BALLOT AGENDA ITEM 653 - 150: Revision 2 – May, 2008

Background and Rationale

The current API 653 Appendix B methodology for evaluating the FFS of a storage tank for out–of–plane settlement does not differentiate between types of tank roof construction; covers only tanks whose settlement includes a plane of rigid tilt that follows a cosine (sine) wave; permits only one goodness of fit (R^2) methodology; permits data to be ignored; and penalizes the use of more closely spaced of settlement readings.

A new methodology is proposed that addresses these issues. It has been developed based on a parametric FEA research study, documented in separate reports and briefs. The proposed methodology can be used on API 650 carbon steel and stainless steel tanks, but is not applicable to aluminum tanks. A separate document includes several solved examples.

Economic Impact

The limitations of the current methodology in API 653 Appendix B, particularly the dependence of permissible out–of–plane settlement on a settlement measurement spacing limit, may result in tanks requiring expensive shell re–leveling or more rigorous analyses. Additionally there are tanks that can not be evaluated with current methods. The proposed FFS approach should reduce the number of tanks needing expensive repairs or more rigorous analyses.

Proposed Revisions

Proposed revisions to API 653 Section 12 and Appendix B are given.

SECTION 12 - EXAMINATION AND TESTING

12.5.1.2

Tank settlement shall initially be surveyed with the tank empty using an even number of elevation measurement points, N, uniformly distributed around the circumference. An initial settlement survey prior to the first hydrostatic test provides base readings for future settlement evaluation. In the absence of this initial survey, the tank shall be assumed to be initially level.

The minimum number of elevation_measurement points shall be as indicated by the following formula:

$$N = \frac{D}{10}$$

where:

N= minimum required number of settlement measurement points, but no less than eight. All values shall be rounded to the next higher even whole number. The maximum spacing between settlement measurement points shall be 32 ft

D= tank diameter, in ft.

APPENDIX B – EVALUATION OF TANK SETTLEMENT

B.1 UNCHANGED

B.2.1 SETTLEMENT MEASUREMENTS

Measurements of tank settlement should be performed by personnel experienced in the types of measurement procedures being performed, using equipment capable of sufficient accuracy to distinguish settlement differences.

The principle types of tank settlement consist of settlements that relate to the tank shell and bottom plate. These settlements can be recorded by taking elevation measurements around the tank circumference and across the tank diameter. Figures B–1 and B–2 show minimum recommended locations on a tank shell and bottom plate for settlement measurements. Data obtained from such measurements should be used to evaluate the tank structure. Additional settlement readings may be required to better define local bottom depressions or edge settlements, to refine shell settlement measurements in areas suspected to have local out–of–plane settlements, or to otherwise improve bottom or shell settlement evaluation. Settlement measurement locations should be re-used in any future settlement surveys and evaluations.

In cases of distortion or corrosion of the tank bottom extending beyond the shell, shell settlement measurements taken near lap welds in the tank bottom can result in significant errors in measured elevation. Repaired or replaced bottom plates, or new slotted–in bottoms may not have been installed parallel to the bottom shell course. In some cases, more consistent and accurate results may be obtained by surveying the elevation of the weld between the first and second courses.

Measure bottom and edge settlement carefully, taking into account that measurements taken when the bottom is not in contact with the soil or foundation under the tank can overestimate or underestimate edge or bottom settlement significantly. If the measured settlement is near the maximum allowable settlement, consider repeating the measurement with the bottom forced down to the soil, e.g., standing on it, or take an additional set of measurements in the same area, where the bottom is in firm contact with the soil.

B.2.2 THROUGH B.2.2.2 UNCHANGED

B.2.2.3

Due to the fact that a tank is a rather flexible structure, the tank may settle in a non-planar configuration, inducing additional stresses in the tank shell. The out–of–plane settlements of the shell can lead to out–of–roundness at the top of the shell, and depending on the extent of the induced out–of–roundness, may impede the proper functioning of the floating roof in such a way that re-leveling is required. The out-of-roundness caused by settlement may also affect internal roof support structures such as columns, rafters, and girders. Also, such settlements may cause flat spots to develop in the tank shell. This type of settlement could affect tank nozzles that have piping attached to them.

