial foundation construction emphasizes the importance of soil condition and consolidation to prevent foundation settlement. However, factors like extreme weather changes, proximity of vegetation or traffic vibrations can still affect a well constructed tank. In all scenarios it is important to monitor bottom settlement because if conditions are deemed unacceptable and releveling is required, it's best to catch it when localized repair techniques can be utilized as opposed to total lifting.[1] Square Robot's robotic surveys consistently identify when a tank owner must take action as well as provide a high concentration of elevation data, usable for further rigorous structural analyses.

[1] API Standard 653: Tank Inspection, Repair, Alteration, and Reconstruction (5th Ed, Nov 2014), B.1.3

Commonly Used Tank Bottom Settlement Surveys

Three commonly used OOS tank bottom settlement surveys, listed below, have been identified as industry areas for improvement by using an autonomous inspection robot to accurately measure the tank bottom elevation while keeping the tank asset in-service.

Measurement of Shell Settlement at Edge Projection
- Often taken using a tape measure and laser level shot off the edge projection, using a rolling wheel to measure the circumferential distance to the next elevation point.

Measurement of Bottom Settlement
- 3D Laser Scanners collect tank bottom height data which can be compared to a horizontal datum to determine the differences in bottom elevation.

Measurement of Edge settlement
- A straight edge is placed on the unsettled tank bottom and the height from the breakover point to where the shell meets the bottom is measured by hand.

Robotic In-Service Tank Bottom Differential Elevation Survey

Tank Bottom Survey data can be provided to refinery and terminal operators for failure prediction without disruption of service. This can be accomplished by leveraging the automated navigation system of Square Robot's robotic inspection platform which collects datasets superior to what a human could achieve.

Inspection Tool Overview

Square Robot designs, manufactures, tests, and certifies autonomous robotic solutions for harsh environments. Square Robot's Houston based office along with its industry experts, provide the go-to-market inspection services utilizing these robots. The SR-1 Inspection Robot measures the tank bottom and annular plate thickness of Aboveground Storage Tanks (AST) filled with water, diesel, distillate, or similar refined products. Inspections are accomplished through the usage of three primary payload technologies — PAUT, PEC, and visual. The robot is designed for Class 1, Division 2, Group D Hazardous Locations and the robot's Non-Destructive Testing (NDT) data has been qualified in accordance with API 653 standards. Simultaneously while performing NDT surveys, bottom elevation data is collected via the inspection robot's onboard pressure sensor. This paper's following section, In-Service Tank Bottom Differential Elevation Methodology, details the procedure about how this pressure data is acquired and evaluated.

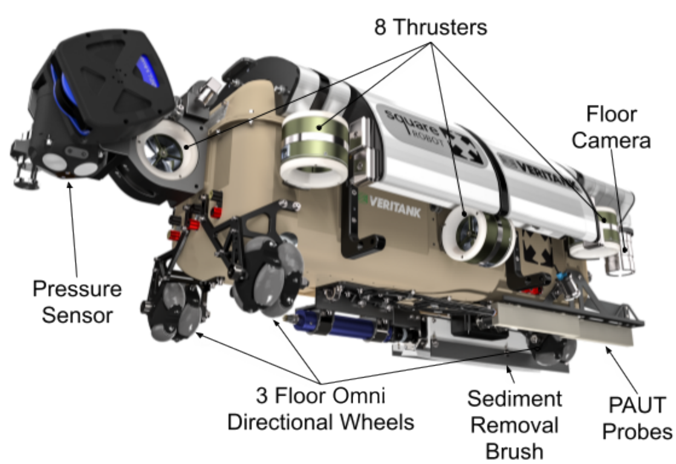

Figure 2 - ISO View of SR-1 Inspection Robot

Certifications

The SR-1 Inspection Robot is certified for use in Class I, Division 2, Group D, T6, or unclassified locations by FM Approvals. All model variants, including a robot equipped with a PAUT NDT payload, are independently certified and approved by FM Approvals for continued HazLoc conformance. FM Approvals is an international third party testing and certification agency recognized by ANSI and ATEX.

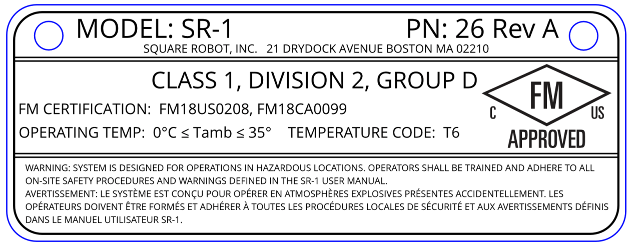

Figure 3 - SR-1 Inspection Robot FM Approvals Label

In-Service Tank Bottom Differential Elevation Methodology

Concept of Operations

The SR-1 Inspection Robot's pitch and roll are trimmed level in the robot's horizontal orientation for its fully submerged environment and it is ballasted to be approximately 10lb negatively buoyant in the tank product. Therefore, the robot naturally sinks to the bottom of the tank under its own weight when deployed through a 24in minimum diameter roof manway/inspection hatch and contacts the bottom via 3 omnidirectional wheels mounted beneath its body. Thrusters are used to propel the robot through the fluid in any direction, while the wheels remain in contact with the bottom.

Depth Data Acquisition

The tank product density (ρ) is used via Pascal's law to determine the change in height within the fluid column based on the change in hydrostatic pressure (P) at each measurement. The pressure sensor, located in the robot's speed sensor (Doppler Velocity Log or DVL), maintains a constant distance to the bottom (see H_{ps} in Figure 4) and measures pressure as the robot moves around in the tank. Pressure is converted to depth (h), the distance from the surface of the fluid product to the pressure sensor, based on $P = \rho g h$ (*Eq 1*). Ideally the product fluid level remains constant for the duration of the differential elevation survey because the depth profile, measured by the pressure sensor, is offset from the tank bottom profile by a fixed distance. If the tank requiring inspection can not maintain a constant product surface height it is possible to alternatively record the product surface height and time throughout the survey, then adjust the depth data accordingly.

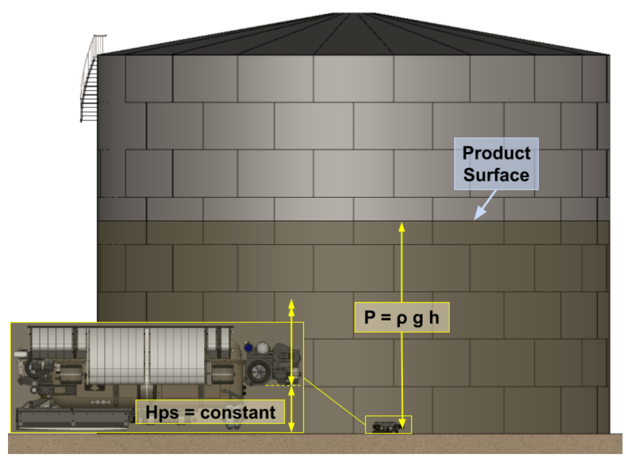

Figure 4 - SR-1 Inspection Robot in an AST

Virtual Reference Point for Depth Measurements

The SR-1 Inspection Robot uses a Depth Reference Point at the intersection of the three below robot planes as shown in Figure 5.

