Attachment 5 to IPN-97-041

Response to Request for Additional Information on the Resolution of Unresolved Safety Issue A-46

Indian Point 3 Nuclear Power Plant
Docket No. 50-286

Client: New York Power Authority Calculation No. C002

Title: Primary Water Storage Tank PWST-21

Project: IPEEE / USI A-46 Outlier Resolution

Method: EPRI NP-6041 Appendix H

Acceptance Criteria: GIP Rev 2 2/14/92 Section 7

Remarks:

NEW YORK POWER AUTHORITY

DOCUMENT REVIEW STATUS

STATUS NO:

1 ☒ ACCEPTED

2 ☐ ACCEPTED AS NOTED RESUBMITTAL NOT REQUIRED

3 ☐ ACCEPTED AS NOTED RESUBMITTAL REQUIRED

4 ☐ NOT ACCEPTED

Permission to proceed does not constitute acceptance or approval of design details, calculations, analysis, test methods or materials developed or selected by the supplier and does not relieve supplier from full compliance with contractual negotiations.

REVIEWED BY: ..... TITLE: SR. ENGINEER

DATE: 1/31/97

REVISIONS

No.	Description	By	Date	Chk.	Date	App.	Date
0	Original Issue	A. ic.	1/30/97	SA	1/30/97	SA	1/30/97

S&A Stevenson and Associates

CALCULATION COVER SHEET

CONTRACT NO. 96C2915

9703270277 970320
PDR ADOCK 05000286
P PDR

Table of Content

Objective 1
Analytical Approach 1
Summary 1
Calculation 4
References 7
Appendix A
Appendix B

Objective

The Primary Water Storage Tank (PWST 21) is a cylindrical flat bottom vertical tank which is 35'-3" tall and 30' in diameter (Ref. 2). The tank is anchored by 18 - 1.75" cast-in-place bolts, equally spaced in a 30'-6" diameter bolt circle around the tank (Ref. 1).

The A-46 evaluation declared the tank an outlier because the tank's anchorage capacity was less than the seismic demand.

This calculation recompiles the A-46 evaluation and also considers the effect of fluid hold-down forces.

Analytical Approach

This calculation follows the computational methodology described in Appendix H of EPRI NP - 6041. This is essentially the same methodology used in Section 7 of the GIP; the procedure in NP-6041 is "equation-based", and allows for a more accurate calculation than the "chart-based" method in GIP Section 7. It should be noted that the critical GIP Section 7 criteria were maintained, namely:

- GIP Appendix C procedures were used to calculate the anchor bolt allowables,
- 4% damping was used to calculate the impulsive mode response,
- a reduction factor of 0.72 was applied to the computed tank shell buckling stress.

The capacity was calculated both ignoring and including the effects of fluid hold-down. Note that GIP Section 7 ignores the effect of fluid hold-down.

Summary

The attached calculations show that the tank has a seismic demand of 0.22g (at the impulsive mode frequency), and has a seismic capacity of 0.35g if fluid hold-down is ignored, and a seismic capacity of 0.42g if fluid hold-down is included. The tank therefore meets GIP requirements with a factor of safety of 1.6, and has a factor of safety of 1.9 if fluid hold-down is included. Therefore, the tank outlier is resolved.

This evaluation yielded a significantly different result than the original A-46 evaluation (Ref 2), which concluded that the seismic demand exceeded the capacity by about a factor of 1.7. The principal reasons for the difference are as follows:

1. Both this and the original evaluation computed an impulsive mode frequency of about 7 Hz. Based on this frequency, this evaluation used a spectral acceleration of 0.22g - the ground response spectra, 4% damping, peak value within 20% of the calculated frequency. The original evaluation used a spectral acceleration of 0.41g - this appears to be the 4% damped ground response spectra value multiplied by 1.875 (under certain conditions, GIP Section 4 permits the use of 1.25 x 1.5 the ground response spectra as the estimate of an in-structure response spectrum). The tank is in the yard, therefore there is no requirement to amplify the ground spectrum - the original evaluation overestimated the demand by a factor of 1.7.

2. The original evaluation and this evaluation used different values for a number of the mechanical parameters, some of which improved the result, and some of which degraded the result. These were:

   - The original evaluation used a yield stress of 45 ksi for SA 240 Type 304 stainless steel; this evaluation used a more conservative value of 30 ksi.

   - The original evaluation used 3.5" as the distance between the bolt chair stiffeners (design value). This evaluation used 5.75" (an average value based on a field survey).