B.2.2.4

While uniform settlement and rigid body tilt of a tank may cause problems as described in B.2.2.1 and B.2.2.2, the out–of–plane settlement is the important component to determine and evaluate in order to ensure the structural integrity of the shell and bottom. Based on this principle, a common approach is to determine the magnitudes of the uniform settlement and rigid body tilt (if a rigid tilt plane exists or can be identified) for each data point on the tank periphery. If a plane of rigid tilt can be distinguished, it becomes important as a datum from which to measure the magnitudes of the out–of–plane settlements. When the out-of-plane settlement pattern of a tank has an easily distinguishable plane of rigid tilt, the methodology in this paragraph can be used to evaluate the acceptability of the tank's out-of-plane settlement. If a rigid tilt plane can not be readily determined, the methodology in B.2.2.5 can be used to evaluate the acceptability of the tank's out-of-plane settlement.

A graphical representation illustrating tank shell settlement with a rigid tilt plane well–defined by a cosine curve fit is shown in Figure B–3. The construction of this settlement plot has been developed in accordance with the following:

a. The actual settlement (in most cases an irregular curve) is plotted using points around the tank circumference as the abscissa.
b. The vertical distance between the abscissa and the lowest point on this curve (point 22) is the minimum settlement, and it is called the uniform settlement component. A line through this point, parallel to the abscissa, provides a new base or datum line for settlement measurements called adjusted settlements.
c. The plane of rigid tilt settlement, if well-defined**,** is represented by the optimum cosine curve. Several methods exist for determining the optimum cosine curve. The least accurate method is by free hand drawing techniques, a kind of trial and error procedure to fit the best cosine curve through the data. A better method is to use the mathematical and graphical capabilities of a computer.
d. The vertical distances between the irregular curve and the cosine curve represent the magnitudes of the out–of–plane settlements (U_i at data point i).
e. A commonly used and accepted method is to use a computer to solve for constants a, b, and c, to find the optimum cosine curve of the form:

$$Elev_{pred} = a + b \times cos(\theta + c)$$

Where $Elev_{pred}$ is the elevation predicted by the cosine curve at angle theta. A typical starting point for a computer best–fit cosine curve is a least–square fit where a, b, and c are chosen to minimize the sum of the square of differences between the measured and predicted elevations. The optimum cosine curve may be considered valid (i.e., accurately fits the measured data) if the value R^2 is greater than or equal to 0.9.

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

where:

S_{yy} = the 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.

Linear least square fitting and the R^2 method of curve fitting are basic statistical tools. The use of a more rigorous statistical method to determine the optimum cosine curve, such as non–linear or iterative procedures, may be used by those experienced in their use.

Obtaining a statistically valid cosine curve may require taking more measurements than the minimums shown in Figure B–1. In many cases, the out–of–plane settlement may be concentrated in one or more areas. In such cases, the least–squares fit approach may under predict the local out–of–plane settlement and is not conservative. In these cases, R^2 will typically be less than 0.9, and more rigorous curve–fitting procedures should be considered. Alternatively, the settlement may not indicate a well–defined rigid tilt plane and the procedure in B.2.2.5 should be considered.

f. The vertical distances between the irregular curve and the optimum curve represent the magnitudes of the out–of–plane settlements (U_i at data point i). S_i is the out–of–plane deflection at point i. Refer to Figure B–3.

Note: When determining the optimum cosine curve described in B.2.2.4e, taking additional measurements around the shell will result in a more accurate cosine curve fit. However, using all of the measurement points in the equation shown in B.3.2.1 will result in very small allowable out-of-plane settlements, S_{max}, since the arc length L between measurement points is small. It is acceptable to all measurement points to develop the optimum cosine curve, but only use a subset of these points spaced no further than 32 ft (8 minimum) when calculating S_i and S_{max}. The points used must include the points furthest from the optimum cosine curve. For example, if 8 points are required, but 16 measurements are taken, and the arc length between measurement points is only 15 ft, calculate the optimum cosine curve using all 16 points, but use only 8 points to calculate S_i. The equations in Figure B–3 would be revised to read:

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

$$S_{11} = U_{11} - \left(\tfrac{1}{2}U_9 + \tfrac{1}{2}U_{13}\right)$$

B.2.2.5

If a well-defined rigid tilt plane can not be determined or the maximum out-of-plane settlement determined in accordance with B.3.2.1 is exceeded, the procedures given in this paragraph may be used in lieu of more rigorous analysis or repair.