- Bottom Roller Horizontal Contact Plane
- Shell Roller Vertical Plane
- Port/Starboard Center Plane

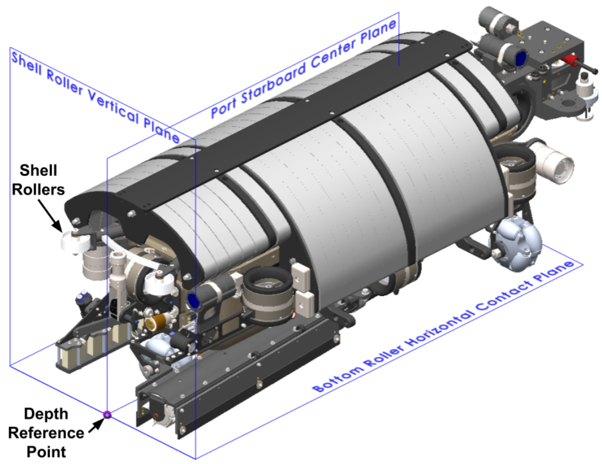

Figure 5 - Depth Reference Point Location

This new reference point allows elevations to be determined directly up against the tank shell. This approach is used because when collecting elevation or NDT data in the critical zone the aft end of the robot faces towards the shell. During these annular plate surveys the robot backs up against the shell and traverses sideways along the inner circumference maintaining contact with the tank shell via the shell rollers. Since the pressure sensor is located at the forward end of the robot, if it's position is used then depths cannot be determined any closer than 4ft from the shell, the distance between the aft end shell rollers and the pressure sensor itself. However, the robot being a rigid body, the lever arm between the pressure sensor and any point on the robot, as well as the robot's attitude (heading, pitch, and roll) are used together to compute the depth at any point.

Robot's Trajectory

The robot is programmed to execute a set of parallel lawnmower tracklines spaced by a configurable distance in order to cover as much of the tank bottom as possible. Internal tank obstacles such as piping, sumps, columns may reduce access to some areas of the bottom. A second lawnmower survey is then run at the same spacing but perpendicularly to the first survey. Finally, the robot is programmed to contact the shell via small rollers located on the robots aft end and move sideways along the inner circumference of the shell to collect additional depth data. All three aforementioned survey paths can be seen in Figure 6 using a dataset from Square Robot's recent tank bottom inspection of a 135 ft Diameter Tank, which will be referred to as Tank 001 throughout this paper.

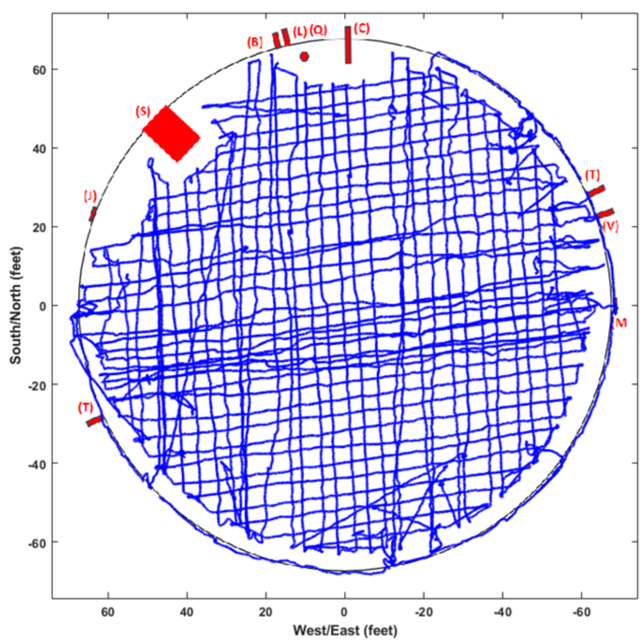

Figure 6 - Depth Reference Point Path During Data Acquisition of Tank 001 (135 ft Dia)

Elevation Datum

The datum for which differential elevations are reported against is defined as the horizontal plane going through the lowest point in the (north, east, depth) data acquired during the survey. Positive elevations indicate locations at higher altitude than the datum.

Data Post-Processing Procedure

1. If needed, the real-time estimate of the pressure sensor position during the survey is post-processed to improve the positioning of the pressure measurements.
2. Pressure measurements are corrected to account for changes in atmospheric pressure using barometric pressure readings taken throughout the tank inspection.
3. For any pressure sensor measurements being sampled at a different time than the inspection robot's position, the robot's position is interpolated at the time of the pressure measurement based on its trackline trajectory.
4. A forward-backward zero-phase filter is applied to the pressure measurements to reduce sensor noise.
5. Depth is calculated from the pressure measurements based on product density.
6. The maximum depth value is also the lowest elevation (0) and used as the reference datum to compute the remainder of the tank bottom differential elevations.
7. A plot showing color-coded differential elevations along the Depth Reference Point's path is created, see Figure 7. Note that deeper areas (lower tank bottom elevations) appear as blue. The shallower areas (higher tank bottom elevations) appear as red.
8. A contour plot is created by resampling the irregularly sampled position data on a grid with fixed spacing of ¼in, see Figure 8.
9. The position, raw differential elevation, and filtered differential elevation data are also provided in a spreadsheet along with the survey report to the customer.

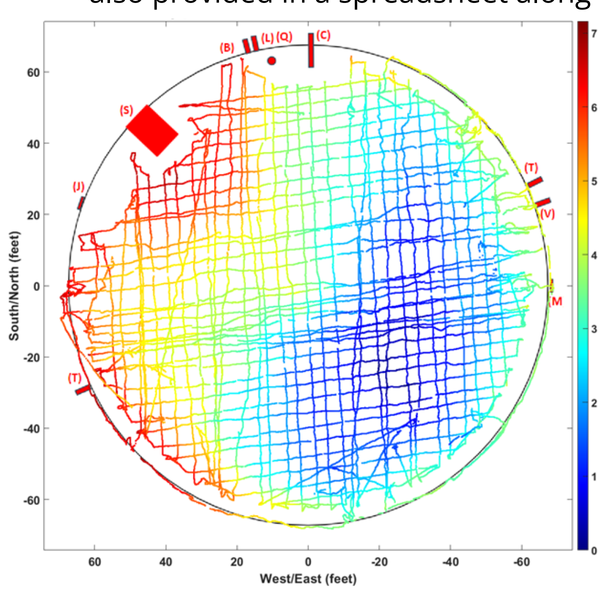

Figure 7 - 2D Scatter Plot of Differential Elevations [in] at Depth Reference Point

