Agenda Item: 650-1080 Rev. 0

Title: Calculation of hydrodynamic liquid hoop stress in the corroded condition

Date: November 9, 2018

Contact:
Name: David Nadel
Company: Chevron Energy Technology Company
Phone: 713-372-7155
Cell: 281-798-5984
Email: david.nadel.pe@gmail.com

Purpose: Correct the definition of the thickness of the shell plate under consideration when calculating the hydrodynamic liquid hoop stress

Source: May 2018 inquiry

Discussion: API-650, Annex E provides minimum requirements for the design and analysis of tanks subject to seismic ground motion.

The fundamental performance goal for Annex E is the protection of life and prevention of catastrophic failure of the tank. Annex E as written does not guarantee the tank will not be damaged during a seismic event.

Annex E is based on the allowable stress design (ASD) methods in ASCE 360-10 with the specific load combinations given in API-650.

ASCE Chapter B – Design Requirements B.3.13 states:

> *"Where corrosion may impair the strength or serviceability of a structure **shall be designed to tolerate corrosion** or shall be protected against corrosion."*

ASCE Commentary on Chapter B – Design Requirements B.3.13 states:

> *"Steel may deteriorate in some service environments. This deterioration … would reduce member strength. The designer should recognize this problem by either **factoring a specific amount of tolerance for damage into the design** or providing adequate coating or cathodic protection and/or planned maintenance programs so that such problems do not occur."*

The pseudo-dynamic design procedures contained in Annex E are based on response spectra analysis methods and consider two response modes of the tank and its contents. The equivalent lateral seismic force and overturning moment applied to the shell as a result of the response of the masses to lateral ground motion are determined. Provisions are ***included to assure stability of***

***the tank shell with respect to overturning and to resist buckling of the tank shell as a result of longitudinal compression*.**

Revised information in red font.

E.2.2 Notations

t Thickness of the shell ring under consideration less corrosion allowance, mm (in.)

E.6.2.2.3 Allowable Longitudinal Shell-Membrane Compression Stress in Tank Shell

$$F_C = 10^6 \, t_s/(2.5D) + 600\sqrt{(GH)} < 0.5F_{ty} \quad \text{(E.6.2.2.3-2b)}$$

If the thickness of the bottom shell course calculated to resist the seismic overturning moment is greater than the thickness required for hydrostatic pressure, ~~both excluding corrosion allowance~~ less corrosion allowance, then the calculated thickness of each upper shell course for hydrostatic pressure shall be increased in the same proportion …

Chevron

David Nadel, P.E.
Tank Specialist

Energy Technology Company
Materials and Equipment Engineering
1400 Smith St., Houston TX 77002
Tel: +1 713 372 7155
Fax: +1 713 372 7100
dnadel@chevron.com

650-1080
Hydrodynamic Liquid Hoop Stress

CLIENT: El Segundo Refinery

PROJECT: API-650 Annex E Sensitivity Analysis on high seismic loads

JOB No: YWEX00171928 **REFERENCE DOC: 192256**

CALCULATION BY: DEN **DATE: 26 June 2018**

OBJECT: Seismic Sensitivity Analysis

CONCLUSION: Corrosion Allowance limits Hydrodynamic Shell Stress

Tank: 220' diameter x 48' high - Shell Material A537 Class 2 - S_d = 28 ksi

$D := 220ft$

$ca := 0.0625in$ Corrosion Allowance

$H := 44ft$

$i := 1..6$

$$ts := \begin{pmatrix} 0.784in - ca \\ 0.619in - ca \\ 0.492in - ca \\ 0.375in - ca \\ 0.375in - ca \\ 0.375in - ca \end{pmatrix}$$

$\sigma := 34.3ksi$

Seismic Design Criteria

$S_{method} := 1$ Seismic method - Mapped ASCE 7 values

$SUG := 1$ Seismic Use Group = 1, not public hazzard or essential to life and health

$FB := 1$ Calculate Minimum Freeboard

$T_L := 8sec$ Regional dependent transition period for longer period ground motion

$SiteClass := "D"$ Site Class - Stiff Soil (default)

$V_{yn} := 1$ Vertical seismic acceleration is required (Calif. Building Code)

$A_{vspec} := 0$ Minimum vertical ground acceleration

$$K_s := \frac{0.578}{\sqrt{\tanh\left(\frac{3.68H}{D}\right)}}$$

Sloshing Coefficient $K_s = 0.73$

Chevron

David Nadel, P.E.
Tank Specialist

Energy Technology Company
Materials and Equipment Engineering
1400 Smith St., Houston TX 77002
Tel: +1 713 372 7155
Fax: +1 713 372 7100
dnadel@chevron.com

$T_c := K_s \cdot sec \cdot \sqrt{\frac{D}{ft}}$ — Natural period of convective (sloshing) mode