B.2.2.5.1

For settlement profiles without a well-defined rigid tilt plane, the settlement arc length, S_{arc}, and out–of–plane settlement at the point under consideration, S_i, must be determined from a plot of the measurement data. Figure B–4a is a graphical illustration of the various measurement terms and procedures for determining estimates of the settlement arc length and the corresponding out-of-plane settlement, including the refinement of measurements, when needed:

a. The actual settlement is plotted using points around the tank circumference as the abscissa.
b. An initial settlement arc length and maximum settlement is determined from the points on the plotted data that indicate a change in direction of settlement slope. Refer to Figure B-4a.
c. Additional settlement measurement points may be needed halfway between the points indicating a change in direction of the settlement slope to further refine the settlement arc length and location and magnitude of maximum settlement.
d. Step c. may need to be repeated. The best estimate of the settlement arc length and maximum settlement shall be considered in the procedure given in B.3.2.2.

B2.2.5.2

If a valid cosine fit of the rigid tilt plane can be determined, but the maximum out-of-plane settlement determined in accordance with B.3.2.1 is exceeded, the procedure in B.3.2.2 may be used to evaluate the settlement. In this case, refer to Figure B-4b for a graphical illustration of the determination of the settlement arc length and the corresponding out-of-plane settlement.

B2.2.5.3

If an examination of the measured settlement plot indicates a fold pattern about a diameter of the tank, the maximum out–of–plane settlement should be determined using a settlement arc length of 50% of the tank's circumference.

B.2.3.1 UNCHANGED

B.2.3.2

The formula given in B.3.4 can be used to evaluate edge settlement. Alternatively, a rigorous stress analysis can be carried out for the deformed profile. The determination of the deformed profile should take into consideration:

a. Locating the breakover point where the settled area begins requires some judgment. Placing a straight edge on the unsettled bottom as shown in Figure B-5, and observing where the bottom separates from the straight edge will help define the breakover point.

b. If the tank bottom is cone up or cone down, the settlement B, should be measured from a projection of the unsettled bottom, not from level. See Figure B-6.

B.2.3.3 THROUGH B.3.1 UNCHANGED

B.3.2 Permissible Out-of-Plane Settlement

From the measurements procedures described in B.2.2.4 and B.2.2.5, determine the maximum out–of–plane settlement. The magnitude (absolute value) of the maximum settlement shall be compared to the permissible values given in B.3.2.1 or B.3.2.2, as applicable. The permissible out-of-plane settlement given in B.3.2.1 and B.3.2.2 do not take into consideration abrupt changes in shell elevation (ridges) or discontinuities near the bottom of the tank in the settled region, such as low nozzles. They also do not consider fold patterns in cone roof tanks when the fold line is adjacent to or through a line of one or more roof columns, or to patterns of settlement that include combined shell and edge settlements. The permissible settlement criteria in B.3.2.2 are applicable to API 650 carbon steel and stainless steel tanks and diameter ranges given in B.3.2.2. Out-of-plane settlement that does not meet these limitations should be further examined by a more rigorous engineering assessment to determine the need for repairs, see B3.2.4

B.3.2.1

When using the procedure with an optimal cosine curve approach defined in B.2.2.4 to determine out–of–plane settlement, the permissible out–of–plane settlement is given by the following formula (see note below):

$$S_{\boldsymbol{max,\,ft}} = \frac{\left(L^2 \times Y \times 11\right)}{2\left[\left(E \times H\right)\right]}$$

Where:

$S_{\boldsymbol{max,\,ft}}$ = permissible out-of-plane settlement*, in ft*

L= arc length between measurement points, in ft,

Y= yield strength of the shell material, in lbf/in.^{2},

E= Young's Modulus, in lbf/in.^{2},

H= tank height, in ft.

Note: This formula is based on "Criteria for Settlement of Tanks," W. Allen Marr, M. ASCE, Jose A. Ramos, and T. William Lambe, F. ASCE, Journal of Geotechnical Engineering Division, Proceedings of the American Society of Civil Engineers, Vol. 108, August, 1982.

