FINAL REPORT ON THE STUDY OF OUT–OF–PLANE TANK SETTLEMENT

API, Washington, D.C.

Submitted to:
API SCAST, SCI
May 2007

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Project Number: APIN004–0–04

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1 INTRODUCTION

This report is a revision of the reports issued in April and November, 2005 containing results of a study performed by The Equity Engineering Group, Inc. (E^2G) aimed at improving out–of–plane (OOP) shell settlement procedures in API 653 Appendix B. A new procedure has been developed for local and fold patterns of out–of–plane settlement for API 650 tanks constructed of carbon or stainless steel. Other shell settlement behaviors such as twisting patterns, combined bottom–shell settlement patterns, and aluminum tanks, do not lend themselves to the procedures developed.

An initial ballot of proposed changes to API 653 Appendix B was developed for the Spring 2006 meeting, but did not achieve sufficient voter return. A ballot resolution meeting was held at the Fall 2006 meeting and additional analyses were desired by those attending this meeting, including a look at natural shell settlement limits (removal of foundation under shell), a review of the effect of other curve fit patterns for applied local shell settlement (e.g., sine curve), a refinement of settlement measurement procedures, and the evaluation of stainless steel and aluminum tanks. These analyses were completed over a period from later 2006 through April, 2007 and a new ballot has been developed based on the new results. This report and a separate ballot document are being provided to SCAST and SCI for their review prior to the Fall 2007 CRE meeting and it is anticipated that formal balloting can occur late summer or fall of this year.

In addition to documenting the additional analyses performed in 2006 and 2007, this report includes the results from the original 2004 and 2005 analyses and corrects a few errata found in the earlier reports. This report should replace all previous reports by E^2G on the OOP settlement evaluation and is the final version of the work product. E^2G is not responsible for any changes as a result of electronic transmission or any changes that the client makes to the work product. E^2G will maintain a hardcopy or a permanent electronic copy (CD) of the work product in a client file and that copy will be considered the final and complete document.

2 EXECUTIVE SUMMARY

Conclusions and recommendations from the study of OOP tank settlement are provided below. We recommend that the reader not rely solely on this Executive Summary; but, rather read and evaluate the entire contents of this report prior to utilizing these engineering conclusions and recommendations.

2.1 Conclusions

There are a number of concerns regarding the current API Standard 653 Appendix B sections dealing with out–of–plane (shell) settlement. The present methodology does not differentiate between types of tank roof construction (open versus cone roof); the current methodology provides only for tanks that settle in an out–of–plane fashion with a component of rigid tilt that can be defined by an optimal cosine curve, which may not be applicable for all tanks, especially larger tanks or tanks with substantial localized settlement; the current methodology penalizes the use of closely spaced settlement readings; the current procedure bases goodness of fit of the optimal cosine curve only on an R^2 approach; and the current curve fitting methodology permits data to be ignored if they do not appear to correlate with an otherwise optimal cosine curve fit.

2.1.1 Focus of Study – Limitations

The focus of the study and the procedures developed is local patterns of OOP settlement in carbon and stainless steel open and cone roof tanks. There are believed to be several potential additional patterns of shell settlement a tank can take, but it was felt that twisting patterns may not lend themselves to practical, straight–forward procedures that can adequately be addressed in a standard such as API 650. Additionally, after an initial evaluation of aluminum tanks, the non–linear behavior of aluminum did not lend itself to the use of the procedures being proposed for carbon and stainless steel tanks. Also it was not considered practical to develop procedures for combined settlement patterns involving both shell and bottom settlement, i.e., OOP shell settlement combined with edge or other near–shell bottom settlement. These and other limitations and/or cautionary notes are included in the proposed ballot.

2.1.2 Results of Parametric Studies – Procedures for Out–of–Plane Settlement

Parametric finite element analyses (FEA) were performed to evaluate out–of–plane settlement of a variety of tank constructions and materials. Maximum strain and out–of–roundness (OOR) were considered as fitness–for–service (FFS) criteria. It was determined that the strain results could be used to develop permissible OOP settlement equations (curves) that take into account tank geometry (open or cone roof), materials of construction (carbon or stainless steel), and tank size (diameter and height). A 3.0% strain criterion was chosen based on current edge settlement rules. OOR was also considered, but as a secondary, or serviceability, criterion. Settlement spacing was not considered a parameter in the final OOP settlement evaluation procedure, but settlement measurement is a critical part of the OOP settlement FFS procedure, as it is for other forms of tank settlement and measurement considerations are part of the proposed ballot.

2.2 Recommendations

2.2.1 Revisions to Procedures on Tank Settlement Measurement

Revisions to measurement procedures in Section 12 and Appendix B of API 653 are recommended. These revisions are included in a draft ballot for AI 653–150 that is a separate document. Revisions include a methodology for refining measurement spacing, if needed, to determine more accurate settled arc length.

2.2.2 Revisions to Procedures on Out–of–Plane Settlement

Revisions to OOP settlement procedures in Appendix B of API 653 are recommended. These revisions leave in place the current optimal cosine curve approach for a tank with a well–define rigid tilt plan, but add additional procedures for the evaluation of other patterns of OOP settlement including local and fold patterns. These revisions are included in a draft ballot for AI 653–150 that is a separate document.

3 BACKGROUND AND DESCRIPTION OF ANALYSES

3.1 Background on Shell Settlement

The settlement of a tank's shell may consist of uniform settlement, rigid body (planar) tilting and out–of–plane settlement. Uniform settlement does not produce stress–strain problems in a tank, provided the settlement of attached appurtenances, such as piping, is accommodated. Rigid tilt reduces free–board and can affect attachments, cause roof seal problems, and produce increased hoop stress related to the increased liquid level. However, Malik's experimental work showed that rigid tilt did not result in deformation, and therefore does not produce secondary or bending stresses in the settled condition. The current API 653 procedure for OOP settlement considers a rigid tilt plane, if one exists, that can be described by an optimal cosine curve after accounting for the uniform settlement. Out–of–plane shell settlement can produce local stresses (strains) that may affect the tank's structural integrity. OOP settlement can also produce OOR that affects the serviceability of the tank.

3.2 Summary of Literature Review

Out–of–plane settlement studies have been documented in the referenced literature. As indicated, Malik provides good background information on types of shell settlement including a discussion of an experimental study of tank shell settlement and various settlement patterns – tilt, local, twisting and folding modes. The single lobe local settlement and fold patterns in Malik's work were considered in the parametric FEA studies described in this report. Multi–lobed patterns and twisting patterns are felt to be of more theoretical or academic significance and may not lend themselves to rule–making in a standard (see Figure 1).

Marr, Ramos and Lambe (Ref. 2) also provide useful background information on settlement criteria, including OOP settlement. Ref. 2 summarizes the criteria proposed by a number of other researchers for various patterns of shell and bottom settlement. One of these is the over–stress criterion for OOP settlement in the current API 653 criterion (B.3.2):

$$|S| \le \frac{\left(L^2 \times Y \times 11\right)}{\left[E \times H\right]}$$

However, this equation is a function of the spacing of shell settlement measurements (L), which is thought to be one drawback of the current methodology.

3.3 Summary of Current API 653 Out–of–Plane Settlement Provisions

The current API 653 shell settlement procedure focuses on OOP settlement where a plane of rigid tilt can be calculated from a best fit cosine curve through settlement points, with a statistically valid curve being one with a R^2 value of at least 0.90. The current procedure permits data to be ignored to improve the rigid tilt curve fit. This is contrary to sound inspection practice, where all verifiable data is considered.

Once the tilt plane is established, out–of–plane settlements can be determined from the distance between the tilt plane curve fit and the actual settlement values. The permissible values are determined from the equation given previously, which is a function of tank size and settlement measurement spacing. For A36 material, the current maximum permissible settlement limit is approximately 2.0 inches for a 40 foot tall tank and 1.65 inches for a 48 foot tall tank. The current criterion is summarized in Table 1.

3.4 Summary of Previous API 653 Out–of–Plane Settlement Proposals

The pursuit of a criterion that avoids the dependence of the permissible out–of–plane settlement on measurement spacing produced several earlier proposals for modification to the equation in B.3.2. Bending analogies led to development of two criteria that were included with API *Conditions on Invitation to Bid* (Ref. 3). Both are a function of the square of the tank diameter. The second of these is based on the work of P. Myers (Ref. 4):

$$S = \frac{\pi^2 \times D^2 \times Y}{12 \times E \times H} (\mathit{1st\ proposal})$$

$$S = \frac{1.7 \times Y \times D^2}{E \times H} (\mathit{2nd\ proposal})$$

The resulting permissible settlements from these equations are given in Table 2 and plotted in Figure 2 for A36 properties. These proposed equations eliminate the previous dependence on settlement measurement spacing. However, the permissible OOP settlement in both equations increases rapidly as a function of the square of diameter and is unbounded. These equations also make no differentiation between types of tank construction. However, they have a desirable feature in that they involve only readily available, well–defined parameters.

3.5 Description of Parametric Studies of Out–of–Plane Settlement

Several series of parametric FEA studies were performed to develop curves and/or equations for permissible out–of–plane settlement that account for differences in tank geometry, size and materials, while eliminating the current penalty on closely spaced settlement data. The methodology used was similar to that used by some of the same researchers to revise the edge settlement rules in API 653 in the mid–1990s. This section describes the FEA modeling effort and results of the parametric FEA study.

3.5.1 Model Assumptions

FEA were performed to evaluate a broad range of API 650 tank designs and settlement patterns. The test matrix (see Table 3) included eight supported cone roof tank geometries in the range of 50 to 180 feet in diameter, and fourteen open tank geometries in the range of 50 to 300 feet in diameter. Three shell heights, including 40, 48 and 64 feet, were considered.

All tank models were constructed from 3D shell element representations of the shell, a flat bottom, and a supported cone roof (where applicable). The required plate thicknesses, stiffeners, roof structures, and annular plate geometry (if needed) were determined based on current API 650 design rules. Some of the geometric assumptions of the models include:

- Shell courses were 8 feet in height
- Shell thickness was determined for G=1.0
- Calculated thickness was increased to the next higher 0.0625 inch increment
- No additional corrosion allowance was considered
- The shell course centerline was held constant (i.e., adjacent course centerlines, not ID, lined up)
- Nozzles, sumps, and other appurtenances were not considered
- General bottom thickness was set at 0.25 inches
- No bottom slope was considered
- No bottom or roof plate overlap was modeled
- Roof plate thickness was 0.1875 inches
- Roof slope of 1:12 was considered
- Roof beams and girders were modeled as plates of equivalent bending stiffness

The commercial ABAQUS FEA software was used to model, run and process the analyses. Modeling was done using a PYTHON subroutine to generate shell element meshes based on overall tank dimensions. Initial analyses included a mesh sensitivity evaluation. Meshes in the areas of settlement were refined to improve the accuracy of the stress (strain) results. Several typical FEA models illustrated the variation in mesh density and are shown in Figure 3, Figure 4, Figure 5 and Figure 6.

3.5.2 Material Properties Assumptions

Two carbon steel and one stainless steel material were considered, including A36, A537 Class 1 and Type 304 SS. All materials were evaluated at ambient temperature. The modulus of elasticity values used included 29,000 ksi for carbon steel and 28,100 ksi for the stainless steel. The initial yield stresses considered included approximately 36 ksi and 50 ksi for the two carbon steels, and approximately 29 ksi for stainless steel. The complete elastic–plastic stress–strain curves for the materials were taken from the ASME Boiler and Pressure Vessel Code Section VIII Division 2 re–write procedures. The higher strength carbon steel material was used only in the shells of some of the 240 foot and all of the 300 foot diameter tanks

3.5.3 Boundary Condition Assumptions

Half–symmetry was used to reduce model size and run efficiency. Appropriate symmetry boundary conditions were employed. Support columns in the cone roof tanks were modeled using a boundary condition in place of an actual structural element. This was accomplished by fixing the vertical displacement between the roof nodes and aligned bottom nodes at the location(s) of column(s). This assumed the columns do not rigidly move out of position (are contained by base plate guides), do not buckle, and do not substantially deform.

Elastic foundation stiffness was considered under the bottom shell elements, consistent with compacted foundation materials. A stiffness value of 300 lb/in^3 was used under the bottom in all regions assumed to be well–supported, i.e., regions on the un–displaced plane (in this case a horizontal plane). In the region undergoing the applied shell settlement, a weakened elastic foundation stiffness, 10 to 20 lb/in^3, was used for numeric stability and to balance the approximate static weight of the shell and roof above the displaced region.

3.5.4 Application of Settlement

As indicated, two patterns of OOP settlement from Malik were applied to the tank models single lobe local settlements and diametric folds (see Figure 1). Twisting modes were not evaluated. The local patterns consisted of two variables:

- Value of maximum deflection, $\left(S_{max}\right)$
- Settlement arc length, $\left(S_{arc}\right)$

Settled arc lengths from 20 feet to one–half the tank circumference were evaluated. Anywhere from 6 to 18 settlement arcs was considered for a given tank geometry. For each settled arc, 10 to 12 center deflections were considered, resulting in a test matrix of approximately 3700 cases.

OOP settlement was applied using two assumed curve fits, a Gaussian curve and a sine curve. The general features of these applied settlement patterns included no abrupt changes in settlement pattern, and essentially zero or near–zero displacement (tangency to the rigid plane) at settlement arc endpoints. These curve fits also were a best fit to several previous settlement analyses done by E^2G.

The Gaussian fit was used on the majority of cases since it was felt that it would likely result in conservative peak strains. The Gaussian curve has a domain of $\pm\infty$ and may produce a small error in displacement (and therefore stress–strain) at the endpoints of the settlement arc, i.e., the ends of the applied deformed shape of the FEA models had a small residual displacement. In early "sensitivity" analyses, the constants used in defining the Gaussian curve fits were evaluated for a number of typical settlement cases and constants were adjusted to the point that the resulting error at the endpoint of the settlement arc, or points of assumed tangency, was minimized. The actual displacement at the end points of the settlement arc in each FEA model was reduced to 0.006 inches. Over the neighboring element in each model, a length typically less than 1.0 inch, the applied displacement was reduced to zero by a modeling procedure. The use of this curve fit for applied settlement did not result in an extraneous strain concentration at the ends of the settlement arc.

One fold case was evaluated for each of the tank geometries, a full diametric folding about the tanks centerline. The full diameter fold was felt to be the most conservative of the potential fold cases. The line of fold was taken as a line of symmetry with respect to columns in cone roof tanks, not a line through any one column or more than one column. In reality, the folding pattern for a cone roof tank could take place along a line through or very near columns, which would require special consideration of structural stability problems.

In later analyses, natural shell settlement displacements were examined by removing applied settlements and letting the tank deflect under its own weight. Natural cases were done to examine if some of the shorter settled arc lengths applied to the tank models (and corresponding maximum settlement), were practical, particularly on smaller tanks.

Additional loads such as product load and thermal loads were not considered in these analyses, to determine solely the effect of the applied settlement. Further, other types of settlement, such as edge settlement, were not applied coincidently with the OOP settlement. These conditions of combined settlement would require special consideration, i.e., rigorous analyses.

4 RESULTS

The OOP settlement models were processed to determine the magnitude of settlement with respect to strain and OOR criteria.