   - The original evaluation used a top plate width of 6" to evaluate the bending stresses imposed on the tank shell by the bolt chairs - no basis given, but this is about the actual distance between the bolt chair stiffeners. This evaluation used 18.75" - the average distance between the outside edges of the bolt chair stiffeners (6.75") plus 2x the depth of the bolt chair top plate (6"). This was used because the bolt chairs' top plate is a continuous ring around the entire tank; the load on the tank shell will therefore be distributed over a longer length than just the distance between the bolt chair stiffeners.

- The original evaluation used a fluid height of 33' - no basis given, but this is the shell height minus 2'. This evaluation used a fluid height of 31'-4" - this is the height of fluid that equals the nominal tank capacity of 165,000 gallons.

The net effect of these differences is that the original evaluation used an effective anchor bolt allowable load of 17.5 k, while this evaluation used 19.7 k, and the original evaluation computed a base moment demand of 18,000 k-ft / g, while this evaluation computed 15,000 k-ft / g.

Calculation

The capacity calculations are attached as appendix A (w/o fluid hold-down) and Appendix B (with fluid hold-down). This section of the calculation computes the bolt hold-down capacity and other various input parameters common to both appendices.

Tank shell material is SA 240 Type 304 Stainless Steel. (assumed same as RWST)
$\sigma_Y = 30$ ksi , $\sigma_U = 75$ ksi & $E_S = 28300$ ksi (Ref. 10)

Nominal capacity = 165,000 gal = 22077 ft^3 (ref. 2)
Fluid height, $H = 22077 / [\pi (15 - 0.1875 / 12)^2] = 31.3$ ft = 376 in

Bolt Hold-Down Capacity: (ref. 5 & 6)

1. Bolt tensile capacity, (assume A307 bolts)

   1.75" Cast-in-Place bolts,
   Nominal bolt area = 2.41 in^2 (ref. 9)
   $T_{nom} = 1.7 \times 20 \times 2.41 = 81.9$ kip

2. Anchorage of bolt into concrete foundation:

   Embedment, L = 32" - 2" (anchor fitting) - 13.5" (chair height) - 3" (assumed length above bolt chair) = 13.5". Reduction per GIP Section C.3.2:

$$\frac{(13.5 + 1.75)13.5}{(17.5 + 1.75)17.5} = 0.6$$

   Edge distance, E = 33" (large)

   Concrete strength = 3 ksi (Ref 3); reduction per GIP Section C.3.5 = SQR(3/3.5) = 0.93.

   Net capacity = 0.61 x 0.93 x 81.9 = 46.5 kip

Part of the bolt hold-down capacity calculation requires the dimension of the bolt chairs. The following dimension designations are shown in reference 6, figure 2-14. (ref. 3 page 19)

a = g + 2j + 2b	c = 0.75"	f = 2.00"	j = 0.50"
a = 18.75" (avg.)	d = 2.00"	g = 5.75" (avg.)	k =3.75" (avg.)
b = 6"	e = 3"	h = 13.5"	t_b = 0.1875"

3. Capacity of plate to transfer load to chair gussets (Ref. 6):

$$S_P = \frac{(0.375g - 0.22d)T_{BS}}{f\,c^2} = \frac{(0.375 \times 5.75 - 0.22 \times 2.00) \times 46500}{2.00 \times 0.75^2} = 70900 \text{ psi}$$

$$S_P = 70900 \text{ psi} > f_y = 30000 \text{ psi} \quad \therefore \; T_P = 46.5 \times \frac{30000}{70900} = 19.7 \text{ kip}$$

4. Capacity of vertical gusset plates (Ref. 6):

- $\frac{k}{j} = \frac{3.75}{0.5} = 7.5 < \frac{95}{\sqrt{\frac{f_y}{1000}}} = \frac{95}{\sqrt{\frac{30000}{1000}}} = 17.35$ (O.K.)

- $j = 0.5" > 0.04\,(h - c) = 0.04\,(13.5 - 0.75) = 0.51"$ and $j = 0.5 = 0.5"$ (Judged OK)

- $\frac{T_P}{2\,k\,j} = \frac{19700}{2 \times 3.75 \times 0.5} = 5250 \text{ psi} < 0.6 \times 30000 = 18000 \text{ psi}$ (O.K.)