$T_c = 10.829\,s$

$S_S := 1.640$ — Mapped MCE, 5% damped, short period (0.2 sec) spectral response acceleration

$S_1 := 0.613$ — Mapped MCE, 5% damped, one second spectral response acceleration

$S_0 := 0.4 \cdot S_S$

$S_0 = 0.656$ — Mapped MCE, 5% damped, maximum spectral response acceleration

Design Ground Accelerations

$F_a := 1 \quad F_v := 1.5 \quad Q := \frac{2}{3} \quad R_w := 3.5 \quad R_{wc} := 2 \quad I_f := 1$

$T_S := \frac{F_v \cdot S_1}{F_a \cdot S_S} \qquad T_S = 0.561$

$S_{DS} := Q \cdot F_a \cdot S_S \qquad S_{DS} = 1.093$

$S_{D1} := Q \cdot F_v \cdot S_1 \qquad S_{D1} = 0.613$

$$A_i := \max\left(\frac{S_{DS} \cdot I_f}{R_w}, \frac{2.5 \cdot Q \cdot F_a \cdot S_0 \cdot I_f}{R_w}, \begin{cases} \frac{S_1 \cdot I_f}{2 \cdot R_w} & \text{if } S_1 \ge 0.6 \\ 0 & \text{otherwise} \end{cases}\right) \qquad A_i = 0.312$$

$K_{sd} := 1.5$

$$A_{c\_case2} := sec \cdot \begin{cases} \max\left(\frac{K_{sd} S_{D1} \cdot I_f}{T_c \cdot R_{wc}}, \frac{2.5 \cdot K_{sd} \cdot Q \cdot F_a \cdot S_0 \cdot T_S \cdot I_f}{T_c \cdot R_w}\right) & \text{if } T_c \le T_L \\ \max\left(\frac{K_{sd} S_{D1} \cdot T_L \cdot I_f}{T_c^2 \cdot R_{wc}}, \frac{2.5 \cdot K_{sd} \cdot Q \cdot F_a \cdot S_0 \cdot T_S \cdot T_L \cdot I_f}{T_c^2 \cdot R_w}\right) & \text{otherwise} \end{cases} \qquad A_{c\_case2} = 0.031$$

$A_c := \min(A_i, A_{c\_case2}) \qquad A_c = 0.031$ — Convective (sloshing) spectral ground motion acceleration parameter using Design method 1

$A_v := \max(0.47 \cdot S_{DS}, 0.7 \cdot A_{vspec}) \qquad A_v = 0.514$ — Vertical ground motion acceleration

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dnadel@chevron.com

$W_s := \pi \cdot D \cdot 96in \cdot (0.283pci) \cdot \sum ts$ Shell Weight $W_s = 596 \cdot kip$

$W_p := 0.25 \cdot \pi \cdot D^2 \cdot H \cdot 62.4pcf$ Product Weight $W_p = 104369.2 \cdot kip$

Determine Seismic Design Coefficients

$\lambda_{dll} := \frac{D}{H}$ $\lambda_{dll} = 5$ Diameter to design liquid level ratio

$$H_{shell\_mid} := \begin{pmatrix} 48in \\ 144in \\ 240in \\ 336in \\ 432in \\ 528in \end{pmatrix}$$

Height to the midpoint of each shell course

$H_{shell\_mid_0} = 48 \cdot in$

$H_{shell\_bottom} := H_{shell\_mid} - 48in$ Height to the bottom of each shell course

Determine Seismic Design Coefficients

$\lambda_{bottom} := \frac{H_{shell\_bottom}}{H}$ Ratio of bottom ring elevation to design liquid level

$$X_i := \begin{cases} 0.375 \cdot H & \text{if } \lambda_{dll} > 1.333 \\ (0.5 - 0.094 \cdot \lambda_{dll}) \cdot H & \text{otherwise} \end{cases}$$

$X_i = 16.5 \cdot ft$ Elevation of the center of impulsive product lateral seismic force, W_i

$$X_c := \left(1 - \frac{\cosh\left(\frac{3.67}{\lambda_{dll}}\right) - 1}{\frac{3.67}{\lambda_{dll}} \cdot \sinh\left(\frac{3.67}{\lambda_{dll}}\right)} \right) \cdot H$$

Elevation of the center of convective (sloshing) product lateral seismic force, Wc

$X_c = 22.937 \cdot ft$

Center of Action for slab overturning moment

$$X_{is} := \begin{cases} 0.375 \cdot \left[1 + 1.33 \cdot \left(\frac{0.866 \cdot \lambda_{dll}}{\tanh(0.866 \cdot \lambda_{dll})} - 1 \right) \right] \cdot H & \text{if } \lambda_{dll} > 1.33 \\ (0.5 + 0.6 \cdot \lambda_{dll}) \cdot H & \text{otherwise} \end{cases}$$