4.1 Strain Criterion

A 3.0% strain criterion was considered. This is consistent with other settlement procedures (edge settlement) in API 653 Appendix B. The curves presented in Figure B–10 and B–11 for edge settlement were derived using parametric FEA similar to the procedures of this study using a limit of approximately 2.0% strain, while a limit of 3.0% strain is permitted by API 653 if more rigorous analyses are performed. API RP 579 (API 579) Appendix B limits surface strains in an FFS assessment to 5.0%. In API 579, a second criterion must also be evaluated. This criterion is related to overall stability (for instance, a limit load analysis). In this study, limiting settlement strains to 3.0%, rather than 5.0% strain, is felt to be appropriate given the fact that the evaluation of out–of–

plane settlement is a “point in time” analysis and does not consider future settlement in the way that future corrosion may be more readily considered in a FFS assessment.

4.2 OOR Criterion

Radial deflection (or OOR) can be found as a criterion considered in some of the published settlement criteria (Ref. 1, 2). Frequently, standards have a stress (or strain) related primary design or FFS criterion, with a secondary serviceability criterion related to displacement (e.g., roof deflection inducing ponding, rotation and loss of flange seal effectiveness, etc.). For tanks, particularly with open roofs, OOR may be a secondary consideration that requires additional consideration, including measurement and comparison with limits based on design. No specific limit on permissible OOR was identified in these analyses as OOR was found to be fairly sensitive to settlement pattern and tank construction, and permissible values would likely be a function of roof design and/or component limitations.

4.3 General Results

The data from approximately 3700 FEA runs was used in the development of the proposed OOP settlement criteria. Several plots of FEA results (strains and deformation) have been included in this report (see Figure 7, Figure 8, Figure 9 and Figure 10). The strain results showed that maximum strains occurred either at the base of the tank (in the shell) in the region of general out–of–plane settlement, at a stiffener, or at the top rim or top–to–cone roof connection.

The maximum permissible settlement $\left(S_{max}\right)$ was determined base on strain criterion and was evaluated versus a number of geometric and material parameters and combinations of these parameters. The parameters varied and evaluated include a number of geometric and material parameters, such as tank diameter $\left(D\right)$, shell height $\left(H\right)$, settlement arc length $\left(S_{arc}\right)$, yield strength $\left(YS\right)$, and elastic modulus $\left(E\right)$. Dimensionless values and powers of some of these basic parameters were also evaluated, such as $\left(D/H\right)$, $\left(YS/E\right)$, $\left(D^2/H\right)$, S_{arc}/H, S_{arc}/D, and S_{arc}^2.

The ratio of the maximum OOP settlement to the settled arc $\left(S_{max}/S_{arc}\right)$ was considered analogous to the relationship B/R in the current edge settlement curves. The use of the settlement arc length as a parameter under consideration was also consistent with beam bending equations involving a distributed load over a partial span.

4.4 Open Tank Results

For the open tanks, maximum strains occurred either at the bottom–to–shell joint (or in the shell) or at the top rim/stiffener. The maximum OOR for all open tanks generally occurred at the top rim or within a foot or two of the top rim depending on the stiffening elements at the top of the tank. However in the case of the shortest of the settlement arcs, S_{arc} equal to 20 feet, the position of the maximum OOR was generally in the middle third of the shell height. An additional discussion of the open tank results versus tank size is given in the next sections.

4.4.1 Small Open Tanks: 50 to 80 Foot Diameter

At shortest settlement arcs, 3.0% strain was achieved with a corresponding OOR of approximately 3.0 to 5.0 inches. At the largest settlement arcs, greater than 12 inches of OOR was achieved without exceeding the 3.0% strain criterion. Generally, 2.0 to 3.0 inches of OOR was achieved without plastic strains occurring. Maximum permissible settlement for 3.0% strain ranged from less than 1.0 inch for a 20 foot settlement arc on a 50 foot diameter tank to over 3.0 inches for an 80 foot x 48 foot tank with a settlement arc equal to half of the tank's circumference.

4.4.2 Mid–Sized Open Tanks: 120 to 180 Foot Diameter

At shortest settlement arcs, 3.0% strain was achieved with a corresponding OOR of approximately 3.0 to 5.0 inches. For some of the mid–sized tanks, greater than 20 inches of OOR was achieved without exceeding the 3.0% strain criterion. Generally, less than 2.0 inches of OOR was achieved without plastic strains occurring. Maximum permissible settlement for 3.0% strain ranged from less than 1.0 inch for a 20 foot settlement arc on a 120 to 180 foot diameter tank to over 4.0 inches for a 120 to 180 foot x 48 foot tank with a settlement arc approaching half of the tank's circumference.

4.4.3 Large Open Tanks: 240 to 300 Foot Diameter

At shortest settlement arcs, 3.0% strain was achieved with a corresponding OOR of approximately 4.0 to 5.0 inches. For some of the large tanks, 40 to 45 inches of OOR was achieved without exceeding the 3.0% strain criterion. Generally, less than 2.0 to 3.0 inches of OOR was achieved without plastic strains occurring. Maximum permissible settlement for 3.0% strain ranged from approximately 1.0 inch for a 20 foot settlement arc to nearly 5.0 inches for a 240 to 300 foot x 64 foot tank with a settlement arc approaching half of the tank's circumference.

4.5 Parametric Evaluation of Open Tank Results

The maximum permissible settlements were plotted and the best correlation was judged to be:

$$S_{max} = K * S_{arc}\left(\frac{D}{H}\right)\left(\frac{YS}{E}\right)$$

Three percent strain results for open roof tanks is plotted versus this parameter in Figure 11. The complete set of 3.0% strain results is given in Figure 13.

Using this relationship, a best linear fit to the data (slope K) was found for several ranges of tank size (diameter). In this way, a family of permissible settlement curves for open tanks (similar to those for edge settlement) was developed. The K values for each size range were determined for two assumed linear fits, a single line (FIT1) that captured the worst case for each diameter, and a bi–linear fit (FIT2) where the values of K given in the table represent the slope of an initial curve that captures all data up to an intersecting horizontal line representing a limit of 4.0 inches of settlement. A few data points lie between 5.0 and 6.0 inches of permissible settlement, but these are exceptions. The resulting K values for both fits are given in Table 4. These curves are shown in Figure 14 and Figure 15. Since the slopes of these curves are monotonically increasing with decreasing diameter, the use of a family of multiple curves appears reasonable and is the focus of proposed revisions for open tanks in the associated API ballot.

One set of fold cases was evaluated, in this case, complete diametric folding. This represents what is considered a worst case of multiple local or general OOP settlements. All of the fold data points meet the proposed equations.

4.6 Cone Roof Tank Results

For the cone tank cases, maximum strains occurred either at the bottom–to–shell joint, in the lower shell, or at the cone roof connection. The maximum OOR for most of the cone roof tanks occurred about one course down from the top of the shell for larger settlement arcs, and in the middle third of the tank for shorter settlement arcs. An additional discussion of the cone roof tank results versus tank size is given in the next sections.

4.6.1 Smaller Cone Roof Tanks: 50 to 80 Foot Diameter

For the smallest tank diameter, 3.0% strain was achieved in all cases before 6.0 inches of OOR occurred. Generally, 1.0 to 2.0 inches of OOR was achieved without plastic strains occurring. Maximum permissible settlement for 3.0% strain ranged from just less than 1.0 inch for a 20 foot settlement arc on a 50 foot diameter tank to 1.50 inches for larger settlement arcs on both the 50 and 80 foot cone roof tanks.

4.6.2 Larger Cone Roof Tanks: 120 to 180 Foot Diameter

For the largest cone roof tanks examined, 3.0% strain was achieved in all cases with the corresponding OOR between 2 and 20 inches. The maximum OOR coincident with 3.0% strain occurred for moderate settlement arcs. At larger settlement arcs, the minimum corresponding OOR (2.0 to 4.0 inches) occurred. At the largest settlement arcs, the 3.0% strain criterion was reached at a corresponding OOR of 1.0 to 2.0 inches. Less than 1.0 inch of OOR was achieved without plastic strains occurring. Maximum permissible settlement for 3.0% strain ranged from just less than 1.0 inch to more than 4.0 inches for larger settlement arcs on the 180 foot tanks.

4.7 Parametric Evaluation of Cone Roof Tank Results

The maximum permissible settlements were plotted and the best correlation was again judged to be:

$$S_{max} = K * S_{arc}\left(\frac{D}{H}\right)\left(\frac{YS}{E}\right)$$

The 3.0% strain results for cone roof tanks is plotted versus this parameter in Figure 12. The complete set of 3.0% strain results is given in Figure 13.

Using this relationship, a best linear fit to the data (slope K) was found for several ranges of tank size (diameter). In this way, a family of permissible settlement curves for cone roof tanks (similar to those for edge settlement) was developed. The K values for each size range were determined for a single assumed linear fit. A bi–linear fit (FIT2) was not examined for the cone roof tanks. The resulting K values for the curve fits are given in Table 5. These curves are illustrated in Figure 16. Since the slopes of these curves are also monotonically increasing with decreasing diameter, the use of a family of multiple curves appears reasonable and is the focus of proposed revisions for cone roof tanks in the associated API ballot.

Again, one set of fold cases was evaluated, complete diametric folding since this represents what is considered a worst case of multiple local differential settlements. The results for the fold cases were plotted on the final criteria plots and all of the fold data points meet the proposed cone roof equations. However, it should be noted that the fold cases were done with the line of fold centered between adjacent column centerlines, not directly under or adjacent to any roof column(s).

4.8 Results of Additional Analyses

A number of additional sets of analyses were done over the past year or two as a result of comments from SCAST or SCI members. The results of these studies are discussed in the following sections.

4.8.1 Stainless Steel Tanks

Additional analyses were done to examine permissible OOP settlement in tanks fabricated from stainless steel. Type 304 SS was considered. A subset of the open roof tanks was used in this analysis, including tanks ranging in size from 50 to 240 feet in diameter. The results of the stainless tank models were plotted along with the original carbon steel tank results (see Figure 17). The results for the stainless steel tanks meet the same criteria proposed for the carbon steel tanks, which will be reflected in the proposed new ballot.

4.8.2 Effect of Applied Settlement Curve Fits

Another set of additional analyses examined the effect of the cure fit used for the applied settlement pattern. The Gaussian curve was used for many of the analyses based on characteristic such its smoothness, expected conservatism, and successful use with actual settlement evaluations in the past. In an additional set of analyses, sine curve fits to applied settlement were also considered. A subset of the original analyses was used for these analyses. Carbon steel open tanks with diameters ranging from 50 to 240 feet were considered. Table 6 lists results of the sine curve fit cases in terms of the following ratio:

$$\frac{S_{max,3.0\%\,Gaussian}}{S_{max,3.0\%\,Sine}}$$

$S_{max,3.0\%\,Gaussian}$ represents the maximum settlement corresponding to 3.0% strain using a Gaussian curve for the applied settlement, while $S_{max,3.0\%\,Sine}$ represents the maximum settlement corresponding to 3.0% strain for the same settled arc length using a sine curve fit for the applied settlement. A ratio less than 1.0 indicates that the Gaussian fit was more conservative. The ratios given in the table range from 0.6 to 1.0 indicating the Gaussian results are generally more conservative, although at a few combinations of tank geometry and settled arc length, the results were nearly equal. The location of the maximum strain in both cases was essentially unchanged.

4.8.3 Natural Settlement Results

The use of an applied displacement to evaluate settlement criteria is consistent with previous edge settlement studies. To evaluate the realism of applied settlement patterns used in these analyses, an additional set of analyses was performed. A subset of cases involving open tanks ranging in size from 50 to 240 feet in diameter was considered. In these analyses, the elastic foundation property was removed over a certain arc length and the shell was allowed to settle under the weight of the tank rather than an applied displacement pattern. The results of these analyses are plotted on Figure 18. Maximum settlement was generally two–thirds or less than the applied settlement that produced 3.0% strain for a given settled arc. Additionally, the maximum settlements for some of the longer settled arcs on the 240 foot diameter tank were a little less than 3.0 inches. These results further support that there is some conservatism in the patterns of settlement applied in the development of the criterion.

4.8.4 <u>Effects of Hydrostatic Load on the Settled Models</u>

Another additional set of analyses was performed to evaluate whether hydrostatic (product) loading had any effect on the results presented in the initial 2005 reports. Two tank geometries were evaluated, a 120 foot x 40 foot open tank and a 120 foot x 40 foot cone roof tank. A subset of approximately three–fourths of the settlement arcs considered in the initial analyses were re–run. Settlement was applied as before, but an additional load equal to full product head (specific gravity of 1.0) was applied.

There was no appreciable change in the maximum settlement that produced the 3.0% strain limit for either tank geometry or any of the range of settlement arcs evaluated in these analyses. Based on this, we believe that no revision to the previously proposed equations is required. Product loading may be a concern in terms of bottom–to–shell joint and near–shell bottom plate stresses when there is significant near–shell local bottom settlement combined with the OOP settlement, but this is outside of the scope of the procedures developed.

4.8.5 <u>Effects of Lapped Plate Welds on the Out–of–Plane Settlement Results</u>

Like previous edge settlement studies, these studies were done with FEA models of tank bottoms that assumed the bottom formed a continuous plane, i.e., was not lap welded. In the case of the edge settlement procedure developed by similar studies, a penalty factor (similar to a joint efficiency) was applied to the FEA results to account for potential strength issues where lap welds crossed the settled area. In the case of these OOP analyses, the maximum strains were found to occur in elements representing the bottom–to–shell corner weld, at shell stiffeners, or at the top of the tank, not in the bottom plates themselves. Therefore, an additional penalty factor on the results of these analyses does not appear to be warranted. For near shell bottom settlement (edge or local) combined with OOP settlement, a penalty factor might need to be considered, but these types of combined settlement are outside of the scope of the proposed procedures.

4.9 Measurement of Settlement

Since the determination of the permissible OOP settlement in the proposed procedure is a function of the settled arc length, the accurate measurement of shell settlement is particularly important. Shell settlement measurements (or shell elevation surveys) should be performed by experienced personnel, using equipment designed for the specific purpose. Improvements to the measurement procedures in Section 12 and appendix B of API 653 are included in the proposed ballot.

4.9.1 <u>Shell Settlement Measurement Spacing</u>

Similar to inspection for thinning damage or bulging, the spacing of settlement measurements should be dependent on the magnitude and variability of the problem. The spacing should be fine enough to permit characterization of the actual damage, in this case, the maximum settlement, settlement pattern(s), and the settled arc length(s).

The current API 653 minimum requirement of eight shell settlement measurement locations (12.5.1.2), with a maximum spacing of 32 feet (nominally 10π) is a reasonable starting point. Initial measurements should be taken on opposing diameters, i.e., at an even–numbered set of data points. This permits a quick, empirical examination of uniform settlement, potential tilt planes, fold patterns, and settlement patterns of a general or global nature. The minimum number of measurement points is shown in Figure 19.

An inspection of this initial plot of settlement data will indicate location(s), if any, where settlement measurements should be reconfirmed or additional measurements taken. For instance, additional measurements will be needed where the endpoints of a settled arc have been estimated to occur. Depending on the gradient of settlement at the endpoints of the potential settled arc, the settlement spacing may need to be halved (or quartered) to more accurately determine the settled arc length. A settlement plot for a tank with a rigid tilt plane fairly well–defined by an optimal cosine curve is shown in Figure 20. Depending on the statistical accuracy of the curve fit, there may be no need to take additional measurements to better define the tilt plane and/or settled arcs about the rigid plane. A settlement plot for a tank that does not have a well–defined rigid tilt plane and includes several areas of local OOP settlement is shown in Figure 22.