5. Tank shell capacity (Ref. 6)

$$S_S = \frac{T_P\,e}{t_s^{\,2}}\left[\frac{1.32\,Z}{\frac{1.43\,a\,h^2}{R\,t_s} + \left(4\,a\,h^2\right)^{0.333}} + \frac{0.031}{\sqrt{R\,t_s}}\right]$$

$$Z = \frac{1.0}{\frac{(0.177 \text{ in}^{-1})\,a\,t_b}{\sqrt{R\,t_s}}\left[\frac{t_b}{t_s}\right]^2 + 1.0} = \frac{1.0}{\frac{(0.177 \text{ in}^{-1}) \times 18.75 \times 0.1875}{\sqrt{180 \times 0.1875}} \times \left[\frac{0.1875}{0.1875}\right]^2 + 1.0} = 0.903$$

$$S_S = \frac{19700 \times 3}{0.1875^2} \times \left[\frac{1.32 \times 0.903}{\frac{1.43 \times 18.75 \times 13.5^2}{180 \times 0.1875} + \left(4 \times 18.75 \times 13.5^2\right)^{0.333}} + \frac{0.031}{\sqrt{180 \times 0.1875}}\right]$$

$$S_S = 1.68 \times 10^6 \times (0.00707 + 0.00534) = 20800 \text{ psi} < f_y = 30000 \text{ psi} \quad \therefore \text{ Shell is OK.}$$

Check the weld between the chair and the tank wall;

$$W_w = T_P \sqrt{\left[\frac{1}{a+2h}\right]^2 + \left[\frac{e}{a\,h + 0.667\,h^2}\right]^2}$$

$$W_w = 19700\sqrt{\left[\frac{1}{18.75+2\times 13.5}\right]^2 + \left[\frac{3}{18.75\times 13.5 + 0.667\times 13.5^2}\right]^2} = 19700\sqrt{0.0219^2 + 0.0080^2}$$

$$W_w = 459 \text{ lbs/in} \le \frac{30600\,t_w}{\sqrt{2}} = \frac{30600\times 0.1875}{\sqrt{2}} = 4057 \text{ lbs/in} \quad \therefore \text{ Weld is adequate.}$$

The conclusion is that the allowable bolt load is governed by bending of the bolt chair's top plate (Step 3 above), which has a value of 19.7 k, and is ductile.

The maximum uplift height, "deltae0" is equal to 1% of the effective bolt length = 0.01(32" -2" - 3") = 0.27".

References

1. "Primary Water Storage Tank Foundation, Concrete & Reinforcing Details", Dwg. No. 9321-F14693-2

2. "Design Calculations 1-30'-0 ϕ x 35'-3 DRT Primary Water Storage Tank T-31 165,000 Gal. Nom. Capacity", Excerpts, SEWS for PWST 21, S&A Log 96C2915-DC-008.

3. Atometrics Calculation No. 18904-IP3-SQ017, Rev. 0., SEWS for CST, S&A Log 96C2915-DC-008.

4. "Summary of Seismic Response Spectra Characteristic", NYPA File No. 44-B-0181, S&A Log 96C2915-DC-005.

5. "A Methodology for Assessment of Nuclear Power Plant Seismic Margin (Revision 1)", EPRI NP-6041-SL, Revision 1, Project 2722-23, Final Report, August 1991.

6. "Seismic Verification of Nuclear Plant Equipment Anchorage (Revision 1), Volume 4: Guidelines on Tanks and Heat Exchangers", EPRI NP-5228-SL, Revision 1, Volume 4, Project 2925-1, Final Report, June 1991.

7. "Seismic Design of Liquid Storage Tanks", Journal of the Technical Council of ASCE, April 1981

8. Mark's Standard Handbook, 9th Edition, Table 3.3.2.

9. Manual of Steel Construction, Allowable Stress Design, AISC, 9th Edition.

10. ASME Boiler and Pressure Vessel Code, 1980 Edition, Appendices.

11. "Generic Implementation Procedure (GIP) for Seismic Verification of Nuclear Plant Equipment", SQUG, Revision 2, Corrected 2/14/92.

Primary Water Storage Tank, PWST 21, GIP Criteria, w/o Fluid Hold-down

$R := 180 \cdot in$ Radius

$H := 376 \cdot in$ Fluid Height

$H_s := 423 \cdot in$ Shell Height

$H_d := 12 \cdot in$ Dome Height

$t_s := 0.1875 \cdot in$ Shell thickness

$t_h := 0.1875 \cdot in$ Head shell thickness

$t_a := 0.1875 \cdot in$ Average shell thickness

$t_b := 0.1875 \cdot in$ Bottom plate thickness

$E_s := 28300 \cdot ksi$ Shell Young's modulus

$\nu := 0.33$ Poisson's ratio

Definitions

$kip := 1000 \cdot lb$

$ksi := \frac{kip}{in^2}$

$psi := \frac{lb}{in^2}$

$pcf := \frac{lb}{ft^3}$

$minx(x, y) := if(x > y, y, x)$

$maxx(x, y) := if(x > y, x, y)$

$K := 316 \cdot ksi$ Water bulk modulus, Mark's Standard Handbook, 9th Ed., Table 3.3.2