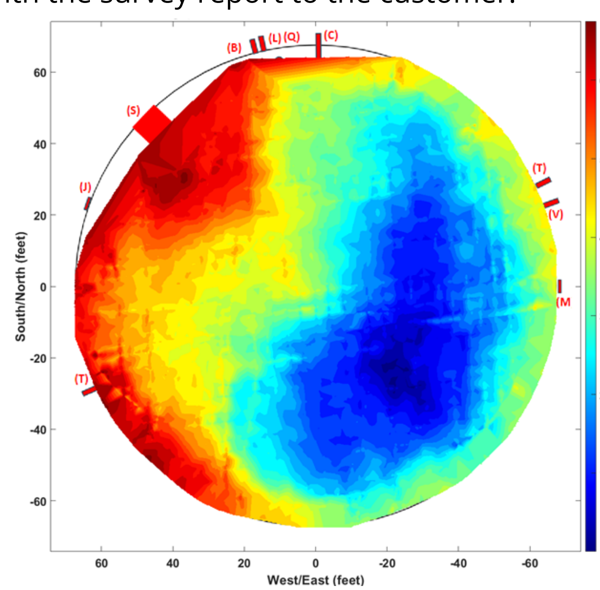

Figure 8 - Contour Plot of Differential Elevation [in]

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API 653 Evaluations of Tank Bottom Settlement

Shell Settlement

Rather than taking measurements around the exterior circumference of the shell, the elevation measurements the robot has taken along the interior of the 135 ft diameter shell can be used to determine shell settlement. The tank elevation measurements have been filtered to only include points directly up against the tank shell and 1.5ft inwards radially from the shell, as depicted in the point plot of Figure 9. The arcs along the shell without elevation measurements indicate the presence of internal tank obstacles that the robot was required to avoid. Square Robot is continually improving inspection algorithms to maximize floor coverage and reduce gaps near internal obstacles to get as many elevation measurements up against the shell for improved shell and edge settlement evaluations.

The measured elevations of these radially filtered positions along with an optimum cosine curve per API 653 in the form of Equation 2 have been plotted in Figure 10 based on their bearing position relative to 0° North with a positive clockwise rotation. A computer using Levenberg-Marquardt Optimization provided the equation constants *a*, *b*, and *c* to ensure a best-fit cosine curve resulting in an R^2 value of 0.847, according to Equation 3.

$$Elev_{pred} = a + b * cos(\theta + c) \quad (Eq\ 2)$$

$$R^2 = \frac{S_{yy} - SSE}{S_{yy}} \quad (Eq\ 3)$$ [2]

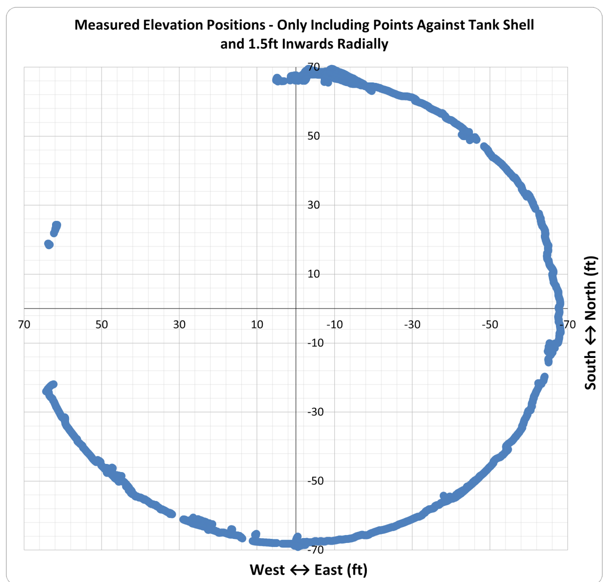

Figure 9 - Radially Filtered Elevations

Since R^2 is not greater than or equal to 0.9 this indicates that the measured data is not defined by a plane of rigid tilt and the measured settlement should be examined in accordance with section B.2.2.5 of API 653, a procedure to determine the permissible out-of-plane settlement. One advantage of using the robot is the high quantity of measurements taken which improves the ability to use these elevation points to determine the optimum cosine curve and evaluate if the tank has experienced rigid body tilt.

Traditionally when taking measurements of the shell settlement during an OOS inspection there must be a maximum spacing of 32ft around the circumference. However additional settlement measurement points may be needed between these points to find where the direction of settlement slope occurs. The inspection robot demonstrates superiority over

[2] API Standard 653: Tank Inspection, Repair, Alteration, and Reconstruction(5th Ed, Nov 2014), B.2.2.4

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OOS hand measurements by avoiding the need for a secondary collection of measurements. The high concentration of elevation measurements along the shell allows the exact points of settlement slope change to easily be determined from the dataset.

After sorting the data by bearing position, the bearings and elevation measurements were averaged in 1.0° increment ranges (ie: 0.0°< X ≤ 1.0°). Slope changes were then identified, disregarding slope changes that would result in arcs lengths less than 20ft. The orange points on Figure 10 indicate the points where the direction of the settlement slope changes. By drawing lines on the graph between the upper settlement slope change points, settlement planes can be established. These planes are then used to determine the maximum out-of-plane settlement. Figure 10 is a graphical illustration including the settlement arcs, S_{arc}, used to evaluate the magnitude of out-of-plane settlement, S, measured from the indicated plane to the lower settlement slope change points.

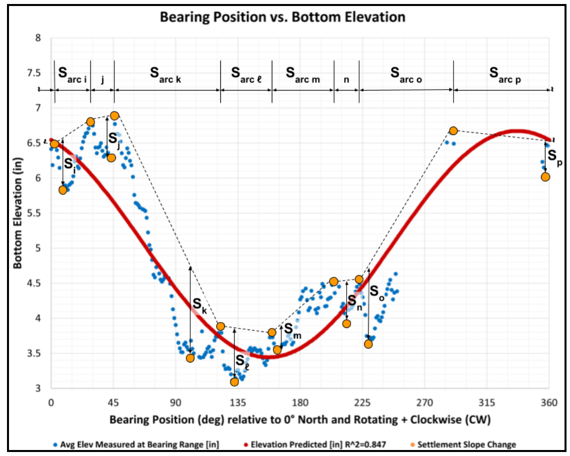

Figure 10 - Graphical Representation of Shell Settlement from Tank 001 per API 653 B.2.2.5

Based on the settlement arc the permissible out-of-plane settlement per API 653[3] is determined by the below Equation 4.

$$S_{max,\,in} = K * S_{arc} * \left(\frac{D}{H}\right) * \left(\frac{Y}{E}\right) \qquad (Eq\ 4)$$

Where:

- $S_{max,in}$ .... is permissible out-of-plane settlement, (in)
- S_{arc} .... is effective settlement arc, (ft)
- D .... is tank diameter, (ft)
- Y .... is yield strength of the shell material, (psi)
- E .... is Young's Modulus, (psi)
- H .... is tank height, (ft).
- K .... is a constant dependent on tank diameter and roof type.