In the determination of the maximum OOP settlement and settled arc, it may be necessary to halve the settlement spacing once or twice in the vicinity of predicted settlement arc endpoints in order to improve the estimate of the settled arc length. This concept, which is also identified in the proposed ballot, is shown in Figure 22.

Once final settlement measurement locations are implemented, future surveys should be taken at the same locations, consistent with the concept of using the same thickness measurement locations (TML) when performing subsequent ultrasonic examination (UT). Tank records should indicate these locations, as well as the consideration of permanent markings on the shell or other layout devices, if needed, to ensure the same locations are used.

4.9.2 Shell Settlement Measurement Frequency

Settlement measurement frequency is also an important aspect of continued assessment of a tank settlement. Section 12.5 of API 653 indicates that shell elevations should be measured before (empty) and during and after full fill when performing a hydrotest. Appendix B of API 653 indicates that continued monitoring of settlement should occur during operation at a planned frequency determined by soil–settlement predictions. The desirable interval of shell settlement measurement should include, as a minimum:

- after initial construction (prior to hydrotest)
- after initial hydrotest
- initially, every two to five years of service (depending on type of foundation, soil conditions, etc.) for until at least five data points are available to assess a settlement trend
- after any upset that may have affected the stability of the foundation, such as overfill, flood, or a failure of drainage systems that resulted in a flooded dike
- until satisfied that the shell settlement rate has reached a negligible value

4.9.3 Shell Settlement Measurement Technique and Accuracy

The shell settlement survey should be performed with instruments capable of sufficient accuracy to be able to distinguish settlement differences of less than or equal to 0.01 feet (or 0.1 inch). A prescribed benchmark should be used as a reference point. Electronic devices are generally accurate at least to one–tenth of a foot and often to one–hundredth of a foot. For comparison, according to Ref. 5, the U.S. Geological Survey (USGS) requires hydrological benchmarks to be surveyed to with in one–hundredth of a foot.

Like edge settlement, the accuracy of measurements and interpretation of measurement data will affect the accuracy of the FFS conclusions. The measured settled length will never be as accurate as the characteristic settlement length defined in the analytical models on which the procedures are based, but this is true of any of the settlement evaluations in Appendix B of API 653 since all depend on a measured settled length typically determined using traditional surveying techniques, while curves and equations have been developed based on advanced computer algorithms. Halving refinement of the measurement spacing at points of concern will not totally bridge this gap between measured and analytical settlement lengths, but should improve the determination of the settlement arc length to sufficient accuracy. The 3.0% strain limit proposed here (and in edge settlement requirements) has a sufficient inherent safety factor to account for inaccuracies such as those in settlement measurement.

4.10 Consideration of Uniform Settlement and Rigid Tilt

Permissible out–of–plane settlements in this study are those local, OOP and diametric fold settlements in excess of any uniform tank settlement, and any rigid planar tilt or local planar shell area. The procedures presented recognize that tanks will not all settle in a rigid tilt plane that can be defined by a cosine curve, as is currently done in Appendix B of API 653. For any tank, regardless of size or type of construction, the uniform portion of the measured settlement can be deducted from the total shell settlement when assessing the effects of out–of–plane settlement, but care must be taken to ensure that the uniform settlement does not adversely affect such things as attached piping and other appurtenances.

In terms of rigid tilt planes, the current methodology to determine an optimal cosine curve fit uses a least squares methodology and a "goodness of fit," value. Currently, an R^2 value of 0.9 is required per API 653 Appendix B to indicate an accurate curve fit for the tilt plane and the procedure allows measured settlement data to be ignored in order to obtain an R^2 of greater than 0.9. The least squares method applied is one of the simplest and most commonly used forms of linear regression, minimizing the vertical offset of data, rather than actual deviations from the function, which would be the perpendicular offset (Ref. 6). While it is relatively easy to apply, this method may not adequately capture the data, especially if there are points that have an extreme deviation from the population.

In the case of tanks that do not possess extreme outlying points, a rigid tilt plane that can be expressed by a cosine curve with linear regression, using the simple current curve fitting procedures in API 653 is believed to be adequate. However, all shell settlement data that is properly measured should be considered in the curve fit and subsequent analysis. Any lack of statistical accuracy using all data points in a linear regression, with a R^2 test may suggest that there is (are) localized settlements that make a statistically accurate cosine fit impractical. As such, to reduce the disproportionate effect of outlying data, other statistical methods and measures may be required to determine if a rigid tilt plane can be defined. The use of any more rigorous statistical method to improve the determination of the optimum cosine curve, such as non–linear or iterative procedures, should be limited to those experienced in their use.

5 DISCUSSION

The results of the study have been used to develop proposed revisions to procedures used to measure settlement and determine fitness for service of out–of–plane settled tanks.

Proposed revisions have been identified in the form of a ballot. Certain limitations have been identified in this report and in the separate ballot.

5.1 Other Modes of Shell Settlement and Combined Settlement

Appendix B of API 653 covers edge settlement, local bottom settlement and shell out–of–plane settlement. Presently, and with this work, procedures do not exist for evaluating the effects of combined settlement modes or some of the patterns that Malik produced experimentally, such as twisting and multi–lobed forms of shell settlement.

5.2 Limitations of the Use of This Parametric FEA

It must be noted that this study and the procedures developed apply only to local out–of–plane shell settlement, including some folding patterns of shell settlement. Shell settlement combined with local bottom or edge settlement, and various out–of–plane settlement behaviors were not examined. Fold patterns in cone roof tanks that involve a fold line directly under one or more columns were not modeled. These would require individual rigorous analysis.

The study did not consider settlements that included abrupt changes in elevation. Unique shell settlement conditions, for example, the loss of a section of ring–wall resulting in a step–change in the shell profile, or a ridge in the shell foundation caused by a tank being built partially over a rigid buried feature such as previous foundation, were not considered in this study and would require individual rigorous analysis.

Unusually thick shell courses for the size of tank were not considered. The FEA study presented here also did not consider nozzles in the shell. Low nozzles at points of large out–of–plane settlement and nozzles in regions of significant OOR may be a concern, particularly if the nozzles have attached piping. In such cases, more rigorous analysis may be required.

Finally, the empirical equations and curves developed here and presented as proposed revisions in the ballot represent the equivalent of a Level 1 or 2 API 579 procedure, or in essence, a screening methodology that can be used to determine FFS or to identify the need for repairs or a more rigorous evaluation. As in any FFS assessment, a pattern of settlement that does not fit the basic assumptions of the adopted procedure should be further examined by a more rigorous engineering assessment.

6 REFERENCES

1. "Ovalization of Cylindrical Tanks as a Result of Foundation Settlement," Z. Malik, J. Morton, and C. Ruiz, University of Oxford, Journal of Strain Analysis, Volume 12, Number 4, 1977.
2. "Criteria for Settlement of Tanks," W. Allen Marr, J. A. Ramos, and T. William Lambe, Massachusetts Institute of Technology, Journal of Geotechnical Engineering Division, Proceedings of the American Society of Civil Engineers, Volume 108, Number GT8, August, 1982
3. "Conditions on Invitation to Bid, API 653 Appendix B, Out–of–Plane Settlement Revisions," American Petroleum Institute, Washington, D.C., August, 2003.
4. "Survey Equipment," Rickley Hydrological Company, www.rickley.com/survey / surveying_equipment.htm, February 21, 1005.
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7 TABLES

Table 1: Current Out–of–Plane Settlement Criteria in API 653 Appendix B

Diameter, ft.	No. Settlement Readings	Max. Reading Spacing, ft.	Height (H1, H2), ft.	Allowable Settlement, in. for H1	Allowable Settlement, in. for H2
50	8	19.63	40, 48	0.77	0.64
80	8	31.42	40, 48	1.98	1.65
100	10	31.42	40, 48	1.98	1.65
120	12	31.42	40, 48	1.98	1.65
140	14	31.42	40, 48	1.98	1.65
180	18	31.42	40, 48	1.98	1.65
240	24	31.42	40, 48	1.98	1.65
300	30	31.42	40, 48	1.98	1.65

Note:

7. Y=36 ksi
8. E=29,000 ksi

Table 2: Other Proposed Out–of–Plane Settlement Criteria

Diameter, ft.	Height ft.	Allowable Settlement for Prop. 1, in.	Allowable Settlement for Prop. 2, in.	Ratio; API / Prop. 1	Ratio; API / Prop. 2
50	40	0.75	1.55	0.97	2.00
80	40	1.92	3.97	0.97	2.00
100	40	3.00	6.20	1.52	3.13
120	40	4.32	8.93	2.18	4.51
140	40	6.75	13.96	3.41	7.05
180	40	9.72	20.10	4.91	10.15
240	40	17.29	35.73	8.73	18.04
300	40	27.01	55.82	13.64	28.19

Note:

1. Y=36 ksi
2. E=29,000 ksi

Table 3: Basic FEA Parametric Study Test Matrix

Diameter x Height, ft.	Roof	YS, ksi	$S_{arc}(ft)$ (1), (2)	SS Also?	Natural Also?	Sine Also?
50 x 40	Open	36	20, 40, 60, 78.54, Fold	N	N	N
50 x 48	Open	36	20, 40, 60, 78.54, Fold	Y	Y	Y
50 x 40	Cone	36	20, 40, 60, 78.54, Fold	N	N	N
50 x 48	Cone	36	20, 40, 60, 78.54, Fold	N	N	N
80 x 40	Open	36	20, 40, 60, 80, 100, 125.66, Fold	N	N	N
80 x 48	Open	36	20, 40, 60, 80, 100, 125.66, Fold	Y	Y	N
80 x 40	Cone	36	20, 40, 60, 80, 100, 125.66, Fold	N	N	N
80 x 48	Cone	36	20, 40, 60, 80, 100, 125.66, Fold	N	N	N
120 x 40 (3)	Open	36	20, 40, 60, 80, 100, 120, 140, 160, 180.50, Fold	N	N	N
120 x 48	Open	36	20, 40, 60, 80, 100, 120, 140, 160, 180.50, Fold	Y	Y	Y
120 x 40 (3)	Cone	36	20, 40, 60, 80, 100, 120, 140, 160, 180.50, Fold	N	N	N
120 x 48	Cone	36	20, 40, 60, 80, 100, 120, 140, 160, 180.50, Fold	N	N	N
180 x 40	Open	36	20, 40, 60, 80, 100, 120, 140, 160, 200, 240, 260, 282.74, Fold	N	N	N
180 x 48	Open	36	20, 40, 60, 80, 100, 120, 140, 160, 200, 240, 260, 282.74, Fold	N	N	N
180 x 40	Cone	36	20, 40, 60, 80, 100, 120, 140, 160, 200, 240, 260, 282.74, Fold	N	N	N
180 x 48	Cone	36	20, 40, 60, 80, 100, 120, 140, 160, 200, 240, 260, 282.74, Fold	N	N	N

Table 3: Basic FEA Parametric Study Test Matrix

Diameter x Height, ft.	Roof	YS, ksi	$S_{arc}\left(ft\right)$ (1), (2)	SS Also?	Natural Also?	Sine Also?
240 x 48	Open	36	20, 40, 60, 80, 100, 120, 160, 180, 200, 240, 280, 320, 360, 376.99, Fold	Y	Y	Y
240 x 64	Open	36	20, 40, 60, 80, 100, 120, 140, 160, 180, 200, 240, 280, 320, 360, 376.99, Fold	N	N	N
240 x 48	Open	50	20, 40, 60, 80, 100, 120, 160, 200, 280, 360, 376.99, Fold	N	N	N
240 x 64	Open	50	20, 40, 60, 80, 100, 120, 160, 200, 280, 360, 376.99, Fold	N	N	N
300 x 48	Open	50	20, 40, 60, 80, 100, 120, 140, 160, 180 ,200, 240, 280, 320, 360, 400, 440, 471.24, Fold	N	N	N
300 x 64	Open	50	20, 40, 60, 80, 100, 120, 160, 200, 280, 360, 400, 471.24, Fold	N	N	N

Notes:

1. Typically 10 to 12 variations in S_{max} were run at each S_{arc} to obtain the 3.0% Strain and various OOR values.
2. The total number of FEA cases run was approximately 3700.
3. The effect of hydrostatic (product load) was examined for these models.

Table 4: Linear Fit to Open Tank Settlement Results

Diameter, ft.	Slope, K, FIT1 [(1)]	Slope, K, FIT2 [(2)]
$D \le 50$ ft	28.7	NA
50 ft $< D \le 80$ ft	7.8	NA
80 ft $< D \le 120$ ft	6.5	NA
120 ft $< D \le 180$ ft	2.5	4.0
180 ft $< D \le 240$ ft	1.8	3.6
240 ft $< D \le 300$ ft	1.1	2.4
300 ft $< D$	NA	NA

Notes:

1. See Figure 14 and Figure 15 for single linear fits for open tanks.
2. See Figure 14 for initial sloped line for second fit (bi–linear) for larger open roof tanks. In these cases, a horizontal line would be placed at a settlement limit of 4.0 inches.

Table 5: Linear Fit to Cone Roof Tank Settlement Results

Diameter, ft.	Slope, K, FIT1 [(1)]	Slope, K, FIT2 [(2)]
$D \le 50$ ft	10.5	NA
50 ft $< D \le 80$ ft	5.8	NA
80 ft $< D \le 120$ ft	3.9	NA
120 ft $< D \le 180$ ft	2.3	NA
180 ft $< D$	NA	NA

Notes:

1. See Figure 16 for linear fits for cone roof tanks
2. No bi–linear fits were developed for cone roof tanks.

Table 6: Sine versus Gaussian Fit for Applied Settlement Pattern

Diameter x Height, ft.	Shorter S_{arc}, $\frac{S_{max,3.0\%\ Gaussian}}{S_{max,3.0\%\ Sine}}$ [(1)]	Longer S_{arc}, $\frac{S_{max,3.0\%\ Gaussian}}{S_{max,3.0\%\ Sine}}$ [(2)]
50 x 48	0.7 to 0.9	0.6 to 0.9
120 x 48	0.6 to 0.7	0.7 to 1.0
240 x 48	0.6 to 1.0	1.0

Note:

1. Ratio of maximum settlement for 3.0% strain for the two assumed settlement curve fits for S_{arc} less than approximately 25% of tank circumference.
2. Ratio for S_{arc} greater than 25% of tank circumference.