B.3.2.2

When using the procedure in B.2.2.5 to determine out–of–plane settlement, the permissible out–of–plane settlement is given by the following formula (see note below):

$$S_{max,in} = min\left[K \; x \; S_{arc} x \left(\frac{D}{H}\right) x \left(\frac{Y}{E}\right), 4.0\right]$$

Tank Diameter	K, Open Top Tanks	K, Fixed Roof Tanks
$D \le 50$ ft	28.7	10.5
50 ft $< D \le$ 80 ft	7.8	5.8
80 ft $< D \le$ 120 ft	6.5	3.9
120 ft $< D \le$ 180 ft	4.0	2.3
180 ft $< D \le$ 240 ft	3.6	Not applicable
240 ft $< D \le$ 300 ft	2.4	Not applicable
300 ft $< D$	Not applicable	Not applicable

Where:

$S_{max,\,in}$ = permissible out-of-plane settlement, in inches,

S_{arc} = effective settlement arc, see B.2.2.5.1, in ft,
D= tank diameter, in ft,
Y= yield strength of the shell material, in lbf/in.^{2},
E= Young's Modulus, in lbf/in.^{2},
H= tank height, in ft.

Note: This formula is based on "Final Report on the Study of Out-of-Plane Tank Settlement," J. Andreani, N. Carr, report to API SCAST, May, 2007.

B.3.2.3

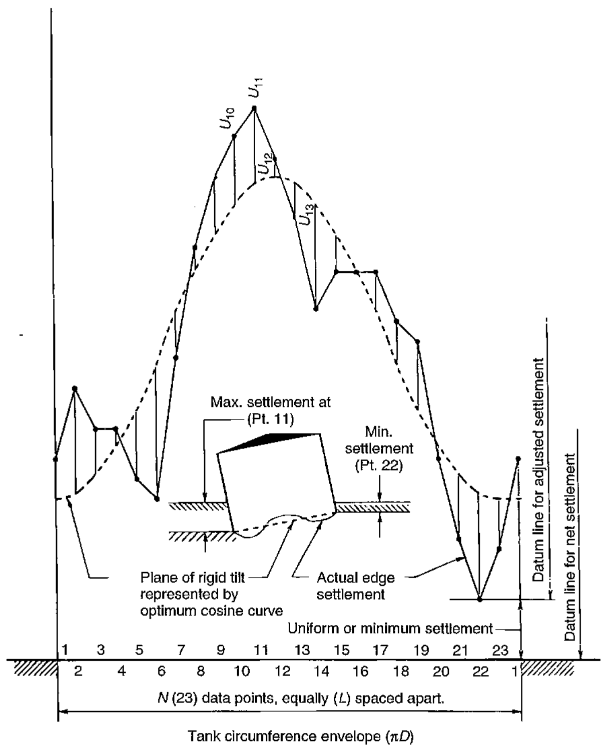
Serviceability may also be a concern for tanks with significant out-of-plane settlement. Out–of–roundness can impede floating roof operation and also affect internal roof support structures. The out–of–roundness that a tank experiences with out-of-plane settlement is fairly sensitive to the actual pattern of settlement. The Owner may wish to specify additional inspection or a more rigorous assessment of the tank's out–of–roundness.

B.3.2.4

If measured out–of–plane settlement exceeds the applicable limits described in B.3.2.1 or B.3.2.2, a more rigorous evaluation may be performed to determine the need for repairs. This evaluation should be done by an engineer experienced in tank settlement analysis.