$\sigma_{ys} := 30 \cdot ksi$ Shell yield stress

$\sigma_{us} := 75 \cdot ksi$ Shell ultimate stress

$\sigma_{yb} := 30 \cdot ksi$ Bottom plate yield stress

$\sigma_{ub} := 75 \cdot ksi$ Bottom plate ultimate stress

$\gamma_f := 62.4 \cdot pcf$ Fluid weight

$\gamma_s := 490 \cdot pcf$ Shell weight

$\rho_f := \frac{\gamma_f}{g}$ $\rho_s := \frac{\gamma_s}{g}$

$I_b := \frac{t_b^3}{12 \cdot (1 - \nu^2)}$ $I_b = 0.000616 \cdot in^3$

$A_v := 0.10 \cdot g$ 2/3 ZPA of ground spectra

$Scale := 1.59$ Spectral acceleration scale factor. Assumed, must iterate so that the demand M_{sh} is close to the capacity M_{sc}, (factor of safety = 1.0).

Weight Summary

$W_H := \pi \cdot R \cdot \sqrt{R^2 + H_d^2} \cdot t_h \cdot \gamma_s$ $W_H = 5 \cdot kip$

$X_H := H_s + \frac{H_d}{2}$ $X_H = 429 \cdot in$

$W_s := \pi \cdot 2 \cdot R \cdot t_a \cdot H_s \cdot \gamma_s$ $\qquad W_s = 25 \cdot kip$

$X_s := \frac{H_s}{2}$

$W_w := \pi \cdot R^2 \cdot H \cdot \gamma_f$ $\qquad W_w = 1382 \cdot kip$

Impulsive Mode

$\frac{t_a}{R} = 0.00104$ $\qquad \frac{H}{R} = 2.089$

$C_{WI} := 0.087$ Frequency coefficient from Haroun and Housner (1981)

$C_{LI} := C_{WI} \cdot \sqrt{\frac{0.127 \cdot \rho_s}{\rho_f}}$ $\qquad C_{LI} = 0.087$

$f_I := \frac{C_{LI}}{2 \cdot \pi \cdot H} \cdot \sqrt{\frac{E_s}{\rho_s}}$

$f_I = 7.219 \cdot Hz$ $\qquad 0.8 \cdot f_I = 5.775 \cdot Hz$ $\qquad 1.2 \cdot f_I = 8.663 \cdot Hz$

$S_{AI} := 0.22 \cdot g$ From IP3 SSE Ground Spectra 5% Damping x(5/4)^0.5 to estimate 4% damping

$S_{AI} := Scale \cdot S_{AI}$ $\qquad S_{AI} = 0.35 \cdot g$

$$W_I := \begin{cases} \left(1 - 0.436 \cdot \frac{R}{H}\right) \cdot W_w & \text{if } \frac{H}{R} \geq 1.5 \\ \left(0.764 \cdot W_w\right) & \text{if } \frac{H}{R} < 1.5 \end{cases}$$

$W_I = 1094 \cdot kip$

$$X_I := \begin{cases} \left[\left(0.5 - 0.188 \cdot \frac{R}{H}\right) \cdot H\right] & \text{if } \frac{H}{R} \geq 1.5 \\ \left(0.304 \cdot H \cdot \frac{W_w}{W_I}\right) & \text{if } \frac{H}{R} < 1.5 \end{cases}$$

$X_I = 154.2 \cdot in$

$V_I := \frac{S_{AI}}{g} \cdot \left(W_H + W_s + W_I\right)$ $\qquad V_I = 393 \cdot kip$

$M_I := \frac{S_{AI}}{g} \cdot \left(W_H \cdot X_H + W_s \cdot X_s + W_I \cdot X_I\right)$ $\qquad M_I = 5139 \cdot kip \cdot ft$

Sloshing Mode

$$f_c := \sqrt{\frac{1.5 \cdot \frac{ft}{sec^2}}{R} \cdot \tanh\left[1.835 \cdot \left(\frac{H}{R}\right)\right]} \qquad f_c = 0.316 \cdot Hz$$