8 FIGURES

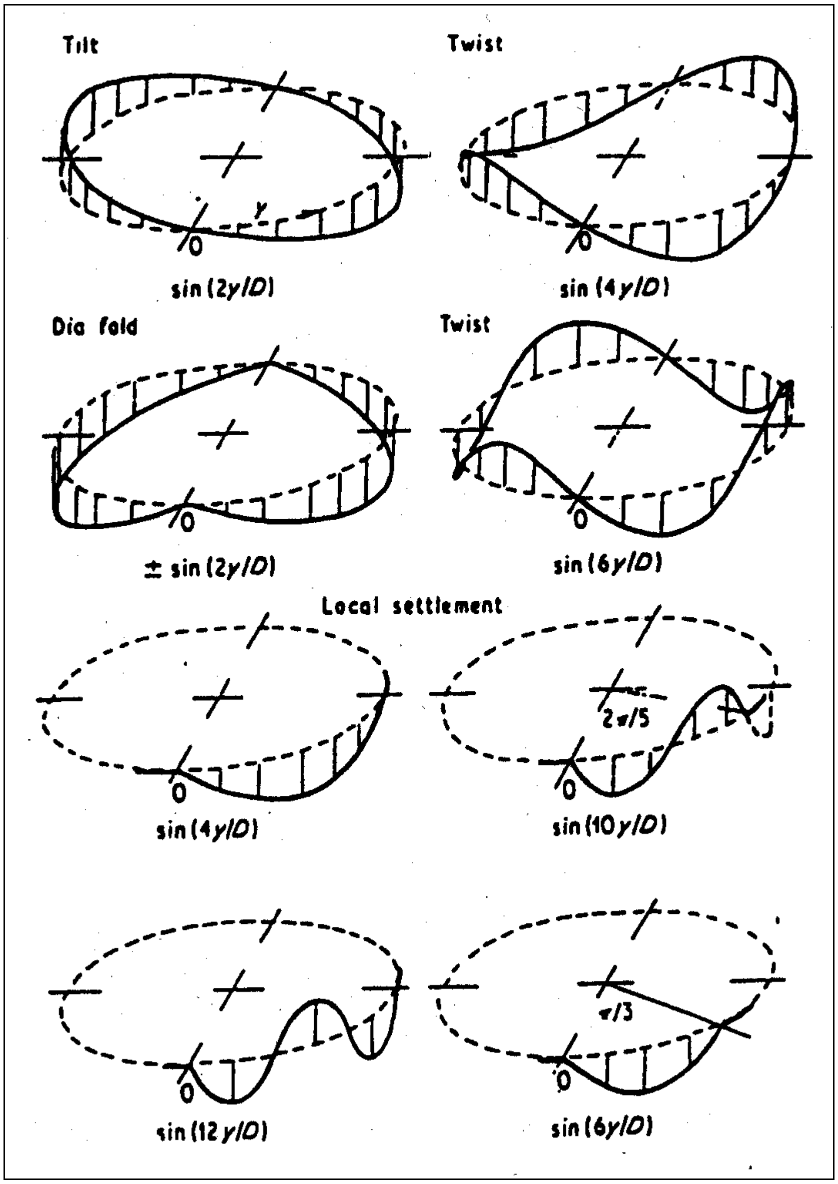


Figure 1: Shell Settlement Patterns – Ref. 1

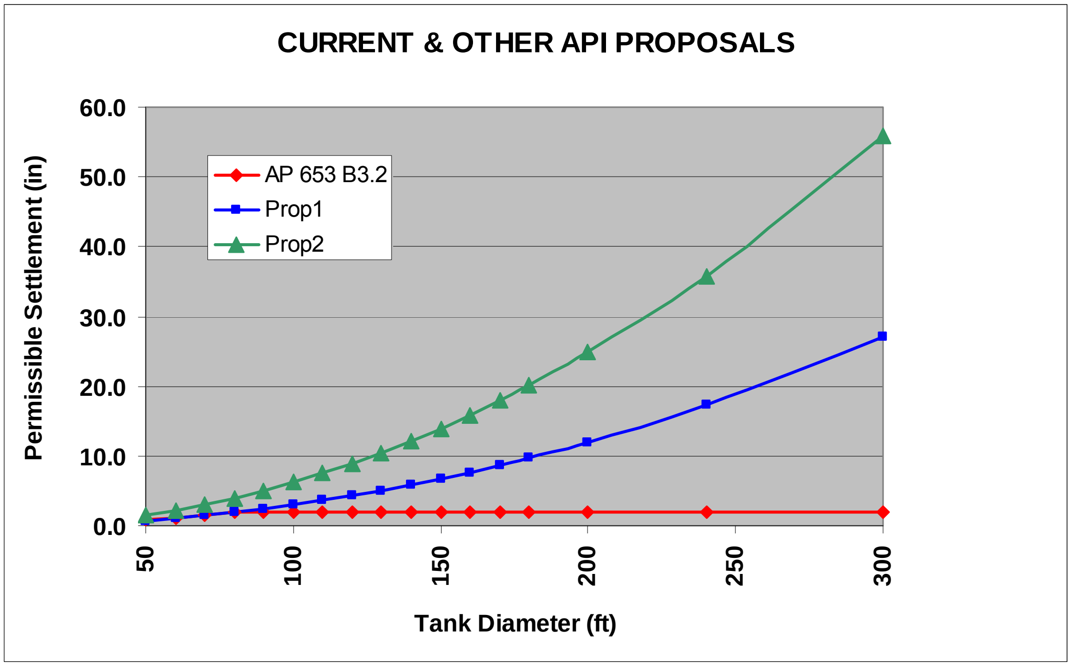


Figure 2: Comparison of Current and Two Early Proposals for OOP Settlement

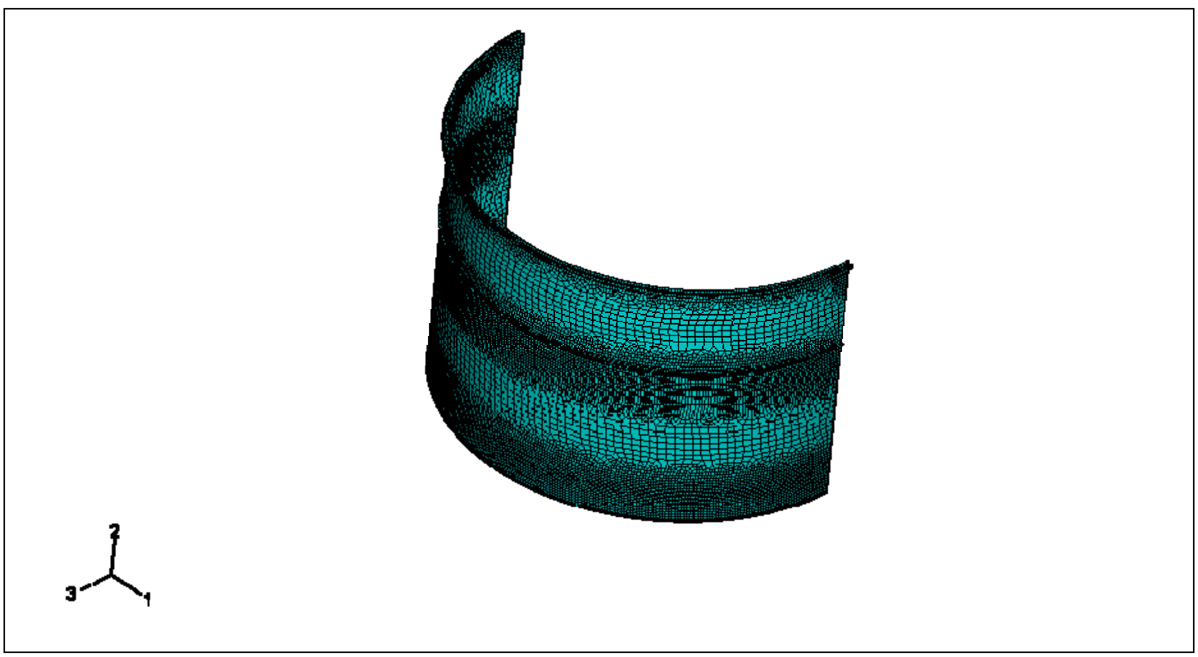


Figure 3: Typical Small Open Tank Model

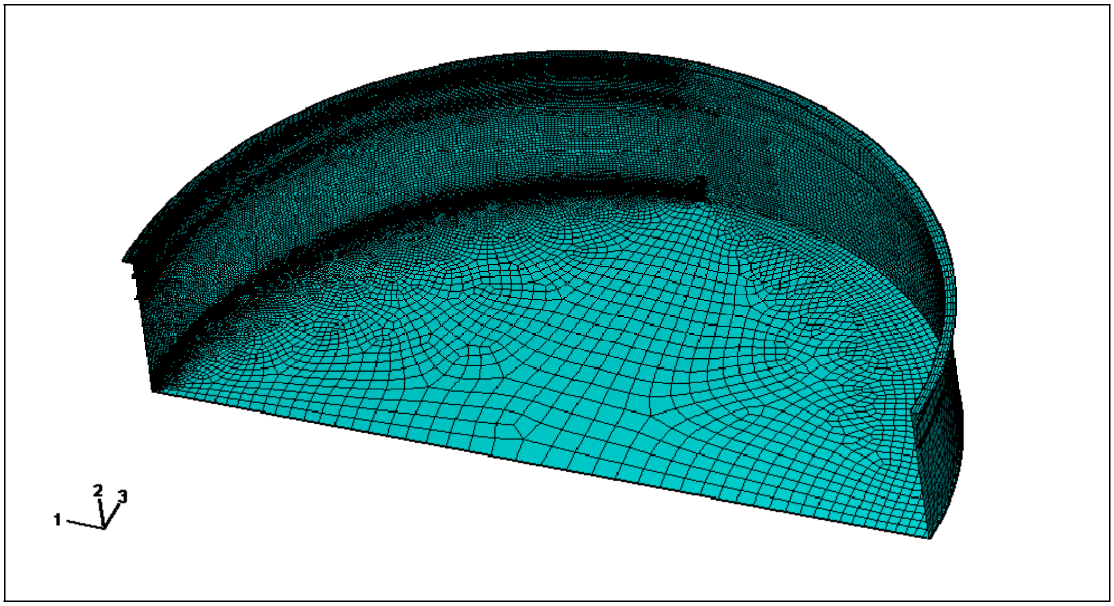


Figure 4: Typical Large Open Tank Model

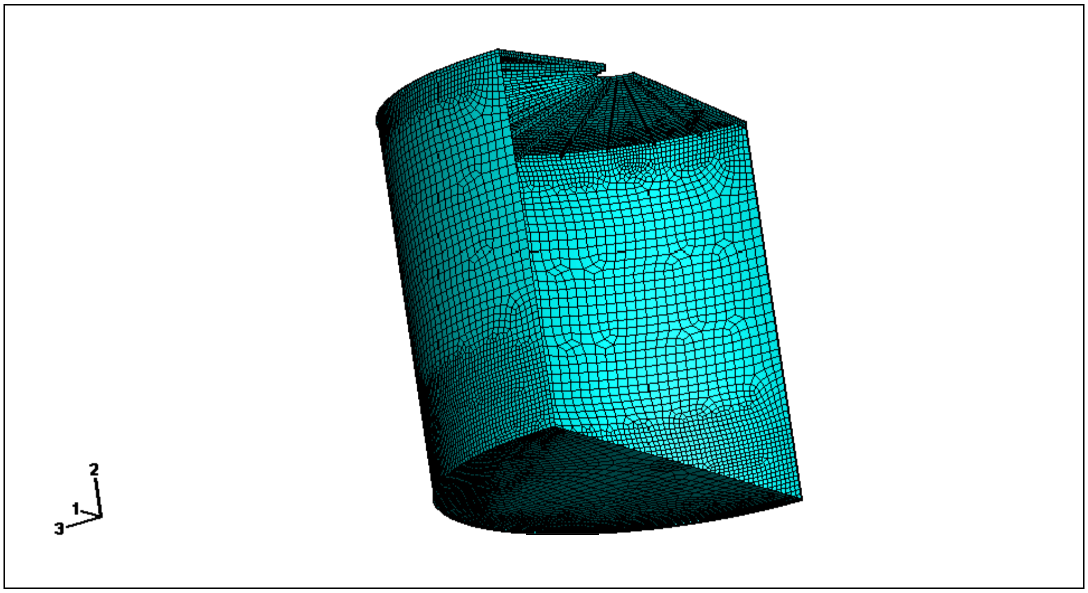


Figure 5: Typical Small Cone Tank Model

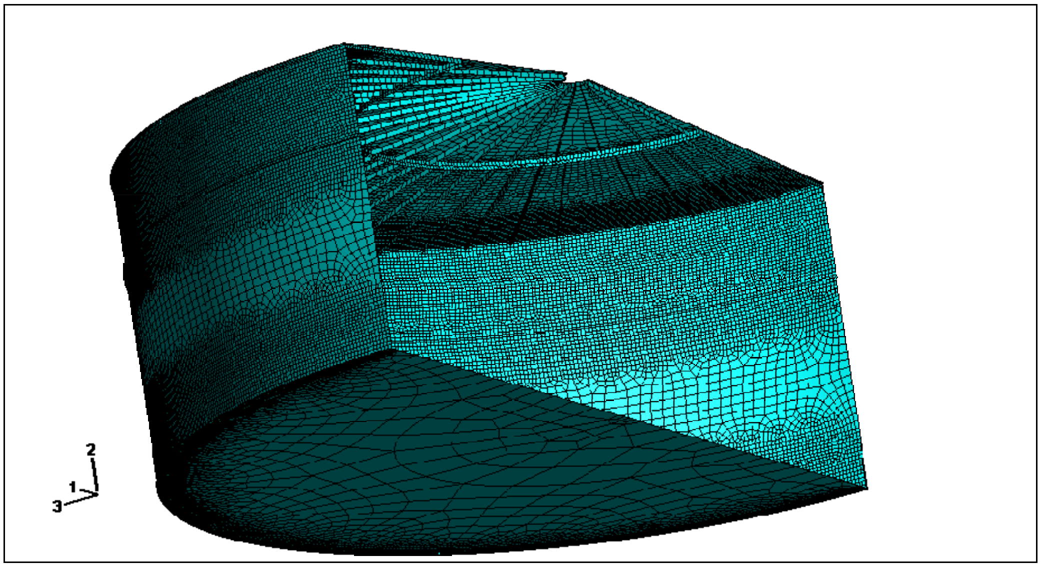


Figure 6: Typical Large Cone Tank Mode

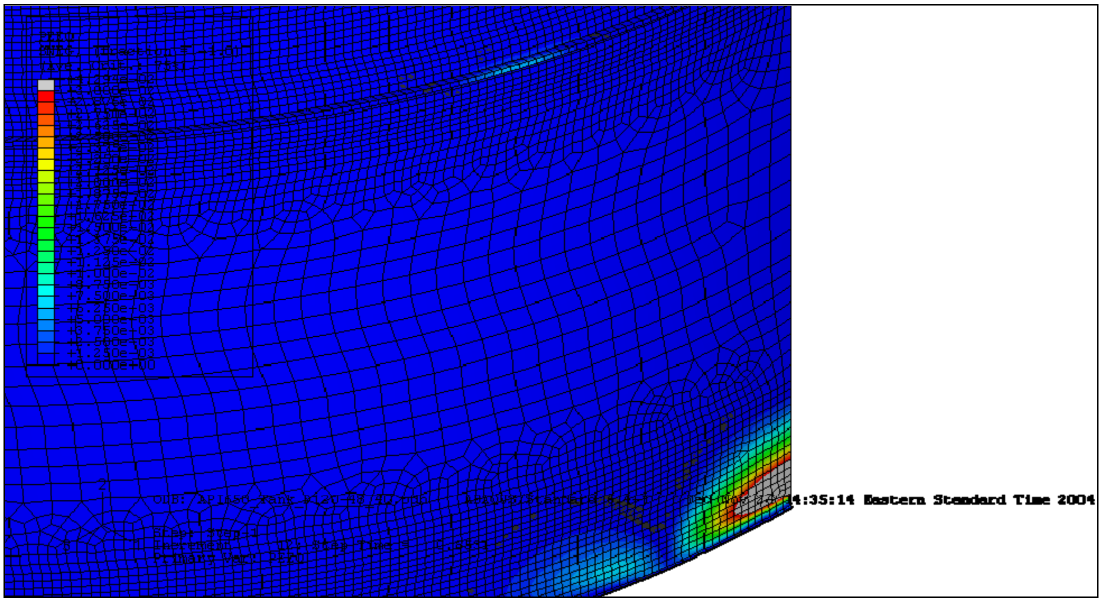


Figure 7: Typical Open Tank Strain Plot for Shorter Settled Arc: Bottom Course

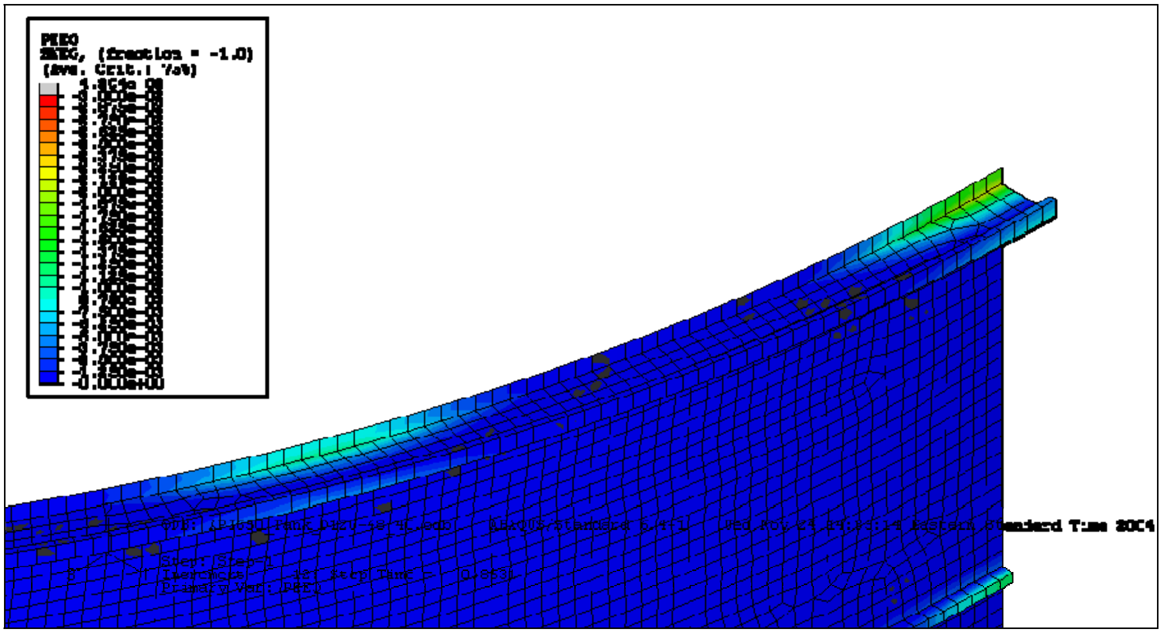


Figure 8: Typical Open Tank Strain Plot for Shorter Settled Arc: Top Course