Table 1 - Tank 001 Dimensions and Material Properties

Tank Diameter	135	[ft]
Tank Height	56	[ft]
A36 Steel Yield Strength	36,000	[psi]
A36 Steel Young's Modulus	29,000,000	[psi]
K for a Fixed Roof Tank, 120 < D ≤ 180	2.3	[unitless]

[3]API Standard 653: Tank Inspection, Repair, Alteration, and Reconstruction(5th Ed, Nov 2014), B.3.2.2

Next, the upper settlement slope change points, defined as maximum elevations, are used to define the settlement arc lengths. The settlement values, S, from the established plane are compared to the permissible out of plane settlement, $S_{max,in}$, for the corresponding arc lengths, S_{arc}, and are shown in Table 2. The settlement for 6 out of 8 established arcs exceeds the limits established by Equation 4 which indicates that a more rigorous evaluation should be performed to determine the need for repairs.

Utilizing the above methodology, Tank 001 was found to have shell settlement at the edge projection along *arc ℓ and k* located at Southeast bearings 100.8° and 132.5°, respectively, that notably exceeds the established limit. As briefly stated in the overview of this paper, Square Robot was approached by the owner of Tank 001 who observed severe inward radial shell distortion at approximately a 20° bearing (NE) and minor inward radial shell distortion at approximately 200° bearing (SW). These distortions could potentially be a result of the deepest settlement (lowest elevation) occurring along southeast *arcs ℓ and k*, which exceeds the established shell settlement limit, causing ovalization of the shell and both the northeast and southwest shell arcs to deflect radially inwards.

Table 2 - Settlement Slope Change Points, Settlement Arcs & Out-of-Plane Settlement

Bearing [°]	Elev [in]	Arc	S_{arc} [ft]	S_{max} [in]	S [in] out of plane	Pass or Fail
2.5	6.48					
8.6	5.83	i	30.72	0.21	0.73	Fail
28.5	6.80					
43.3	6.29	j	20.47	0.14	0.58	Fail
45.9	6.88					
100.8	3.44	k	90.22	0.62	1.30	Fail
122.5	3.88					
132.5	3.10	ℓ	43.61	0.30	0.76	Fail
159.5	3.79					
163.5	3.55	m	53.03	0.36	0.31	Pass
204.5	4.52					
213.5	3.92	n	21.34	0.15	0.62	Fail
222.6	4.56					
229.4	3.64	o	80.13	0.55	1.13	Fail
290.6	6.67					
357.2	6.02	p	84.61	0.58	0.47	Pass

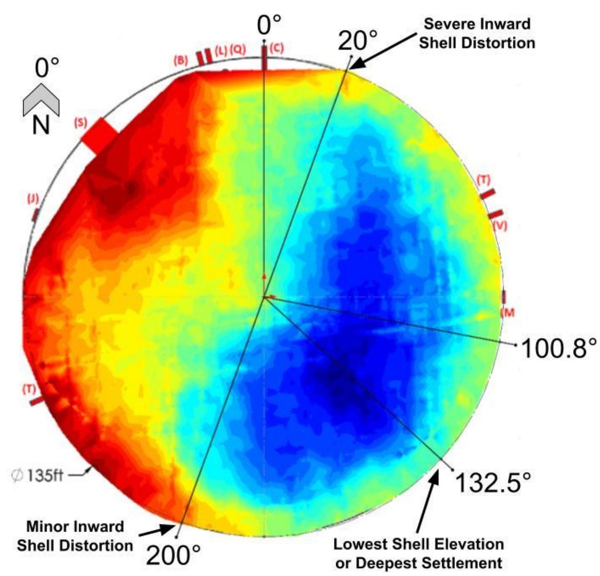

Figure 11 - Contour Plot of Diff Elevation [in] with Shell Distortion Bearings Identified

Internal Bottom Settlement - Depressions and Bulges

Elevation data collected by the SR-1 Inspection Robot covers the free space of each tank with a data concentration high enough to perform thorough identification and assessment of localized internal bottom depressed or bulged areas per API 653 standards. Traditional manual methods for such analysis do not typically consider the tank bottom as a whole, meaning that additional insights can be determined using SR-1 Inspection Robot elevation data. This section contains information about a novel approach used by Square Robot for the detection and classification of internal bottom depressions and bulges per API 653 standards.

First, spurious elevation readings are removed by spatially binning collected data and applying a median filter. Both the median filter kernel size and bin size are determined by tank geometry. This results in a filtered elevation data set such as the one shown in Figure 12 to the right. Next, a Trend Surface, which represents the tank bottom geometry without any areas of anomalous depression or bulging is fit to the filtered data. This 2D polynomial is determined using regression analysis, with the polynomial degree selected to best fit the tank bottom geometry. Table 3 below shows the polynomial degree for various tank bottom geometries.

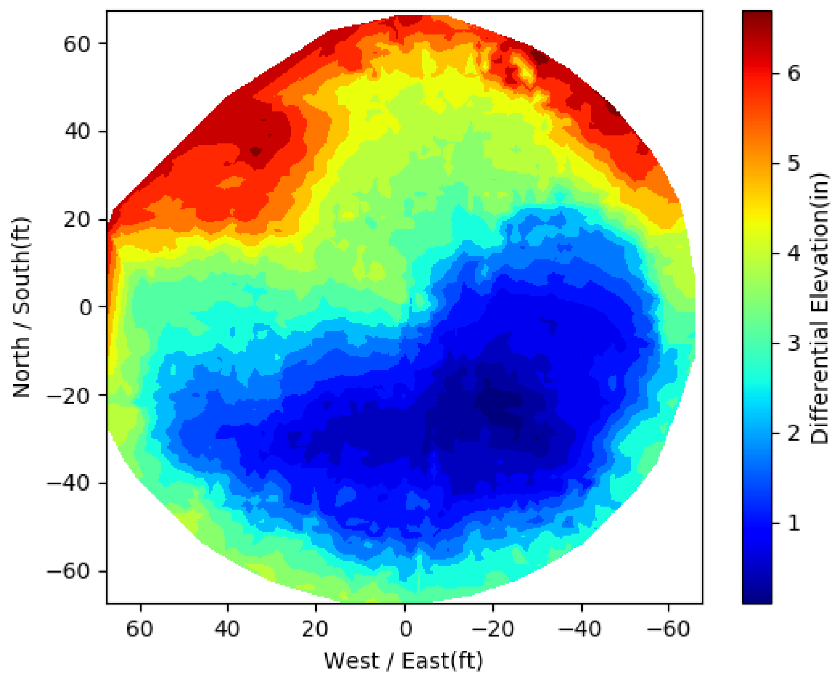

Figure 12 - Median Filtered Elevation Data

Table 3 - Trend Surface Polynomial Degree for Various Tank Bottom Geometries

Tank Bottom Geometry	Degree (n)
Flat	1
Sloped	1
Cone up/down	2
Shovel	3

Figure 13 to the right shows the Trend Surface for the elevation data of Figure 12. A polynomial degree of 3 typical of a shovel bottom was chosen to best represent the current tank bottom geometry, despite the tank bottom being flat, because the trend surface must account for the tilting that the entire tank bottom has experienced due to settlement. For each point in the filtered elevation data, the difference between its elevation $E_{measured}$ and the Trend Surface elevation when evaluated at that point $E_{polyfit}$ is calculated using equation