$S_{Ac} := 0.100 \cdot g$ IP3 SSE Ground Spectra @ 0.5% Damping at 0.5 Hz

$S_{Ac} := Scale \cdot S_{Ac}$ $\qquad S_{Ac} = 0.159 \cdot g$

$$W_c := 0.46 \cdot \frac{R}{H} \cdot \tanh\left[1.835 \cdot \left(\frac{H}{R}\right)\right] \cdot W_w \qquad W_c = 304 \cdot kip$$

$$X_c := \left(1 - \frac{\cosh\left(1.835 \cdot \frac{H}{R}\right) - 1}{1.835 \cdot \frac{H}{R} \cdot \sinh\left(1.835 \cdot \frac{H}{R}\right)}\right) \cdot H \qquad X_c = 282.1 \cdot in$$

$$V_c := \frac{S_{Ac}}{g} \cdot W_c \qquad V_c = 48 \cdot kip$$

$$M_c := \frac{S_{Ac}}{g} \cdot W_c \cdot X_c \qquad M_c = 1136 \cdot kip \cdot ft$$

Vertical Mode

$$f_v := \frac{1}{4 \cdot H} \cdot \left[\rho f \cdot \left(\frac{2 \cdot R}{t_s \cdot E_s} + \frac{1}{K}\right)\right]^{-\frac{1}{2}}$$

$f_v = 8.159 \cdot Hz$ $\qquad 0.8 \cdot f_v = 6.527 \cdot Hz$ $\qquad 1.2 \cdot f_v = 9.79 \cdot Hz$

$S_{Av} := 0.15 \cdot g$ 2/3 Horizontal, 5% Damping Spectra x(5/4)^0.5 to estimate 4% damping.

$S_{Av} := Scale \cdot S_{Av}$ $\qquad S_{Av} = 0.238 \cdot g$

Demand

$$SRSS(x, y) := \sqrt{x^2 + y^2}$$

$$V_{sh} := SRSS(V_l, V_c) \qquad V_{sh} = 396 \cdot kip$$

$$M_{sh} := SRSS(M_l, M_c) \qquad M_{sh} = 5263 \cdot kip \cdot ft$$

Pressures

$y := (H - 198 \cdot in), H .. H$

$P_{st}(y) := \gamma_f \cdot y$

$$P_i := \frac{W_l \cdot X_l \cdot \frac{S_{Al}}{g}}{1.36 \cdot R \cdot H^2} \qquad P_i = 1.704 \cdot psi$$

$$P_c(y) := \frac{0.267 \cdot W_w \cdot \frac{S_{Ac}}{g}}{R \cdot H} \cdot \frac{\cosh\left[1.835 \cdot \left(\frac{H - y}{R}\right)\right]}{\cosh\left[1.835 \cdot \left(\frac{H}{R}\right)\right]}$$

$$P_v(y) := 0.8 \cdot \gamma_f \cdot H \cdot \frac{S_{Av}}{g} \cdot \cos\left(\frac{\pi}{2} \cdot \frac{H - y}{H}\right)$$

$P_{sh}(y) := SRSS(P_i, P_c(y))$

$P_{sm}(y) := SRSS(P_{sh}(y), P_v(y))$

$\frac{y}{in}$	$\frac{P_{st}(y)}{psi}$	$\frac{P_c(y)}{psi}$	$\frac{P_v(y)}{psi}$	$\frac{P_{sh}(y)}{psi}$	$\frac{P_{sm}(y)}{psi}$
178	6.428	0.144	1.754	1.71	2.449
376	13.578	0.038	2.591	1.704	3.101

$P_{cp} := P_{st}(H) + P_{sh}(H) + 0.4 \cdot P_v(H) \qquad P_{cp} = 16.318 \cdot psi$

$P_{cm} := P_{st}(H) + P_{sh}(H) - 0.4 \cdot P_v(H) \qquad P_{cm} = 14.246 \cdot psi$

$P_{tm} := P_{st}(H) - P_{sh}(H) - 0.4 \cdot P_v(H) \qquad P_{tm} = 10.837 \cdot psi$

$P_a := P_{st}(H) - 0.4 \cdot P_v(H) \qquad P_a = 12.542 \cdot psi$

Elephant Foot Buckling

$S_1 := \frac{R}{400 \cdot t_s} \qquad S_1 = 2.4$

$\sigma_{ye} := \sigma_{ys} \qquad \sigma_{ye} = 30 \cdot ksi$

$$\sigma_p := \frac{0.6 \cdot E_s}{\left(\frac{R}{t_s}\right)} \cdot \left[1 - \left(\frac{P_{cp} \cdot R}{\sigma_{ye} \cdot t_s}\right)^2\right] \cdot \left(1 - \frac{1}{1.12 + S_1^{1.5}}\right) \cdot \left(\frac{S_1 + \frac{\sigma_{ye}}{36 \cdot ksi}}{S_1 + 1}\right)$$