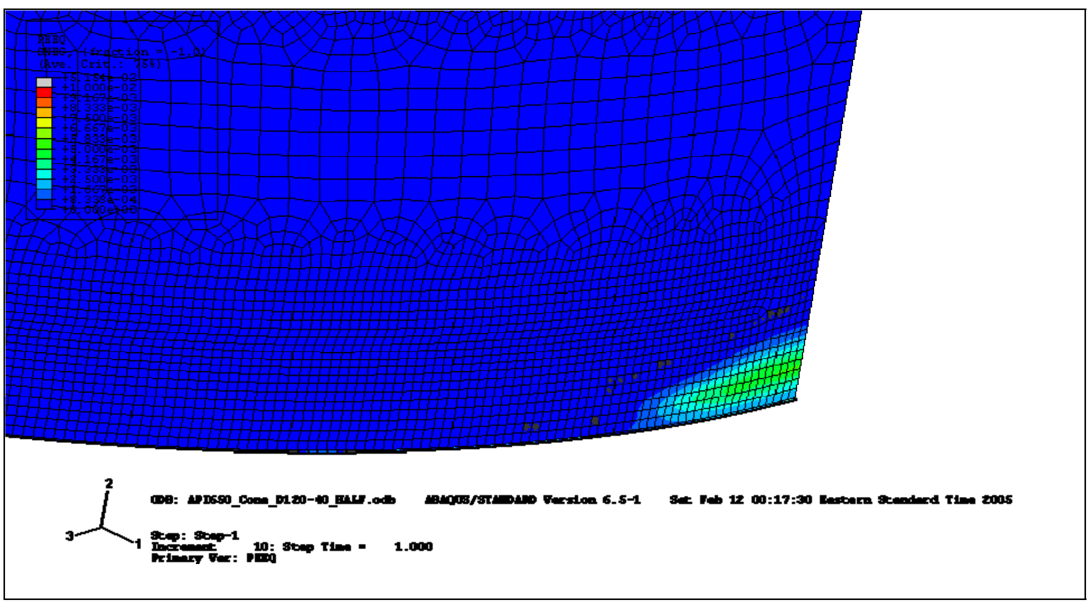


Figure 9: Typical Cone Roof Tank Strain Plot for Large Settled Arc: Bottom Course

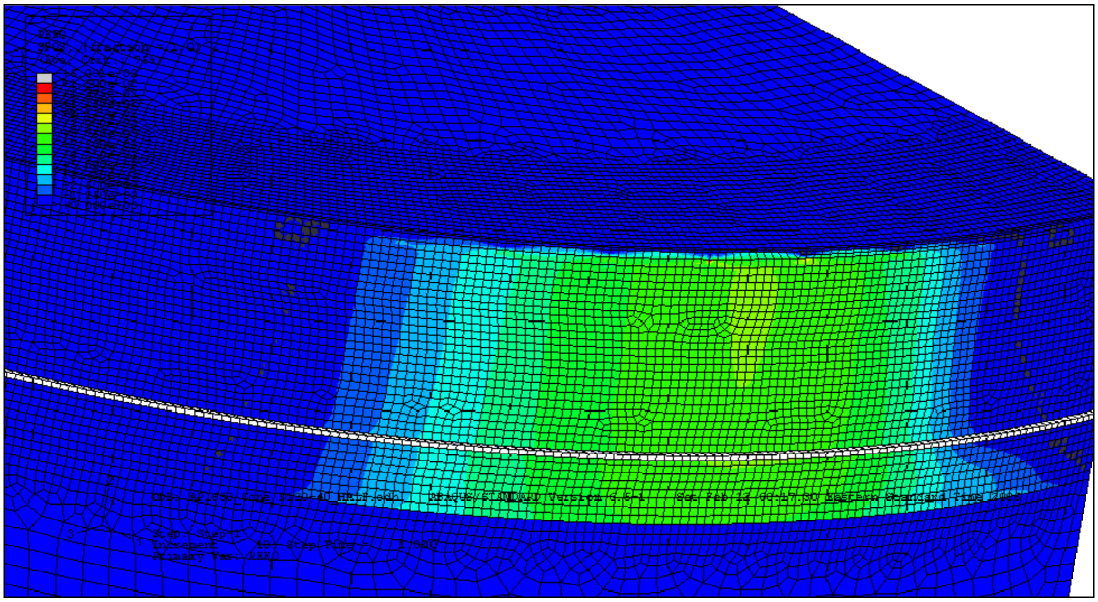


Figure 10: Typical Cone Roof Tank Strain Plot for Large Settled Arc: Top Course

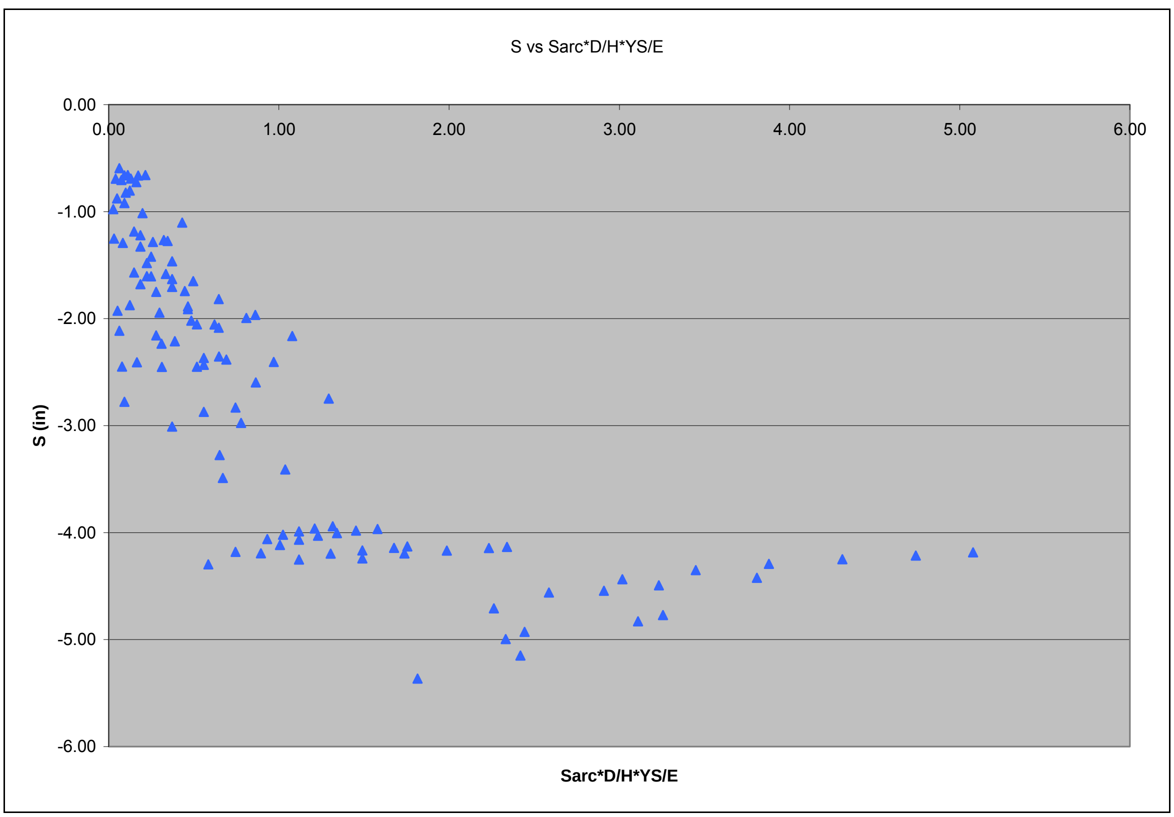


Figure 11: Data for Open Roof Tanks versus Proposed Parameter, $S_{aec}\left(\frac{D}{H}\right)\left(\frac{YS}{E}\right)$

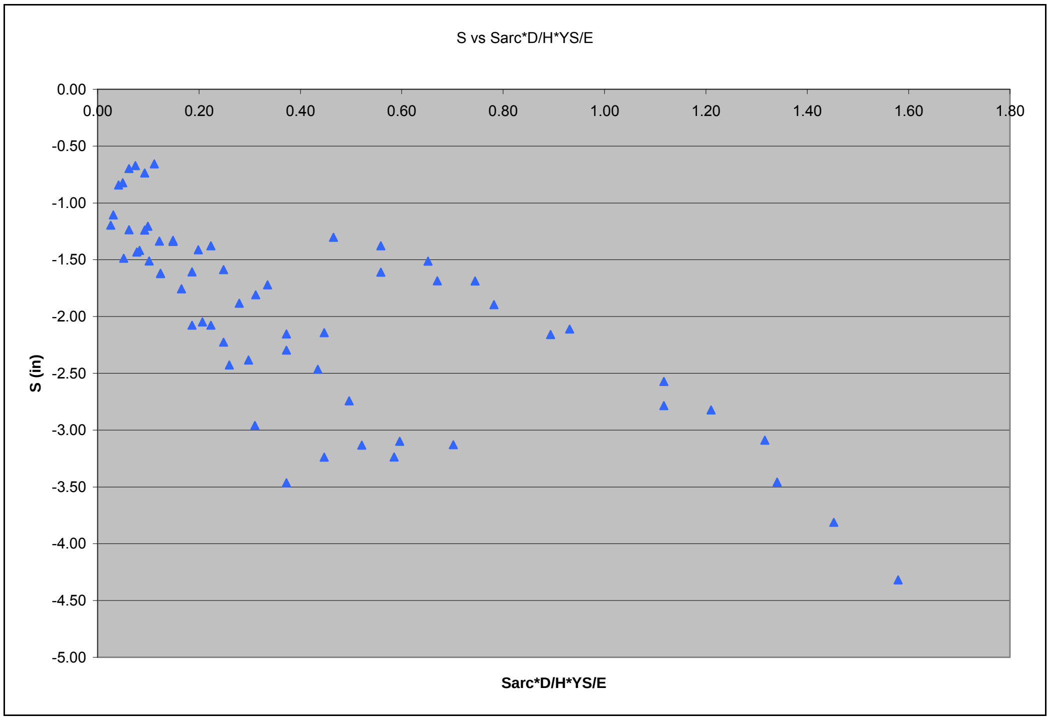


Figure 12: Data for Cone Roof Tanks versus Proposed Parameter, $S_{aec}\left(\frac{D}{H}\right)\left(\frac{YS}{E}\right)$

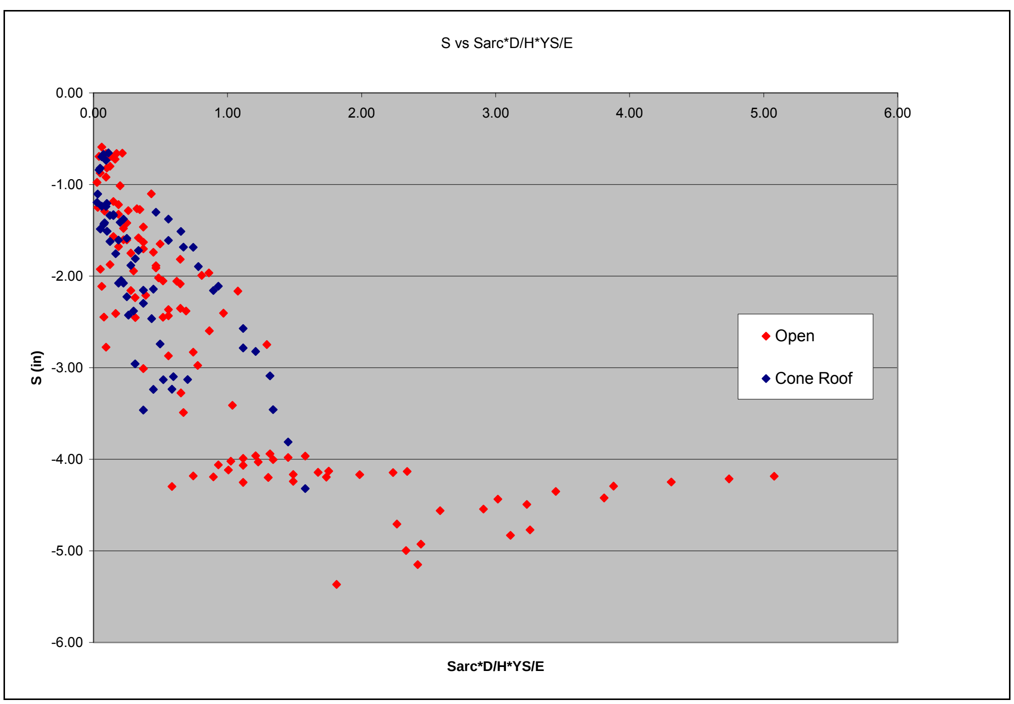


Figure 13: Data for All Tanks versus Proposed Parameter, $S_{aec}\left(\frac{D}{H}\right)\left(\frac{YS}{E}\right)$