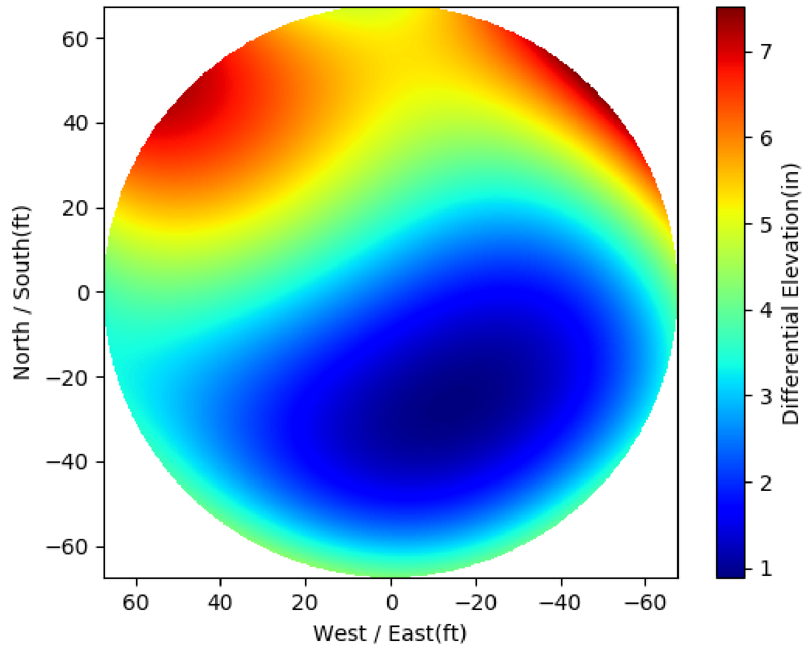

Figure 13 - 3rd Order Polynomial Fit Trend Surface

$$D_{elevation} = E_{measured} - E_{polyfit} \qquad (Eq\ 5).$$

This difference $D_{elevation}$ is the variation between the actual tank bottom elevation and the expected tank bottom elevation, as shown in Equation 5. Distances below a threshold (with value based on tank geometry) are discarded so that they don't pollute the plot of $D_{elevation}$ over the entire filtered elevation dataset. Figure 14 to the right shows the resultant $D_{elevation}$ of depression over the entire tank bottom using the filtered elevation data from Figure 12 and the Trend Surface from Figure 13. These areas of

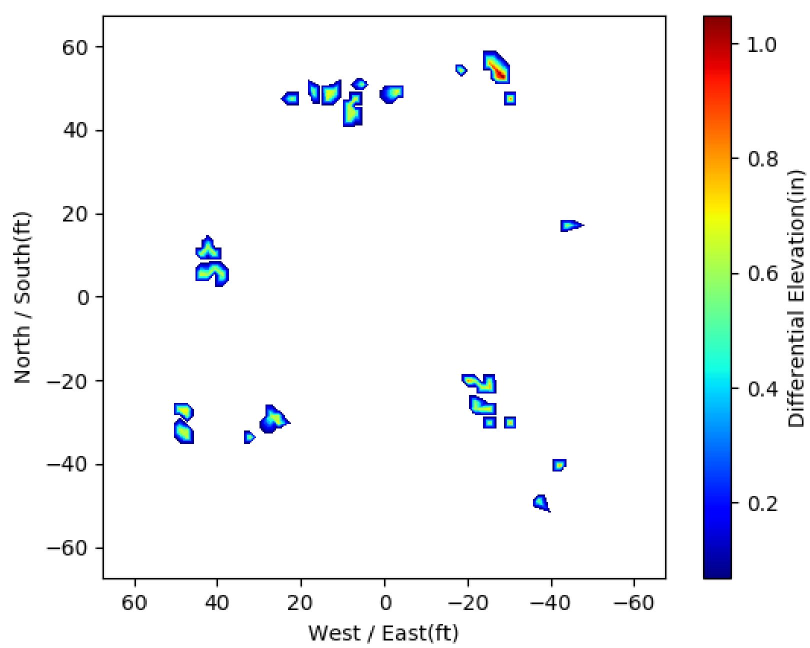

Figure 14 - $D_{elevation}$ of Depression

depression and bulging are then grouped such that points belonging to the same depression or bulge are combined into discrete entities. This is accomplished through thresholding and filtering algorithms. Figure 15 to the right illustrates outlines of the calculated discrete areas of depression for the elevation dataset on the contour map.

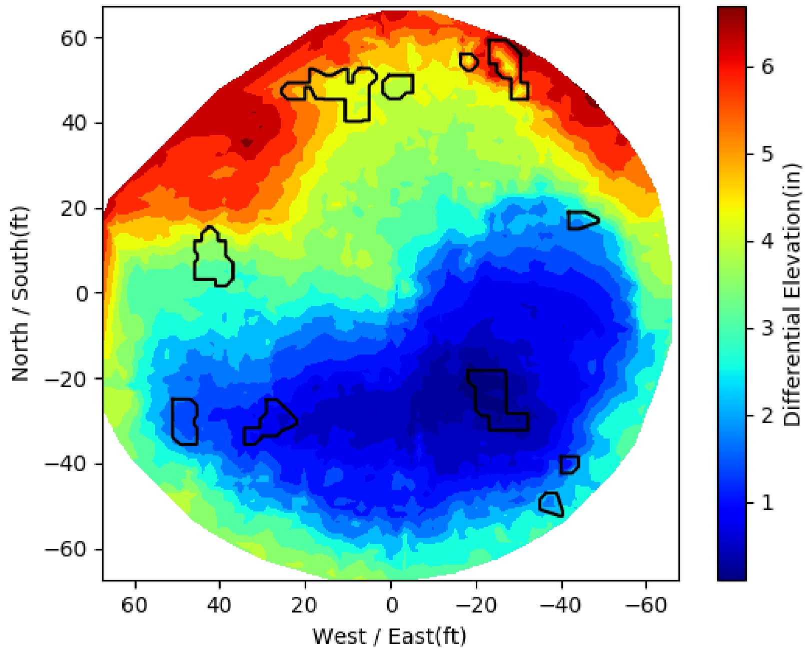

Figure 15 - Distinct Depression Entities

For each of these distinct depressed or bulged areas, an algorithm is used to compute B_B, the maximum permissible local depression depth or bulge height in inches, and R, the radius of the largest inscribed circle within the depressed or bulged area in feet.

$$B_B = 0.37 * R \quad (Eq\ 6)$$

Equation 6 for maximum permissible depression settlement depth or bulge height is applied to each of the grouped depressed and bulged areas to determine whether they are severe enough to warrant more detailed assessment per API 653 B.3.3. Figure 16 graphs Equation 6 to display the localized tank bottom settlement limits as a line.