CHANGES TO FIGURES

Figures B-1, B-2 UNCHANGED

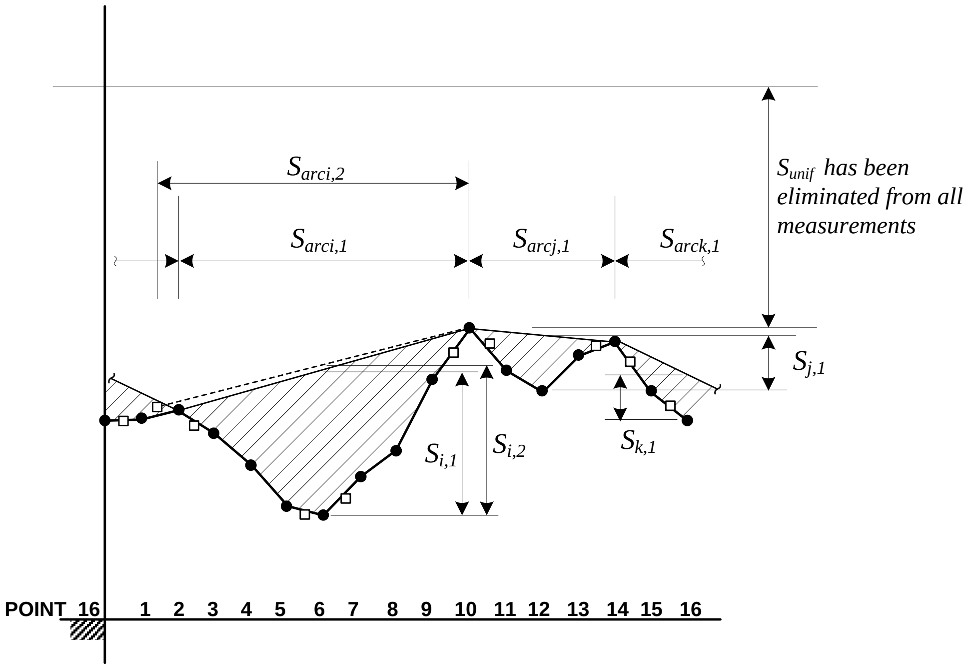


Out-of-plane deflection for point "i" is
$S_i = U_i - (\frac{1}{2} U_{i-1} + \frac{1}{2} U_{i+1})$, for example
$S_{11} = U_{11} - (\frac{1}{2} U_{10} + \frac{1}{2} U_{12})$

U_i = out-of-plane settlement of point "i",
(+) when above cos. curve;
(–) when below cos. curve, for example:
$U_{11} = (+)$
$U_{13} = (-)$

Note: See 12.5.1.2 for definition of "N."

Figure B-3–Graphical Representation of Shell Settlement per B.2.2.4



● *initial 16 measurements*

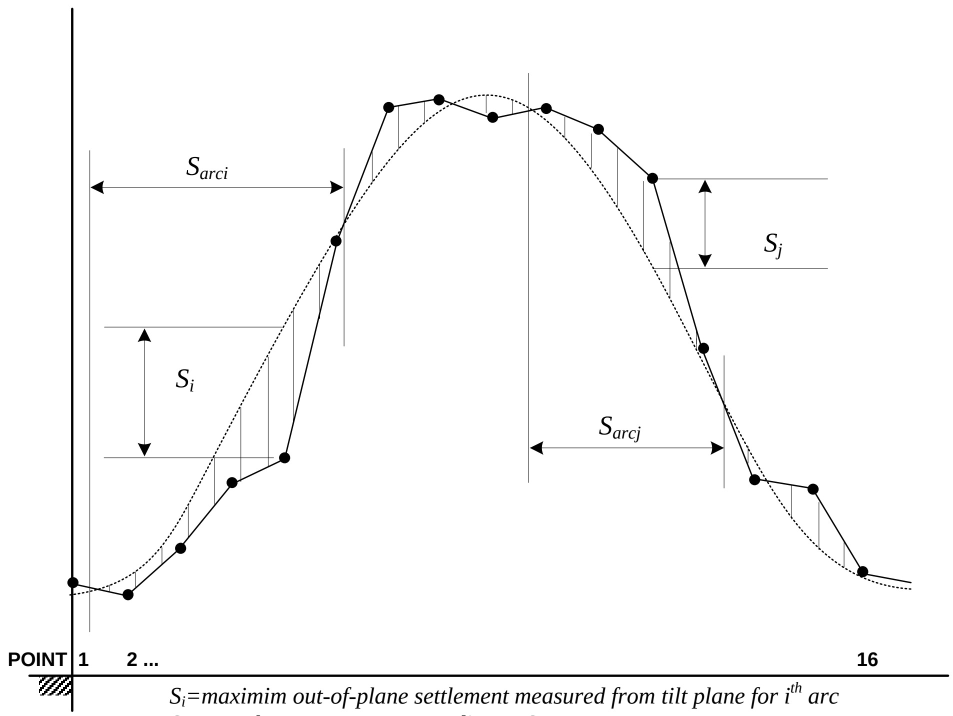
□ *additional measurements to better define settlement arc and maximum settlement*

$S_{i,N}$ = *maximum out-of-plane settlement measured from indicated plane, Nth estimate*

$S_{arci,N}$ = *settlement arc corresponding to* $S_{i,N}$

Figure B-4a–Graphical Representation of Shell Settlement per B.2.2.5

(Tilt Plane Not Described by an Optimal Cosine Curve)



S_i=maximim out-of-plane settlement measured from tilt plane for i^{th} arc
S_{arci}=settlement arc corresponding to S_i
S_{unif} has been eliminated from all measurements

Figure B-4b–Graphical Representation of Shell Settlement per B.2.2.5

(Tilt Plane Described by Optimal Cosine Curve)