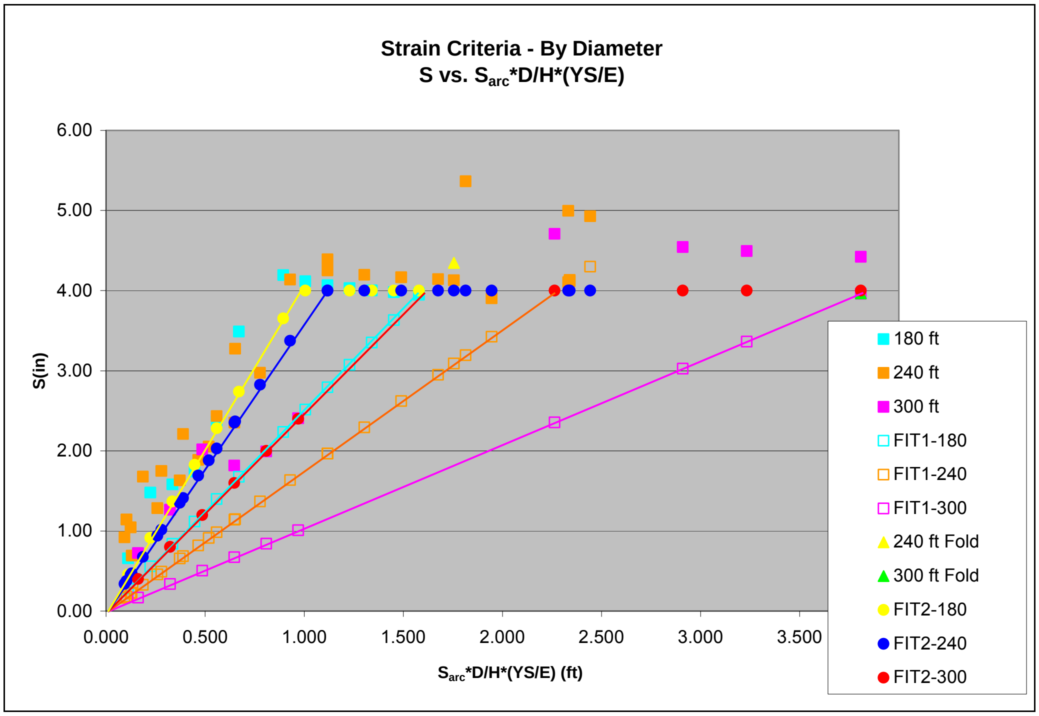


Figure 14: Curve Fit of Best Open Tank Strain Criterion: Larger Tanks

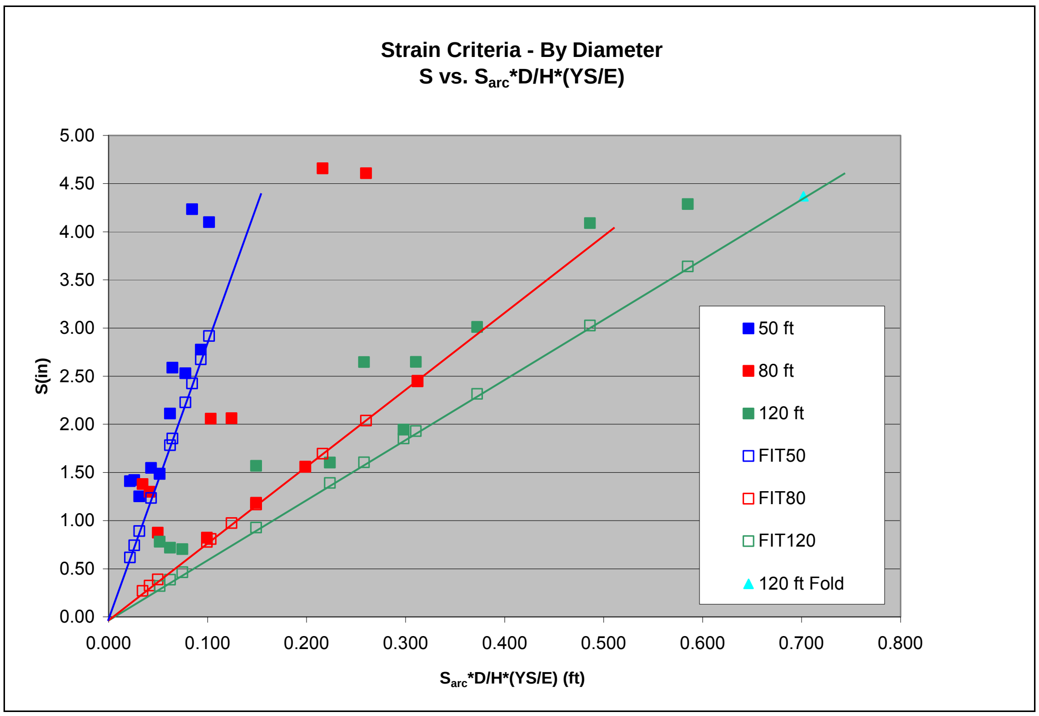


Figure 15: Curve Fit of Best Open Tank Strain Criterion: Smaller Tanks

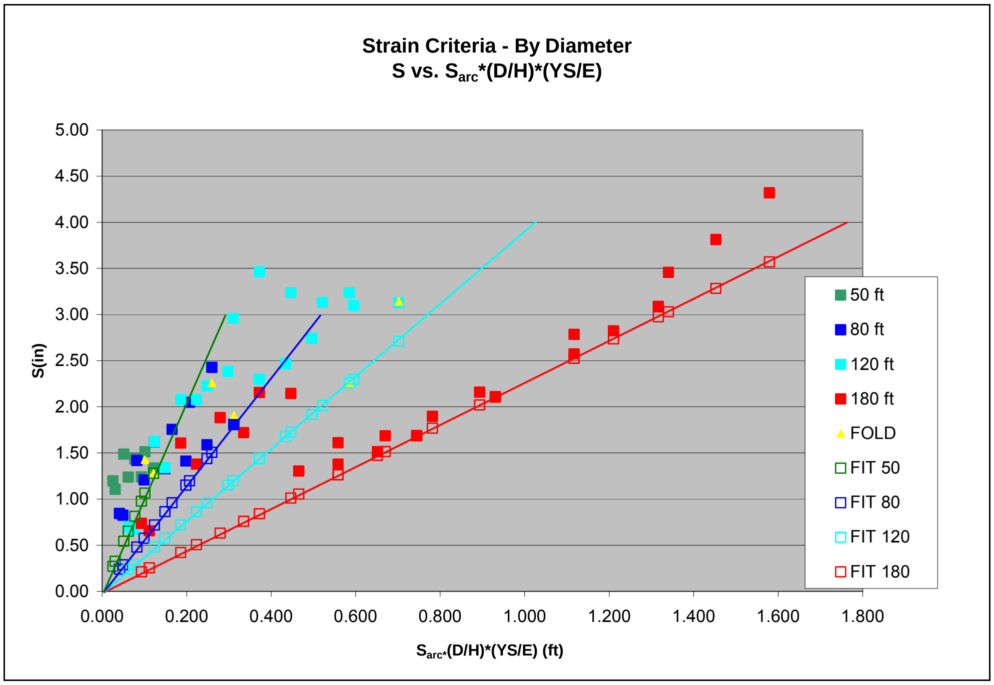


Figure 16: Curve Fit of Best Cone Tank Strain Criterion

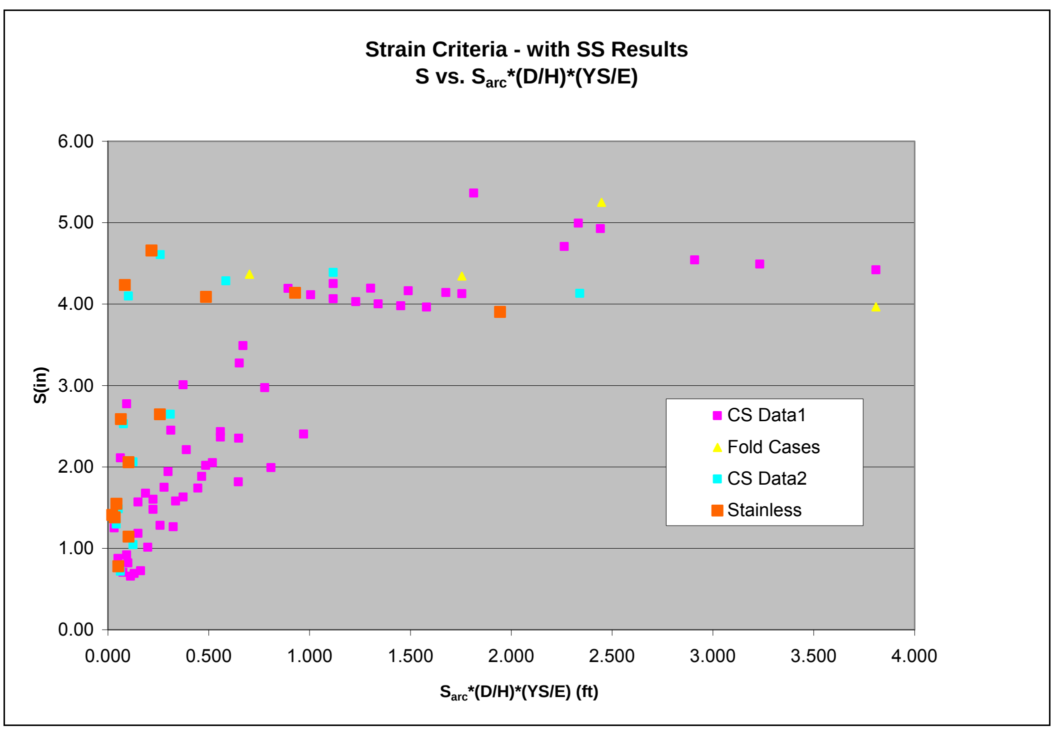


Figure 17: CS Data with SS Data: Best Fit Strain Criterion Curve

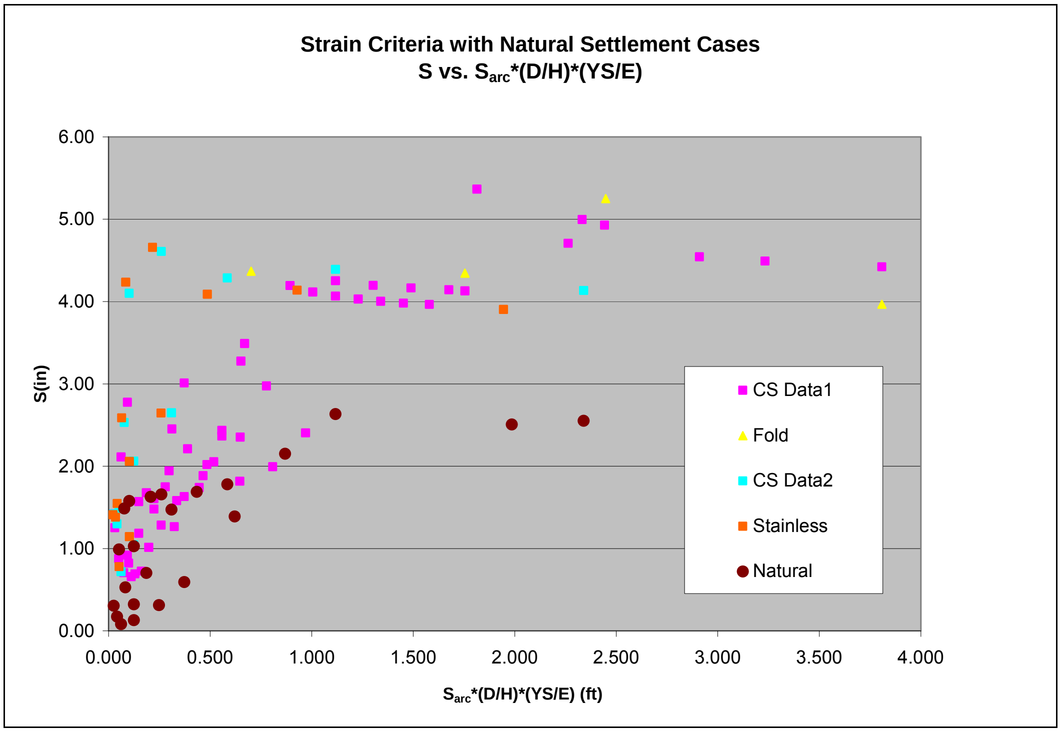


Figure 18: Natural Settlement Results with Applied Settlement Cases

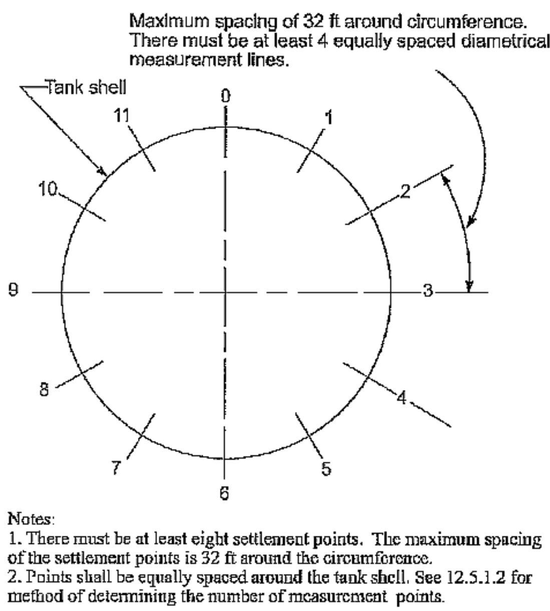


Figure B-1—Measurements of Shell Settlement (External)

Figure 19: Minimum Shell Settlement Measurement Locations (API 653 Fig. B–1)