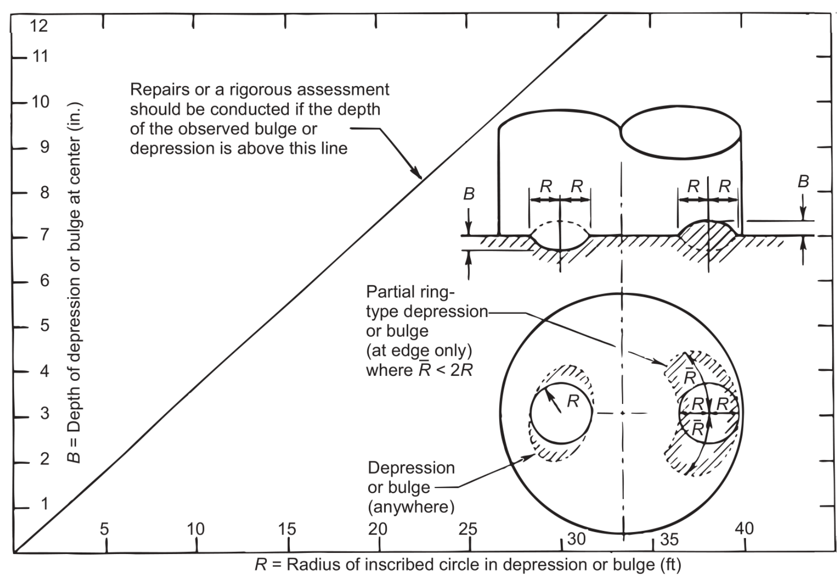

Figure 16 - Bulge and Depression Severity [4]

[4] API Standard 653: Tank Inspection, Repair, Alteration, and Reconstruction(5th Ed, Nov 2014), B.3.3

The diameter of the inscribed circle is then compared to the distance from the inscribed circle's center to the tank shell in order to classify whether anomalous areas are localized bottom settlement remote from the tank shell or if they are bottom settlement near the tank shell. The results of the outlined analysis for depression areas are shown in Table 4.

Table 4 - Tank 001 (135 ft Dia) Depression Area Information

Depression ID	Location [X,Y ft]	Inscribed Radius Max [ft]	Distance to Shell [ft NWU]	API 653 Shell Distance Classification	Differential Elevation [in]	B/R Ratio	API 653 Pass or Fail
0	[37.385, 49.262]	2.29	5.641	Near	-0.894	0.390	F
1	[41.974, 40.355]	2.006	9.256	Remote	-0.990	0.494	F
2	[-26.318, 29.422]	3.054	28.007	Remote	-0.937	0.307	P
3	[-48.183, 27.803]	2.969	11.854	Remote	-0.961	0.324	P
4	[23.619, 21.864]	3.779	35.297	Remote	-0.990	0.262	P
5	[-41.704, -6.748]	3.779	25.236	Remote	-0.937	0.248	P
6	[43.729, -17.006]	2.024	20.564	Remote	-0.917	0.453	F
7	[0.945, -48.318]	2.834	19.156	Remote	-0.961	0.339	P
8	[-7.828, -46.428]	3.084	20.399	Remote	-0.937	0.304	P
9	[18.220, -54.256]	1.816	10.249	Remote	-0.961	0.529	F
10	[27.668 -54.796]	3.054	6.098	Near	-1.068	0.350	P

For Tank 001, 4 of 11 identified depressions and 12 of 16 identified bulges had heights severe enough to exceed the settlement limits defined by API 653. Only 1 of the excessive depressions and 2 of the excessive bulges were classified as near the shell, while all others were classified as localized bottom settlement remote to the shell.

The technique outlined above is effective at identifying and classifying areas of depression or bulging from an elevation dataset gathered in a tank with an unknown initial settlement. For tanks where previous internal settlement data is available, whether manually acquired or acquired autonomously with a robotic inspection system, the previous data can be used in lieu of a Trend Surface. This allows for an even higher degree of accuracy of bottom settlement evaluation. Lastly the localized settlement during these robotic inspections could be higher than an OOS because of the product's head pressure loading the bottom.

Edge Settlement

Except for obstructed areas of the tank where the robot cannot navigate safely, the SR-1 Inspection Robot collects elevation measurements across the entire tank bottom, including the critical zone directly up against the shell. While the robot's shell rollers are in contact with the tank shell, the aft omnidirectional wheels are 7.5in from the shell. This allows the robot to detect settlement of bottom plates near the shell-to-bottom corner junction as shown in Figure 17.

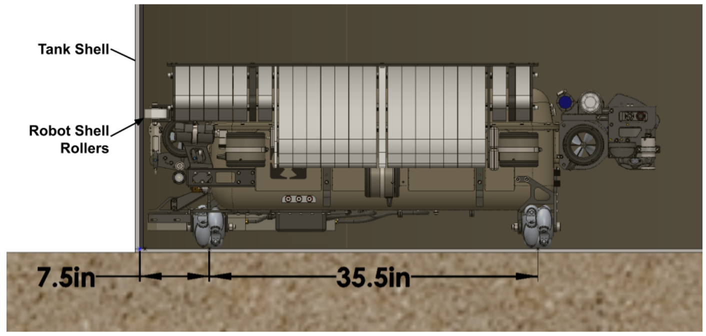

Figure 17 - Robot Wheelbase from Tank Shell during Annular Plate Survey (APS)

API 653 Section 3.4 contains two graphs which are used to determine the maximum allowable edge settlement. One graph is used for tank bottoms with lap welds approximately parallel to the shell and the other for tank bottoms with lap welds approximately perpendicular to the shell. Since Tank 001 has both lap weld geometries, the more conservative parallel weld values for maximum allowable edge settlement B_{ew} were selected to interpolate the allowable settlement limits for a 135 ft diameter tank which has been shown by the red line on Figure 18.