$X_{is} = 89.61 \cdot ft$

Chevron

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Tank Specialist

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Center of Gravity of tank shell

$$X_s := \frac{H_{shell\_mid} \cdot ts}{\sum ts}$$ $X_s = 19.623 \cdot ft$

No roof

$X_r := 0ft$ $W_r := 0lbf$

$W_f := 10.2psf \cdot 0.25 \cdot D^2$ $W_f = 123.42 \cdot kip$

$W_s = 596 \cdot kip$

$W_p = 104369.2 \cdot kip$

$$W_i := W_p \cdot \begin{cases} \frac{\tanh(0.866 \cdot \lambda_{dll})}{0.866 \cdot \lambda_{dll}} & \text{if } \lambda_{dll} > 1.33 \\ (1 - 0.218 \cdot \lambda_{dll}) & \text{otherwise} \end{cases}$$

Effective weight of product which moves with the tank shell

$W_i = 24095 \cdot kip$

$$W_c := 0.23 \cdot \lambda_{dll} \cdot \tanh\left(\frac{3.67}{\lambda_{dll}}\right) \cdot W_p$$

Effective weight of sloshing product

$W_c = 75076 \cdot kip$

Seismic Base Shear

$V_i := A_i \cdot (W_s + W_r + W_f + W_i)$ $V_i = 7751.7 \cdot kip$

Sloshing component

$V_c := A_c \cdot W_c$ $V_c = 2354.6 \cdot kip$

$V := \sqrt{V_i^2 + V_c^2}$ $V = 8101.4 \cdot kip$

Seismic Overturning moment at tank base

$$M_{rw} := \sqrt{[A_i \cdot (W_i \cdot X_i + W_s \cdot X_s + W_r \cdot X_r)]^2 + (A_c \cdot W_c \cdot X_c)^2}$$ $M_{rw} = 138787 \cdot kip \cdot ft$

$G := 1$ $Y := H - H_{shell\_bottom}$

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Dynamic Liquid Hoop Forces & Stresses (Bottom to top)

$$N_c := \frac{0.98 \cdot A_c \cdot G \cdot D^2 \cdot \cosh\left[\frac{3.68 \cdot (H - Y)}{D}\right]}{\cosh\left(\frac{3.68}{\lambda_{dll}}\right)} \cdot \left(\frac{lbf}{in \cdot ft^2}\right)$$

$$N_c = \begin{pmatrix} 1159 \\ 1170 \\ 1201 \\ 1254 \\ 1329 \\ 1428 \end{pmatrix} \cdot \frac{lbf}{in}$$

$$N_i := \frac{lbf}{in \cdot ft^2} \cdot \begin{cases} \left[4.5 \cdot A_i \cdot G \cdot D \cdot H \cdot \left[\frac{Y}{H} - 0.5 \cdot \left(\frac{Y}{H}\right)^2\right] \cdot \tanh(0.866 \lambda_{dll})\right] & \text{if } \lambda_{dll} \geq 1.333 \\ 2.77 \cdot A_i \cdot G \cdot D^2 \cdot \left[\left(\frac{Y}{0.75 \cdot D}\right) - 0.5 \cdot \left(\frac{Y}{0.75 \cdot D}\right)^2\right] & \text{if } (\lambda_{dll} < 1.333) \wedge (Y < 0.75 \cdot D) \\ 1.39 \cdot A_i \cdot G \cdot D^2 & \text{otherwise} \end{cases}$$

$$N_i = \begin{pmatrix} 6801.3 \\ 6576.5 \\ 5902.0 \\ 4777.8 \\ 3203.9 \\ 1180.4 \end{pmatrix} \cdot \frac{lbf}{in}$$

$$N_h := \frac{Y \cdot G \cdot D \cdot 62.4pcf}{2} \qquad N_h = \begin{pmatrix} 25168 \\ 20592 \\ 16016 \\ 11440 \\ 6864 \\ 2288 \end{pmatrix} \cdot \frac{lbf}{in}$$

$$\sigma_t := \frac{N_h + \sqrt{N_i^2 + N_c^2 + \left(\frac{A_v \cdot N_h}{2.5}\right)^2}}{ts}$$

$$\frac{A_v \cdot N_h}{2.5} = \begin{pmatrix} 5173.2 \\ 4232.6 \\ 3292.0 \\ 2351.5 \\ 1410.9 \\ 470.3 \end{pmatrix} \cdot \frac{lbf}{in}$$

$$\sigma_t = \begin{pmatrix} 46.835 \\ 51.213 \\ 53.271 \\ 54.114 \\ 33.948 \\ 13.439 \end{pmatrix} \cdot ksi$$

$$\sigma_{allow} := \min(1.33 \cdot 32ksi, 0.9 \cdot 60ksi) \qquad \sigma_{allow} = 42.56 \cdot ksi$$