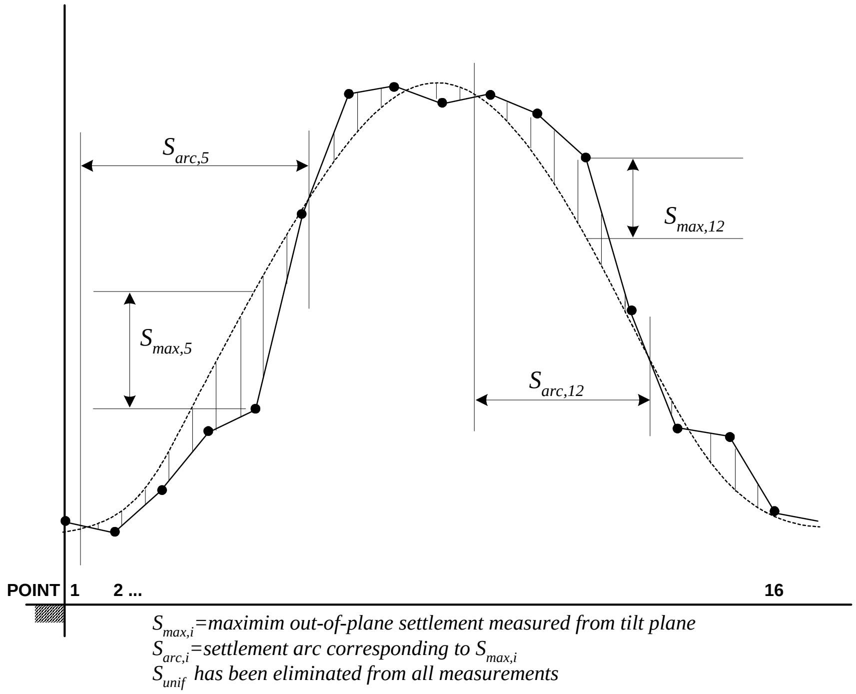


Figure 20: Settlement Measurements with an Optimal Tilt Plane

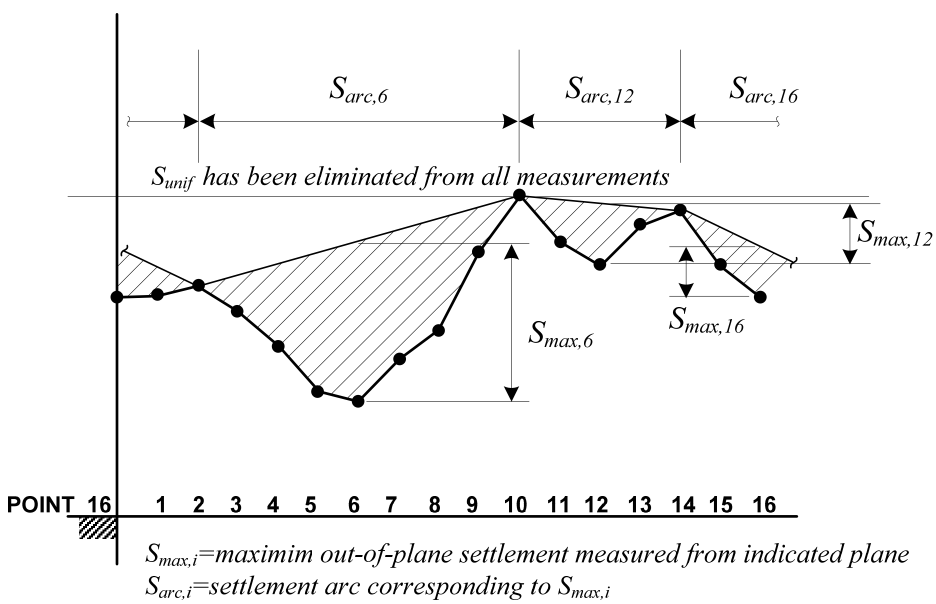
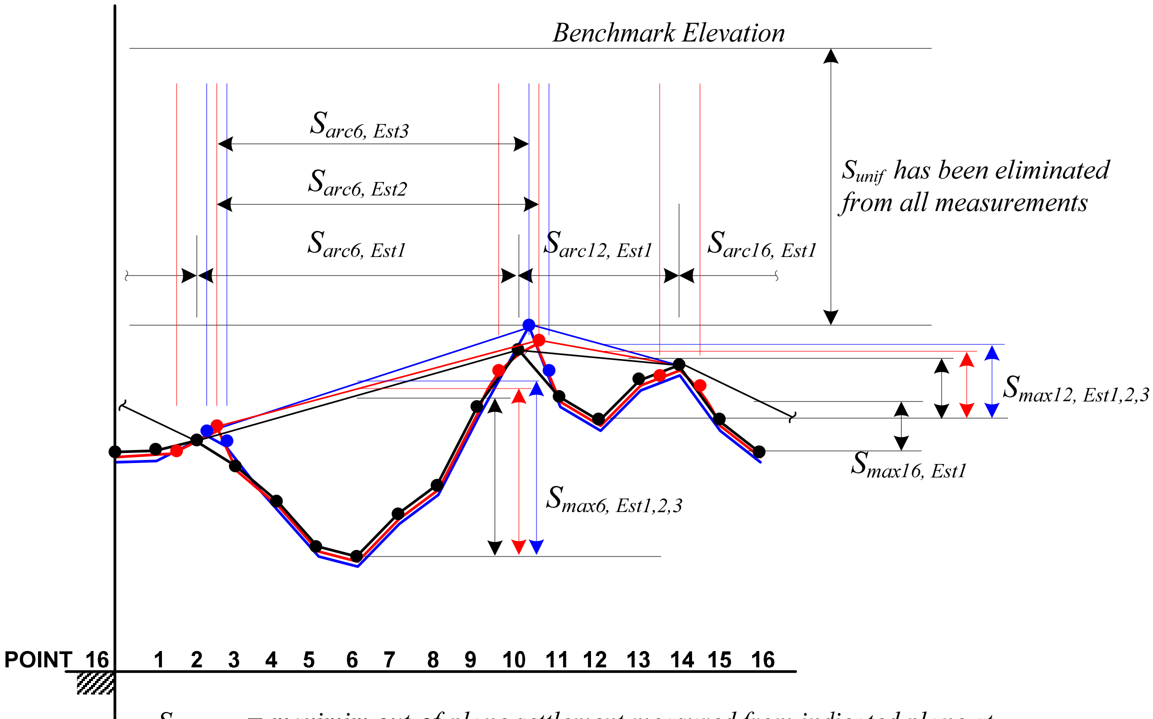


Figure 21: Settlement Measurements without an Optimal Tilt Plane



$S_{maxi,\ Estj}$ = maximim out-of-plane settlement measured from indicated plane at point i, for Estimate j

$S_{arci,\ Estj}$ = settlement arc corresponding to $S_{maxi,\ Estj}$

- *Initial meas. locations (Est1)*
- *Additional "half" points (Est2)*
- *Additional "quarter" points (Est3)*

Figure 22: Settlement Measurement Spacing Refinement

Four examples illustrated the proposed changes, but not part of the proposed API 653 revisions, are included below. The first is a case where a rigid tilt plane can be identified, but the out–of–plane settlement does not meet the current API B3.2 permissible value. The second is a case with a localized out–of–plane settlement that could not be fit with an optimal cosine curve defining a rigid tilt plane. A third has a rigid tilt plane meeting the current requirements, and the settlement meets the current B.3.2 permissible value, and the last has a localized shell settlement that does not meet the proposed revision and refinement of measurements will not help. In the second example, refinement of measurements is illustrated.

Example 1

A 150 foot x 40 foot external floating roof tank had a routine shell settlement survey. The material of the tank was an unknown carbon steel, with an assumed modulus of 29,000,000 psi and yield strength of 30,000 psi.

In accordance with 12.5.1.2, sixteen (16) equal–spaced measurement points were used:

$$N_{\min} = \frac{D}{10} = \frac{150}{10} = 15 \; (\textit{rounded to next even number})$$

Measurements were taken with standard surveying devices of sufficient accuracy. The measured data was recorded relative to a benchmark (given below in inches):

POINT	1	2	3	4	5	6	7	8
$\lvert EL_{actual} \rvert$	12.60	10.33	9.40	8.20	7.00	5.30	3.90	3.36

POINT	9	10	11	12	13	14	15	16
$\lvert EL_{actual} \rvert$	3.10	3.50	3.00	5.40	6.60	8.10	9.50	10.20

The uniform settlement of 3.0 inches was subtracted from all data points and the resulting data set was input into a commercial curve fitting program was used to determine a possible least squares fit. Using the statistical measure of fit, $R^2 \geq 0.90$, an optimum cosine curve fit for the rigid tilt plane was found to be:

$$EL_{pred} = -3.70 + 3.52 \times \cos\left[\left(\frac{2\pi x}{471.24} + 4.00\right) - \frac{\pi}{2}\right] \textit{inches}$$

Based on 16 settlement points, the settlement measurement spacing was calculated:

$$L = 150 * \pi / 16 = 29.45 \; ft$$

Using the proposed equation in B.3.2.1 (current B.3.2), the permissible settlement was found to be 0.123 ft (1.48 inches).

$$|S| = \frac{(29.45)^2 \times 30,000 \times 11}{2(29,000,000 \times 40)} = 0.123\ ft$$

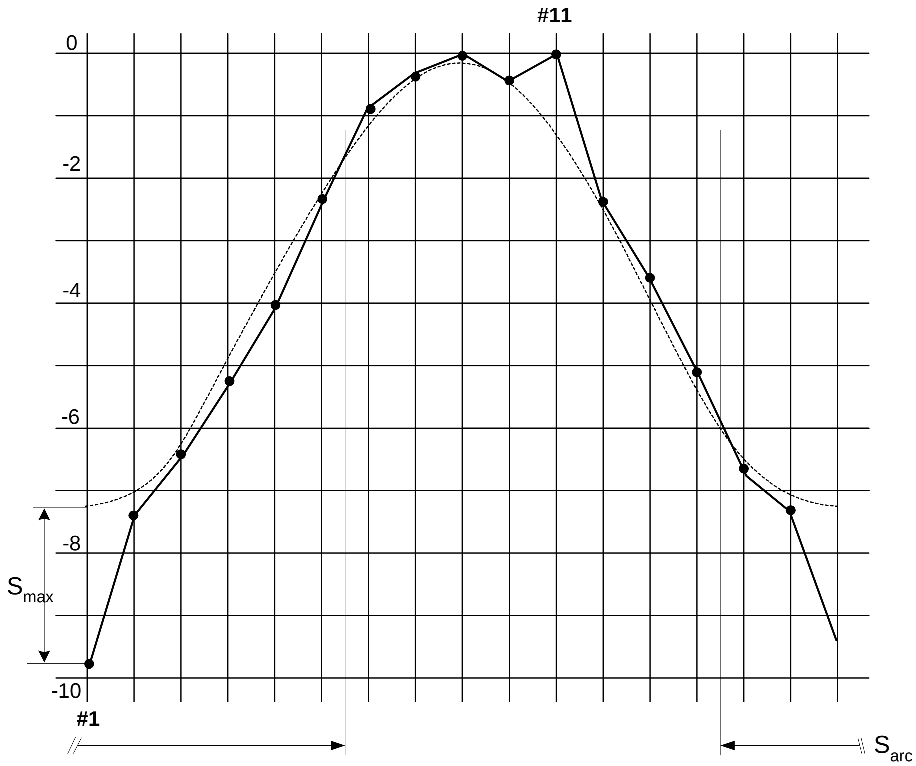
The actual out–of–plane settlement was determined from the residuals of the actual settlements and values predicted by the curve fit, and the out–of–plane settlement was calculated using the procedure in Figure B–3. The data and resulting calculations are shown in the following table:

POINT	1	2	3	4	5	6	7	8
$\lvert EL_{pred} \rvert$	7.21	6.85	6.00	4.81	3.44	2.12	1.04	0.36
$\lvert EL_{actual} \rvert$	9.60	7.33	6.40	5.20	4.00	2.30	0.90	0.36
$\lvert U_i \rvert$	2.39	0.48	0.40	0.39	0.56	0.18	0.14	0.00
$\lvert S_i \rvert$	2.07	0.91	0.04	0.08	0.27	0.17	0.23	0.11

POINT	9	10	11	12	13	14	15	16
$\lvert EL_{pred} \rvert$	0.19	0.55	1.40	2.59	3.96	5.28	6.36	7.04
$\lvert EL_{actual} \rvert$	0.10	0.50	0.00	2.40	3.60	5.10	6.50	7.20
$\lvert U_i \rvert$	0.09	0.05	1.40	0.19	0.36	0.18	0.14	0.16
$\lvert S_i \rvert$	0.06	0.69	1.27	0.68	0.17	0.07	0.15	1.10

Notes:
Actual settlement values are negative
All values in inches

The out–of–plane settlement at Point #1 (2.07 inches) exceeds the value. At Point #11, out–of–plane settlement is also significant (1.27 inches), but meets the B.3.2.1 (current B3.2) permissible value.



From the settlement data plot above, the settlement arc length, S_{arc}, for out–of–plane settlement at Point #1 was found to be between 7 and 8 times the measurement spacing or:

$$S_{arc} = 7.0 \times 29.45 = 206.17 \ ft$$

$$to$$

$$S_{arc} = 8.0 \times 29.45 = 235.62 \ ft$$

Conservatively, the value of 206.17 feet was used in the determination of the permissible settlement per B.3.2.2. For an open tank and D = 150 feet, K = 4.0

$$S_{max} = min\left[4.0 \times S_{arc} \times \left(\frac{D}{H}\right) \times \left(\frac{Y}{E}\right), 4.0 \ inches\right]$$

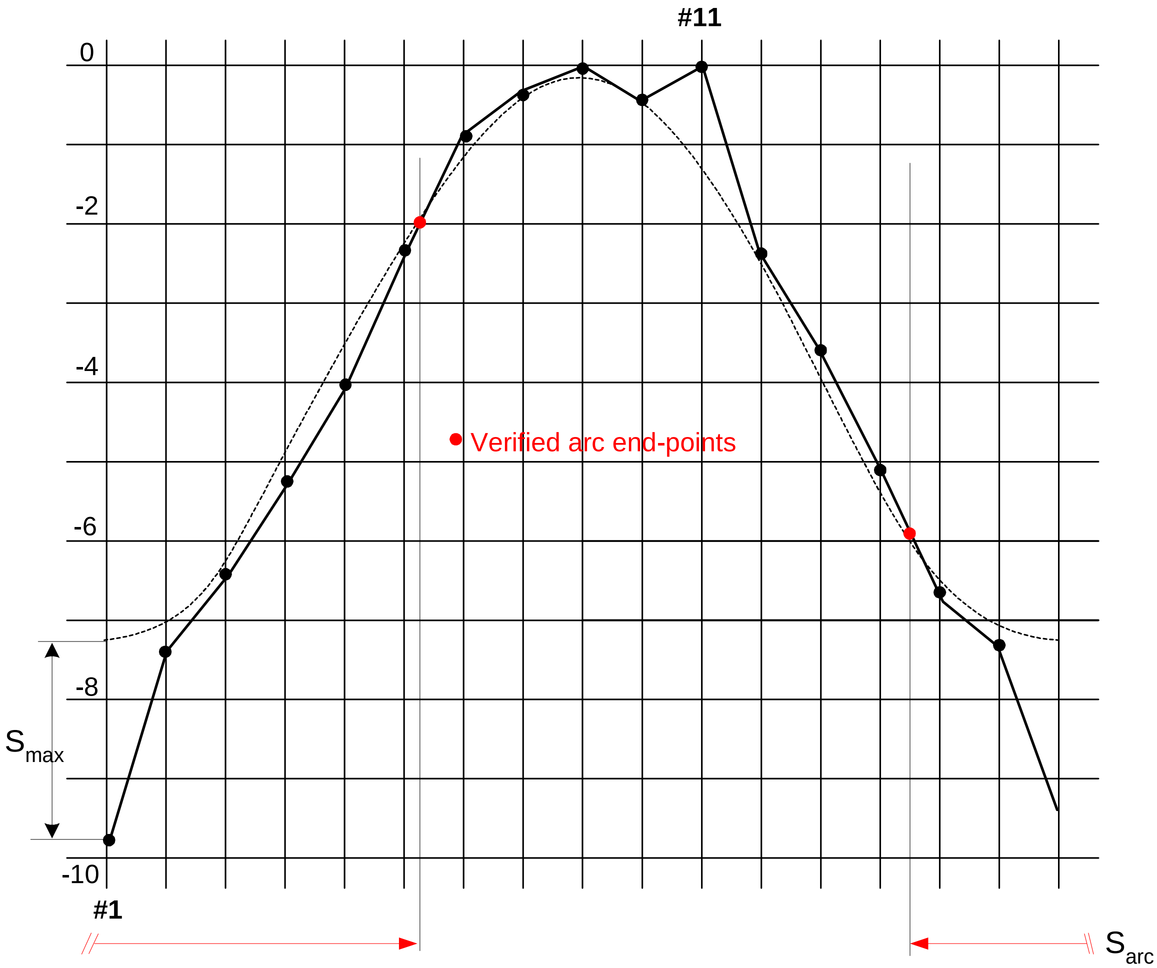
$$S_{max} = 4.0 \times 206.17 \times \left(\frac{150}{40}\right) \times \left(\frac{30{,}000}{29{,}000{,}000}\right) = 3.20 \, inches$$

At Point #1, the maximum out–of–plane settlement was measured from the previous plot to be:

$$S_{max} = 2.39 \, inches$$

This value is 75% of the B.3.2.2 allowable and the settlement is acceptable. Additional measurements taken at the quarter points of the original settlement measurements were used to improve the confidence in the determination of the settlement arc length. The revised plot below shows the additional measurements (at the quarter points of the other measurements) that verified the arc length as 7.75 times the original basic spacing of measurements, or the allowable could be increased to:

$$S_{arc} = 7.75 * 29.45\, ft. = 228.25\, ft.$$



Using this full value the settlement arc, the permissible settlement per equation B.3.2.2 becomes:

$$S_{max} = min\left[4.0 \times S_{arc}\left(\frac{D}{H}\right) \times \left(\frac{YS}{E}\right), 4.0\ inches\right]$$

$$S_{max} = 4.0 \times 228.25 \times \left(\frac{150}{40}\right) \times \left(\frac{30,000}{29,000,000}\right) = 4.0\, inches$$

In any case, the maximum settlement of 2.39 inches is less than the allowable based on strain criteria. The serviceability of the tank may be an issue and the Owner may specify additional inspection to determine if the out–of–roundness has effected the floating roof's operation. The Owner may also wish to set the next out–of–service settlement measurement based on an examination of the rate of settlement between the last two surveys.