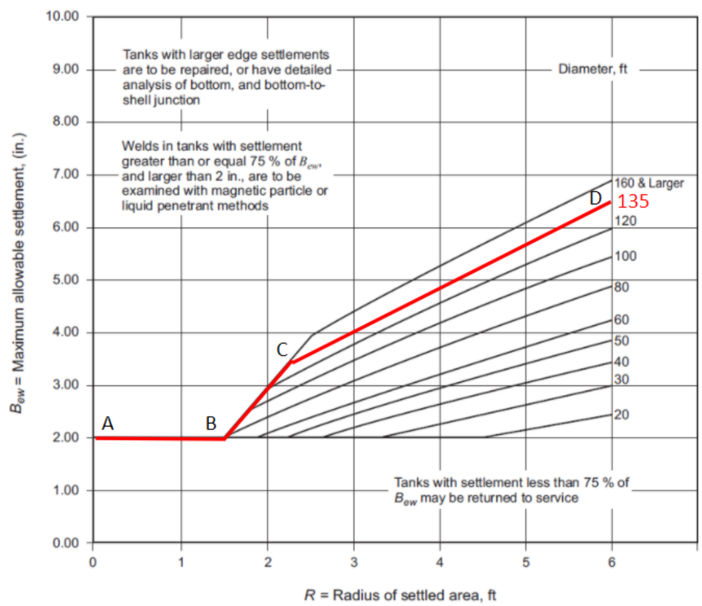

Figure 18 - Allowable Edge Settlement Limits for Tank 001 (135 ft Dia) Tank[5]

The high concentration of tank bottom elevation measurements from Tank 001 significantly exceeds the API 653 standard of 10ft internal spacing along diametrical lines per measurement. The large amount of data collected allows for various cross sections of the elevation measurements to be used to determine if the tank has settled sharply around the periphery. In order to exceed API 653 maximum spacing of 32 ft around the

Table 5 - Maximum Allowable Settlement Points used to Create Line in Figure 18

Point	Distance from Shell [ft]	Elevation [in]
A	0.00	2.0
B	1.50	2.0
C	2.25	3.5
D	6.00	6.5

[5]API Standard 653: Tank Inspection, Repair, Alteration, and Reconstruction(5th Ed, Nov 2014), B.3.4.3

circumference requirement an angular spacing of 10° between diametrical lines was selected, resulting in an 11.8ft arc length around the tank shell. In order to achieve these diametrical lines, cross sections of the tank were taken from 0° to 170° rotating counterclockwise from North at 10° intervals and displayed graphically below in Figure 19 and Figure 20. Only 1 out of 18 cross sectional views has been shown in this paper to save space; however, Square Robot would gladly provide a full sample report upon request. The black line on the elevation contour plot, Figure 19, represents the diametrical cross section of the tank bottom. In Figure 20, the blue line represents the bottom elevation across the selected cross section and the red lines represent the allowable settlement limits for a 135-ft diameter tank. This method of using the inspection robot elevation data avoids any in the field human interpretation of the breakover point location since the entire elevation cross section can be graphically represented. Additionally, the tank bottom type is accounted for when determining and plotting the allowable edge settlement limits.

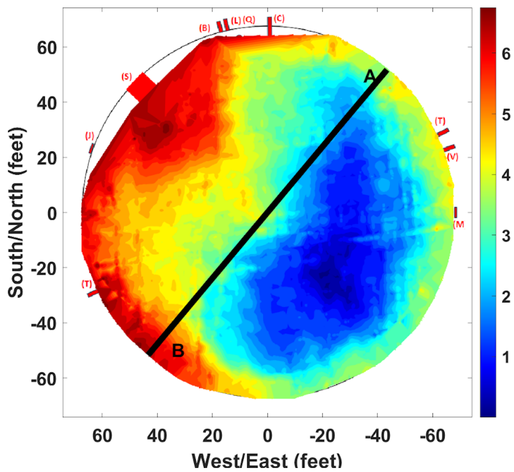

Figure 19 – Tank Bottom Cross Sections at Fixed Angular Intervals

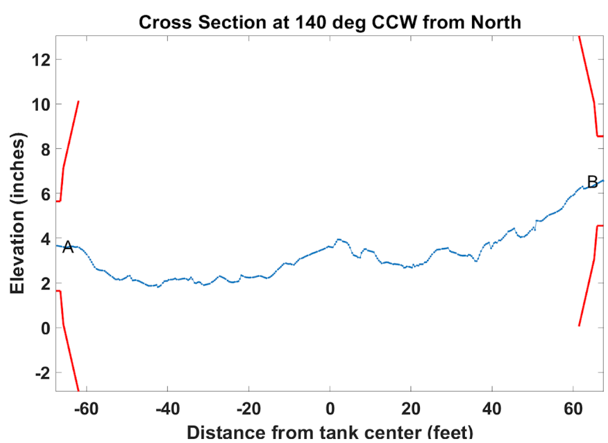

Figure 20 – Tank Bottom Elevation along Selected Diametrical Cross Section

In all 18 cross sections, the slope of the tank bottom elevation never exceeds 75% of the allowable settlement limit B_{ew} which can be seen for the 140° cross section in Figure 19. The only two cross sections that display settlement larger than 2in within a 6ft radius (R) of the shell are sides B of cross sections 0° and 10° CCW. Typically when settlement greater than 2in within 6ft of the shell occurs it is recommended that these areas should be examined with magnetic particle or liquid penetrant methods. However, elevation measurements on side B of both these cross sections were not able to get directly up against the shell because of internal obstacles. Side B of cross section 0° had to avoid a shell nozzle area for pump suction. Side B of cross section 10° had to avoid a shell nozzle area for recirculation. Since no data was actually collected against the shell in these areas edge settlement cannot be evaluated in those locations. These areas of the bottom outside of the robot tracklines where the obstacles are located were slightly filled in when creating the differential elevation contour plot, however these areas of the contour plot should not be trusted because of lack of data and the resampling interpolation going linearly in between actual measurements along the shell.

Discussion of Results

Data collection and analysis from this paper show clear benefits of conducting an in-service Aboveground Storage Tank bottom elevation survey with the SR-1 Robotic Inspection System. The robot is very methodical during data collection and is extremely efficient. The dataset from this 135 ft tank used throughout this paper took the robot 7 hours to collect. API 653 Annex B requires a minimum of 99 elevation measurements for an OOS inspection of a tank this size. While conducting the inspection of Tank 001, the SR-1 Inspection Robot recorded over 100,000 elevation measurements, significantly exceeding the standard. Additionally the navigational precision of SR-1 Inspection Robot and its use of a single elevation datum for the entire dataset eliminates the human subjectivity present in many OOS surveys such as repositioning a laser level during an external shell settlement survey.

The positional accuracy and high concentration of elevation measurements taken by the robot using this novel depth sensor approach allow for a thorough differential elevation map of the entire tank bottom to be created during post-processing. The differential elevation map by itself, as shown in Figure 21, can be compared to the original construction of the tank for a quick determination of settlement. The construction specifications of Tank 001 required the foundation to be within ±⅛in of level in 30ft of circumference, and that no point shall vary more than ±¼in from an established elevation. Without historical bottom elevation survey data, assuming the tank was built to its construction specifications, and accounting for manufacturing tolerances, it can be concluded that this tank bottom has experienced non-uniform settlement of greater than 6.5in.