$\sigma_p = 9705 \cdot psi \qquad C_{Be} := \sigma_p \cdot t_s \qquad C_{Be} = 1820 \cdot \frac{lb}{in}$

Diamond Shape Buckling

$\phi := \frac{1}{16} \cdot \sqrt{\frac{R}{t_s}}$ $\phi = 1.936$

$\gamma := 1 - 0.73 \cdot \left(1 - e^{-\phi}\right)$ $\gamma = 0.375$ $\frac{P_{cm}}{E_s} \cdot \left(\frac{R}{t_s}\right)^2 = 0.464$

$\Delta\gamma := 0.19$ Manually from Figure 6 of NASA SP-8007 based on Pcm

$\sigma_{cb} := (0.6 \cdot \gamma + \Delta\gamma) \cdot \frac{E_s}{\left(\frac{R}{t_s}\right)}$ $\sigma_{cb} = 12.239 \cdot ksi$

$C_{Bd} := \sigma_{cb} \cdot t_s$ $C_{Bd} = 2295 \cdot \frac{lb}{in}$

$C_B := 0.72 \cdot minx\left(C_{Be}, C_{Bd}\right)$ $C_B = 1310 \cdot \frac{lb}{in}$

Calculate Capacity

$h_a := 27 \cdot in$ $\delta_{e0} := 0.01 \cdot \left(h_a\right)$ $\delta_{e0} = 0.27 \cdot in$

$h_c := 13.5 \cdot in$ Assumed, not sensitive

$W_{te} := \left(W_H + W_s\right) \cdot \left(1 - 0.4 \cdot \frac{Scale \cdot A_v}{g}\right)$ $W_{te} = 29 \cdot kip$

$C_1(\beta) := \frac{1 + \cos(\beta)}{\sin(\beta) + (\pi - \beta) \cdot \cos(\beta)}$

$C_2(\beta) := \frac{\sin(\beta) \cdot \cos(\beta) + \pi - \beta}{1 + \cos(\beta)}$

$\beta 1 := 2.22$ Initial Guess $N_b := 18$

$i := 1, 2 .. N_b$ $A_b := 2.41 \cdot in^2$

$\alpha_i := i \cdot \frac{360}{N_b} \cdot deg$ $T_{BC} := 19.7 \cdot kip$

$\delta_{e_i} := \delta_{e0} \cdot \frac{\cos\left(\alpha_i\right) - \cos(\beta 1)}{1 - \cos(\beta 1)}$ $K_b := \frac{A_b \cdot E_s}{h_a}$

$T_{b_i} := maxx\left(minx\left(\delta_{e_i} \cdot K_b, T_{BC}\right), 0 \cdot kip\right)$

$\beta_d := 2.0, 2.1 .. 3$

$$\beta := root\left[\frac{W_{te} + \sum_i T_{b_i}}{2 \cdot R} \cdot C_1(\beta 1) - minx\left[\frac{E_s \cdot t_s \cdot \left(\delta_{e0} \cdot \frac{1 + \cos(\beta 1)}{1 - \cos(\beta 1)}\right)}{h_c}, C_B\right], \beta 1\right]$$

$\beta = 2.222$

$$\delta_c := \delta_{e0} \cdot \frac{1 + \cos(\beta)}{1 - \cos(\beta)}$$

$$C_m := \min x\left(\frac{E_s \cdot t_s \cdot \delta_c}{h_c}, C_B\right) \qquad C_m = 1310 \cdot \frac{lb}{in}$$

$$M_{sc} := C_m \cdot C_2(\beta) \cdot R^2 + \sum_i T_{b_i} \cdot R \cdot \cos(\alpha_i)$$

$M_{sc} = 5233 \cdot kip \cdot ft$

$COF := 0.55$

$$W_{ve} := W_{te} + P_a \cdot \pi \cdot R^2$$

$$V_{sc} := COF \cdot W_{ve} \qquad V_{sc} = 718 \cdot kip$$

$$Factor_of_Safety := \min x\left(\frac{M_{sc}}{M_{sh}}, \frac{V_{sc}}{V_{sh}}\right) \qquad Factor_of_Safety = 0.994$$