Example 2

A 120 foot x 40 foot external floating roof tank had a routine shell settlement survey. The material of the tank was A 131 material with yield strength of 34,000 psi. The tank was assumed to have a modulus of 29,000,000 psi.

In accordance with 12.5.1.2, a minimum of twelve settlement data points would be required:

$$N_{\min} = \frac{D}{10} = \frac{120}{10} = 12$$

However, sixteen (16) equal–spaced measurements were taken, for a settlement measurement spacing of:

$$L = 120 * \pi / 16 = 23.56\,ft$$

Measurements were taken with standard surveying devices of sufficient accuracy. The measured data was recorded relative to a benchmark (given below in inches):

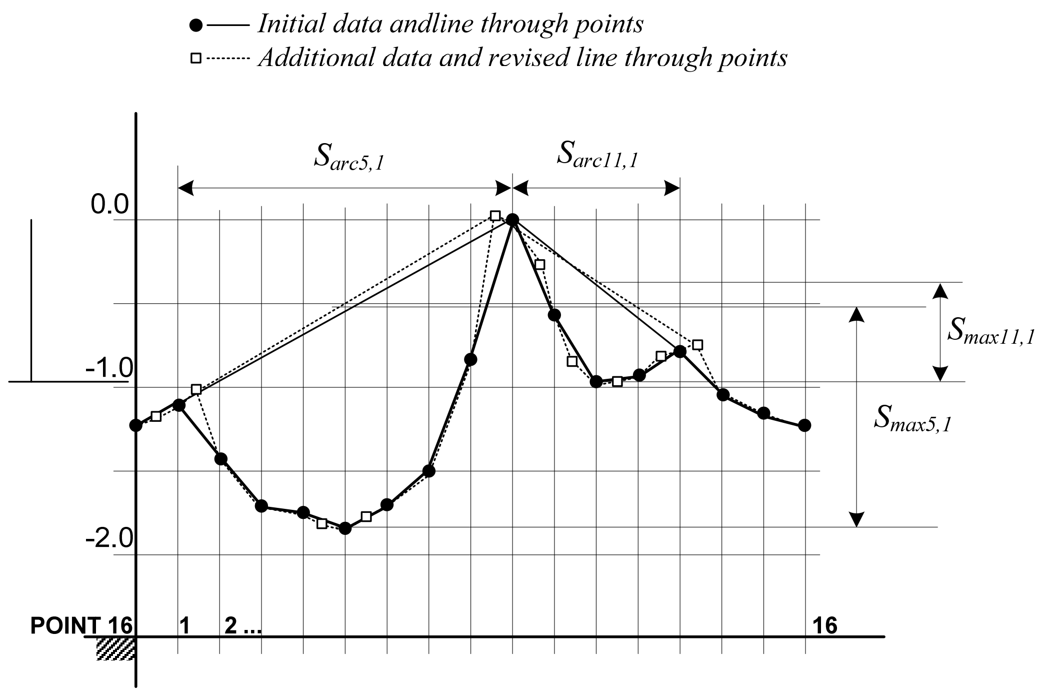
The settlement data, with uniform settlement eliminated, are given in the following table:

POINT	1	2	3	4	5	6	7	8
$\lvert EL_{actual} \rvert$	1.10	1.42	1.70	1.73	1.84	1.63	1.50	0.80
$\lvert S_i \rvert$					1.32			

POINT	9	10	11	12	13	14	15	16
$\lvert EL_{actual} \rvert$	0.00	0.54	0.97	0.90	0.80	1.05	1.20	1.17
$\lvert S_i \rvert$			0.59					

Notes:
Actual settlement values are negative
All values in inches

The data is also plotted in the following graph:



$S_{maxi,1}$ = *maximum out-of-plane settlement measured from indicated plane*
$S_{arci,1}$ = *settlement arc corresponding to* $S_{maxi,1}$ *for the 1st settlement readings*
S_{unif} *has been eliminated from all measurements*

A valid rigid tilt plane defined by a cosine curve fit could not be determined for the tank. The current API 653 procedure could not be used.

From the settlement data plot, the settlement arc length, S_{arc}, for out–of–plane settlement for Point #5 was found to be approximately eight times the measurement spacing (half the circumference – a limiting value). Additional measurements were taken to determine a better estimate of settled arc. These are shown in the figure. The final estimate for the settlement arc at Point #5 was 7.0 times the spacing considered, or:

$$S_{arc} = 7.0 \times 23.56 = 164.9\ ft$$

Using this value, the permissible settlement per equation B.3.2.2 becomes:

$$S_{max} = min\left[6.5 \times S_{arc}\left(\frac{D}{H}\right) \times \left(\frac{Y}{E}\right),\ 4.0\ inches\right]$$

$$S_{max} = min\left[6.5 \times 164.9 \times \left(\frac{120}{40}\right) \times \left(\frac{34,000}{29,000,000}\right), 4.0\right] = 3.77\ inches$$

From the graph of plotted data, the maximum out–of–plane settlement at Point #5 is estimated at:

$$S_{max} = 1.84 - 0.52 = 1.32\ inches$$

The maximum settlement at Point #5 is less than the permissible settlement with a conservative assumption for the settled arc so no further data collection is needed.

Similarly, checking Point #11, the settlement arc length for Point #11 is 3.0 to 4.0 times one–half the arc for Point #5, or conservatively:

$$S_{arc} = 3.0 \times 23.56 = 70.7\ ft$$

Using this value, the permissible settlement per equation B.3.2.2 becomes:

$$S_{max} \ = \ 6.5 \times 70.7 \times \left(\frac{120}{40}\right) \times \left(\frac{34,000}{29,000,000}\right) = 1.62\, inches$$

From the graph, the maximum out–of–plane settlement at point #11 is:

$$S_{max} = 0.97 - 0.39 = 0.58\ inches$$

The maximum settlement at Point #11 is also less than the permissible settlement. By inspection, the settlement between the areas for point #5 and point #11 is acceptable.

Maximum settlements of the regions locally settled are less than the allowable based on strain criteria. The serviceability of the tank may be an issue and the Owner may specify additional inspection to determine if the out–of–roundness has effected the floating roof's operation. The Owner may also wish to set the next out–of–service settlement measurement based on an examination of the rate of settlement between surveys.

Example 3

A 140 foot x 48 foot cone roof tank had a routine shell settlement survey. The material of the tank was an unknown carbon steel with an assumed modulus of 29,000,000 psi and yield strength of 30,000 psi.

In accordance with 12.5.1.2, fourteen (14) equal–spaced settlement measurements were used:

$$N_{\min} = \frac{D}{10} = \frac{140}{10} = 14$$

Measurements were taken with standard surveying devices. The measured data was recorded relative to a benchmark (given below in inches with uniform settlement eliminated):

POINT	1	2	3	4	5	6	7
$\left\| EL_{actual} \right\|$ (2)	1.00	2.00	4.20	6.00	7.00	9.00	9.30

POINT	8	9	10	11	12	13	14
$\lvert EL_{actual} \rvert$ (2)	9.50	8.00	5.80	3.80	2.00	1.00	0.50

The data is also plotted in the figure at the end of this problem.

A computer curve fitting program was used as a permissible alternative to the least squares fit procedure found in B.2.2.4 and an optimal cosine curve fit for the rigid tilt plane was found to be:

$$EL_{pred} = -5.0 + 4.5 \times \cos\left[\left(\frac{2\pi x}{440.} + 2.0\right) - \frac{\pi}{2}\right] inches$$

Results of the application of current least squares approach for this same curve fit and data are also shown below for comparison, where in accordance with B.2.2.4.e:

$$R^2 = \frac{\left(S_{yy} - SSE\right)}{S_{yy}}$$

where

S_{yy} = *sum of the squares of the differences between average measured elevation and the measured elevations,*

SSE = *sum of the square of the differences between the measured and predicted elevations*

POINT	1	2	3	4	5	6	7
$\lvert EL_{pred} \rvert$	0.91	2.13	3.91	5.91	7.73	9.01	9.50
$\lvert EL_{actual} \rvert$	1.00	2.00	4.20	6.00	7.00	9.00	9.30
S_{yy}	15.5	8.62	0.54	1.13	4.26	16.5	19.0
SSE	0.01	0.02	0.08	0.01	0.54	0.00	0.04
$\lvert U_i \rvert$	0.09	0.13	0.29	0.09	0.73	0.01	0.20
$\lvert S_i \rvert$	0.16	0.32	0.31	0.31	0.77	0.45	0.40

POINT	8	9	10	11	12	13	14
$\left\|EL_{pred}\right\|$	9.09	7.88	6.09	4.09	2.27	0.99	0.50
$\left\|EL_{actual}\right\|$	9.50	8.00	5.80	3.80	2.00	1.00	0.50
S_{yy}	20.8	9.39	0.75	1.29	8.62	15.5	19.7
SSE	0.16	0.01	0.09	0.09	0.07	0.00	0.00
$\left\|U_i\right\|$	0.41	0.12	0.29	0.29	0.27	0.01	0.00
$\left\|S_i\right\|$	0.44	0.07	0.21	0.01	0.13	0.15	0.05

The calculated statistical quantities for a least squares approach would be:

$S_{avg} = -4.94$, $\sum S_{yy} = 141.65$, $\sum SSE = 1.12$, and the resulting $R^2 = 0.99$

Based on 14 settlement data points, the settlement measurement spacing was calculated:

$$L = 140 * \pi / 14 = 31.42 \ ft$$

Using the equation in B.3.2.1 (current B.3.2), the permissible settlement was found to be 0.12 ft (1.40 inches).

$$|S| = \frac{(31.42)^2 \times 30,000 \times 11}{2(29,000,000 \times 48)} = 0.12 \ ft$$

The out–of–plane settlement at each point (see table above) was determined from:

$$U_i = EL_{actual,i} - EL_{predicted,i}$$

and

$$S_i = U_i - \left(\tfrac{1}{2} U_{i-1} + \tfrac{1}{2} U_{i+1} \right)$$

The actual out-of–plane settlement ranges from 0.01 inches at Point #11 to 0.77 inches at Point #5 (see table above).

The permissible value is 0.12 ft. or 1.40 inches. All the current shell settlement points meet the B.3.2.1 criterion. No additional analyses would be required. The Owner may wish to set the next out–of–service settlement measurement based on an examination of the rate of settlement between the last two surveys.

Example 4

A 90 foot x 40 foot cone roof tank had a routine shell settlement survey. The material of the tank was A36 modified material, with a modulus of 29,000,000 psi and yield strength of 36,000 psi.

In accordance with 12.5.1.2, ten (10) equal–spaced measurements were used:

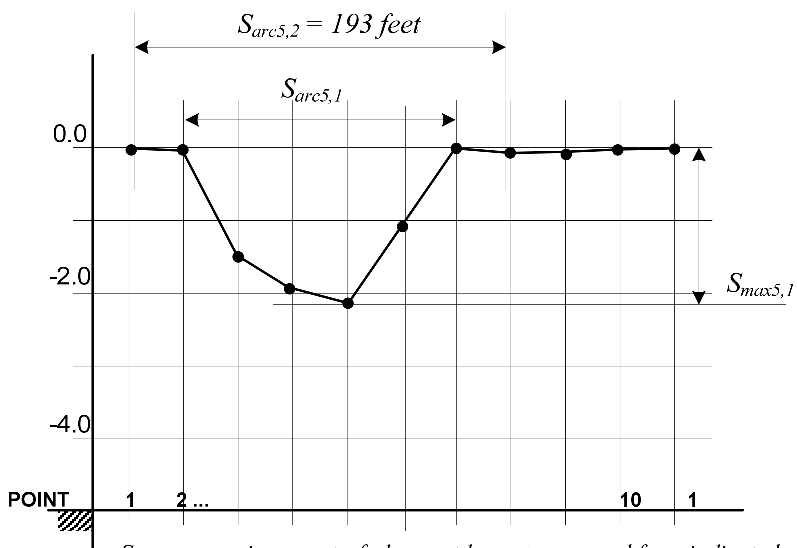
$$N_{\min} = \frac{D}{10} = \frac{9}{10} = 9 \ \left(rounded\ to\ next\ even\ number\right)$$

The settlement spacing was:

$$L = 90 * \pi / 10 = 28.27\ ft$$

Measurements were taken with standard surveying devices of sufficient accuracy. The measurements were recorded relative to a benchmark, and are given in the table below (in inches with uniform settlement eliminated) and in the following graph:

POINT	1	2	3	4	5	6	7	8	9	10
$\lvert EL_{actual} \rvert$	0.02	-0.11	-1.61	-1.91	-2.10	-1.09	0.00	-0.14	-0.11	0.01



$S_{max5,1}$ = maximum out-of-plane settlement measured from indicated plane
$S_{arc5,1}$ = settlement arc corresponding to S_{max5} for 1st set of measurements
$S_{arc5,2}$ = settlement arc corresponding to 193 feet required for S_{max5} to be acceptable
S_{unif} has been eliminated from all measurements

By inspection, a valid rigid tilt plane cannot be determined for the tank. The current API 653 procedure could not be used. From the settlement data plot, the initial estimate for the settlement arc length, $S_{arc5,1}$, for out–of–plane settlement for Point #5 was found to be 141.37.

Using this initial value as the settlement arc length, the permissible settlement for a cone roof tank per B.3.2.2 becomes:

$$S_{max} = 3.9 \times S_{arc}\left(\frac{D}{H}\right)\left(\frac{YS}{E}\right)$$

$$S_{max,cone} \quad = \quad 3.9 \times 141.37 \times \frac{90}{40} \times \left(\frac{36,000}{29,000,000}\right) = 1.54\, inches$$

The maximum local shell settlement at Point #5 is 2.10 inches, or using initial measurements, the settlement is unacceptable. For B.3.2.2 to provide a permissible settlement of 2.10 inches, a settlement arc length of 193 feet is required (about 2/3rd of the tank's circumference). The additional 52 feet required for the settlement length, is more than 1.5 times the initial settlement measurement spacing. Additional settlement measurements to improve the permissible settlement estimate could be proven (see the previous figure), by inspection, not to be worthwhile, although this magnitude of settlement on this smaller tank may raise some concern with the original measurements. More rigorous analysis or repair is required.