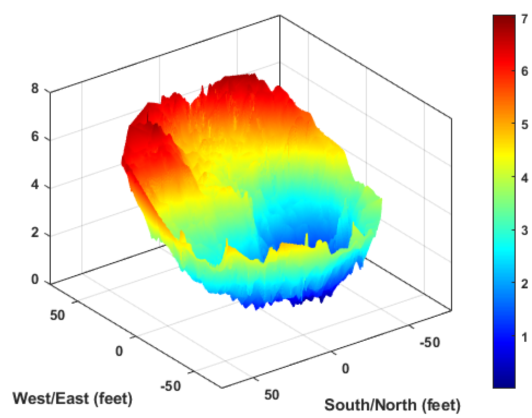

Figure 21 - 3D Contour Plot with a Stretched Z-axis [in] to Exaggerate Tank Bottom Slope

Additionally, this extensive elevation dataset can be used to evaluate shell settlement, localized bottom settlement, and edge settlement of the tank, adhering to API 653 standards all compiled into a comprehensive report for the tank owner. The elevation measurements up against the tank shell were used, along with computer solvers, to optimize a cosine curve to the data, determine that Tank 001's settlement is not well defined by a rigid body tilt plane, and evaluated out-of plane settlement per API 653 Annex B. Tank 001 was found to have shell settlement along *arc ℓ and k* located at Southeast bearings 100.8° and 132.5°, respectively, that notably exceeds the established limit, which correlates with possible shell ovalization based on the customer's observed inwards radial deflection along the shell arcs of the northeast and southwest portions of this tank's shell.

Surveys completed by the SR-1 Inspection Robot provide full bottom coverage with the exception of tank bottom areas containing internal obstacles. The concentration of elevation measurements is high enough to assess the entire bottom for localized depressions and bulges per API 653 Standards. Throughout the course of inspecting Tank 001, Square Robot's novel approach identified the severity and location of 27 instances of localized bottom settlement, 11 classified as depressions and 16 as bulges. Of the detected settlement areas, 4 depressions and 12 bulges exceeded the settlement limits defined by API 653. The bulges and depressions identified in this approach may be higher than an OOS survey because of the head pressure in the tank. However, this just shows another advantage of using the robot while the tank is in-service which is the ability to measure the bottom elevation while under load from the tank product.

A significant amount of pressure is applied to the edge of the tank from the tank shell which can cause the edges of the tank bottom to settle quicker than the tank bottom remote from the shell. The SR-1 Inspection Robot is agile enough to traverse along the internal circumference of the tank maintaining contact with the shell in order to survey the critical zone and measure bottom elevation directly against the tank shell, as shown by the proximity of the robot's NDT array in Figure 22. Using the elevation measurements against the shell along with the complete tank bottom coverage allowed the data to be evaluated at any diametrical cross section for edge settlement and found none to exceed 75% of the allowable limit. This method accounts for the tank bottom type and removes any human interpretation of the breakover point location by post processing the data with state of the art algorithms and reliably plotting the entire bottom elevation along the selected cross section.

Figure 22 - PAUT Scanning Bottom against Tank Shell during APS in Isononyl Alcohol

Conclusion

The SR-1 Inspection Robot provides a novel and safe approach to differential bottom elevation measurements using its onboard pressure sensor and surveying Aboveground Storage Tanks containing product. This methodology utilizes a single dataset to evaluate tank shell, edge and localized bottom settlement empowering tank owners with asset integrity information without disruption to service. It is apparent that keeping a tank in-service for integrity inspections is highly advantageous over the operationally disruptive, time consuming, and costly nature of out-of-service (OOS) tank inspections. The case study from Tank 001 in this paper exhibits data collection superiority of an autonomous inspection robot over the human subjectivity present in most OOS measurements. In conclusion, AST settlement monitoring can be safer, faster, and cheaper through automation and regularly scheduled robotic inspections using the innovative SR-1 Platform.

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NDT Tank Bottom Examinations from Square Robot

The tank bottom differential elevation surveys discussed in this paper can be performed simultaneously with an NDT bottom plate remaining thickness inspection using Square Robot's standard SR-1 Inspection Robot. This robotic inspection method which eliminates many health, safety, and environmental (HSE) implications also mitigates human error present in traditional OOS inspections while providing incredible bottom coverage using a Phased Array UT (PAUT) payload that meets API 653 standards. Figure 23 displays the PAUT coverage from a 100 ft diameter tank that Square Robot successfully scanned over 94% of the bottom, providing the client with comprehensive and precise data on the interior condition of their aboveground storage tank, without taking the tank out of service, eliminating the need for venting, and doing away with confined space entry.

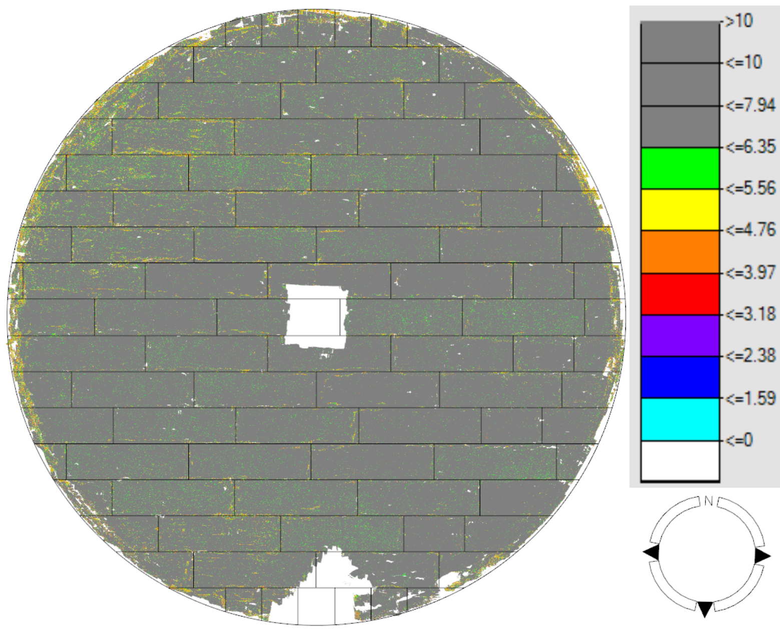

Figure 23 - PAUT Scan 94% Bottom Coverage, Thickness in mm with Original Plate Thickness of 7.9375mm nominal

Inspection Solutions from Square Robot

Square Robot now offers Tank Bottom Differential Elevation Surveys and Settlement Evaluations, as well as other tank inspection capabilities.

[Learn more about Square Robot here.]

Please contact us for more information or to discuss your specific tank inspection needs.

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