Capacity: $S_{Al} = 0.35 \cdot g$

Primary Water Storage Tank, PWST 21, GIP Criteria plus Fluid Hold-down

$R := 180 \cdot in$ Radius

$H := 376 \cdot in$ Fluid Height

$H_s := 420 \cdot in$ Shell Height

$H_d := 12 \cdot in$ Dome Height

$t_s := 0.1875 \cdot in$ Shell thickness

$t_h := 0.1875 \cdot in$ Head shell thickness

$t_a := 0.1875 \cdot in$ Average shell thickness

$t_b := 0.1875 \cdot in$ Bottom plate thickness

$E_s := 28300 \cdot ksi$ Shell Young's modulus

$\nu := 0.33$ Poisson's ratio

Definitions

$kip := 1000 \cdot lb$

$ksi := \frac{kip}{in^2}$

$psi := \frac{lb}{in^2}$

$pcf := \frac{lb}{ft^3}$

$minx(x,y) := if(x>y,y,x)$

$maxx(x,y) := if(x>y,x,y)$

$K := 316 \cdot ksi$ Water bulk modulus, Mark's Standard Handbook, 9th Ed., Table 3.3.2

$\sigma_{ys} := 30 \cdot ksi$ Shell yield stress

$\sigma_{us} := 75 \cdot ksi$ Shell ultimate stress

$\sigma_{yb} := 30 \cdot ksi$ Bottom plate yield stress

$\sigma_{ub} := 75 \cdot ksi$ Bottom plate ultimate stress

$\gamma_f := 62.4 \cdot pcf$ Fluid weight

$\gamma_s := 490 \cdot pcf$ Shell weight

$\rho_f := \frac{\gamma_f}{g}$ $\rho_s := \frac{\gamma_s}{g}$

$I_b := \frac{t_b^3}{12 \cdot (1 - \nu^2)}$ $I_b = 0.000616 \cdot in^3$

$A_v := 0.10 \cdot g$ 2/3 ZPA of ground spectra

$Scale := 1.90$ Spectral acceleration scale factor. Assumed, must iterate so that the demand M_{sh} is close to the capacity M_{sc}, (factor of safety = 1.0).

Weight Summary

$W_H := \pi \cdot R \cdot \sqrt{R^2 + H_d^2} \cdot t_h \cdot \gamma_s$ $W_H = 5 \cdot kip$

$X_H := H_s + \frac{H_d}{2}$ $X_H = 426 \cdot in$

$W_s := \pi \cdot 2 \cdot R \cdot t_a \cdot H_s \cdot \gamma_s$ $\qquad W_s = 25 \cdot kip$

$X_s := \frac{H_s}{2}$

$W_w := \pi \cdot R^2 \cdot H \cdot \gamma_f$ $\qquad W_w = 1382 \cdot kip$

Impulsive Mode

$\frac{t_a}{R} = 0.00104$ $\qquad \frac{H}{R} = 2.089$

$C_{WI} := 0.087$ Frequency coefficient from Haroun and Housner (1981)

$C_{LI} := C_{WI} \cdot \sqrt{\frac{0.127 \cdot \rho_s}{\rho_f}}$ $\qquad C_{LI} = 0.087$

$f_I := \frac{C_{LI}}{2 \cdot \pi \cdot H} \cdot \sqrt{\frac{E_s}{\rho_s}}$

$f_I = 7.219 \cdot Hz$ $\qquad 0.8 \cdot f_I = 5.775 \cdot Hz$ $\qquad 1.2 \cdot f_I = 8.663 \cdot Hz$

$S_{AI} := 0.22 \cdot g$ From IP3 SSE Ground Spectra 5% Damping x(5/4)^0.5 to estimate 4% damping

$S_{AI} := Scale \cdot S_{AI}$ $\qquad S_{AI} = 0.418 \cdot g$

$$W_I := \begin{cases} \left(1 - 0.436 \cdot \frac{R}{H}\right) \cdot W_w & \text{if } \frac{H}{R} \geq 1.5 \\ \left(0.764 \cdot W_w\right) & \text{if } \frac{H}{R} < 1.5 \end{cases}$$

$W_I = 1094 \cdot kip$

$$X_I := \begin{cases} \left[\left(0.5 - 0.188 \cdot \frac{R}{H}\right) \cdot H\right] & \text{if } \frac{H}{R} \geq 1.5 \\ \left(0.304 \cdot H \cdot \frac{W_w}{W_I}\right) & \text{if } \frac{H}{R} < 1.5 \end{cases}$$

$X_I = 154.2 \cdot in$

$V_I := \frac{S_{AI}}{g} \cdot \left(W_H + W_s + W_I\right)$ $\qquad V_I = 470 \cdot kip$

$M_I := \frac{S_{AI}}{g} \cdot \left(W_H \cdot X_H + W_s \cdot X_s + W_I \cdot X_I\right)$ $\qquad M_I = 6138 \cdot kip \cdot ft$

Sloshing Mode

$$f_c := \sqrt{\frac{1.5 \cdot \frac{ft}{sec^2}}{R} \cdot \tanh\left[1.835 \cdot \left(\frac{H}{R}\right)\right]} \qquad f_c = 0.316 \cdot Hz$$

$S_{Ac} := 0.100 \cdot g$ IP3 SSE Ground Spectra @ 0.5% Damping at 0.5 Hz

$S_{Ac} := Scale \cdot S_{Ac}$ $\qquad S_{Ac} = 0.19 \cdot g$

$$W_c := 0.46 \cdot \frac{R}{H} \cdot \tanh\left[1.835 \cdot \left(\frac{H}{R}\right)\right] \cdot W_w \qquad W_c = 304 \cdot kip$$

$$X_c := \left(1 - \frac{\cosh\left(1.835 \cdot \frac{H}{R}\right) - 1}{1.835 \cdot \frac{H}{R} \cdot \sinh\left(1.835 \cdot \frac{H}{R}\right)}\right) \cdot H \qquad X_c = 282.1 \cdot in$$

$$V_c := \frac{S_{Ac}}{g} \cdot W_c \qquad V_c = 58 \cdot kip$$

$$M_c := \frac{S_{Ac}}{g} \cdot W_c \cdot X_c \qquad M_c = 1358 \cdot kip \cdot ft$$

Vertical Mode

$$f_v := \frac{1}{4 \cdot H} \cdot \left[\rho_f \cdot \left(\frac{2 \cdot R}{t_s \cdot E_s} + \frac{1}{K}\right)\right]^{-\frac{1}{2}}$$

$f_v = 8.159 \cdot Hz$ $\qquad 0.8 \cdot f_v = 6.527 \cdot Hz$ $\qquad 1.2 \cdot f_v = 9.79 \cdot Hz$

$S_{Av} := 0.15 \cdot g$ 2/3 Horizontal, 5% Damping Spectra x(5/4)^0.5 to estimate 4% damping

$S_{Av} := Scale \cdot S_{Av}$ $\qquad S_{Av} = 0.285 \cdot g$

Demand

$$SRSS(x, y) := \sqrt{x^2 + y^2}$$

$$V_{sh} := SRSS(V_l, V_c) \qquad V_{sh} = 473 \cdot kip$$

$$M_{sh} := SRSS(M_l, M_c) \qquad M_{sh} = 6286 \cdot kip \cdot ft$$

Pressures

$y := (H - 198 \cdot in), H .. H$

$P_{st}(y) := \gamma_f \cdot y$

$$P_i := \frac{W_I \cdot X_I \cdot \frac{S_{AI}}{g}}{1.36\ R \cdot H^2}$$

$P_i = 2.036 \cdot psi$

$$P_c(y) := \frac{0.267 \cdot W_w \cdot \frac{S_{Ac}}{g}}{R \cdot H} \cdot \frac{\cosh\left[1.835 \cdot \left(\frac{H - y}{R}\right)\right]}{\cosh\left[1.835 \cdot \left(\frac{H}{R}\right)\right]}$$

$$P_v(y) := 0.8 \cdot \gamma_f \cdot H \cdot \frac{S_{Av}}{g} \cdot \cos\left(\frac{\pi}{2} \cdot \frac{H - y}{H}\right)$$

$P_{sh}(y) := SRSS(P_i, P_c(y))$

$P_{sm}(y) := SRSS(P_{sh}(y), P_v(y))$

$\frac{y}{in}$	$\frac{P_{st}(y)}{psi}$	$\frac{P_c(y)}{psi}$	$\frac{P_v(y)}{psi}$	$\frac{P_{sh}(y)}{psi}$	$\frac{P_{sm}(y)}{psi}$
178	6.428	0.172	2.096	2.043	2.927
376	13.578	0.045	3.096	2.037	3.706

$P_{cp} := P_{st}(H) + P_{sh}(H) + 0.4 \cdot P_v(H)$ $\qquad P_{cp} = 16.853 \cdot psi$

$P_{cm} := P_{st}(H) + P_{sh}(H) - 0.4 \cdot P_v(H)$ $\qquad P_{cm} = 14.376 \cdot psi$

$P_{tm} := P_{st}(H) - P_{sh}(H) - 0.4 \cdot P_v(H)$ $\qquad P_{tm} = 10.303 \cdot psi$

$P_a := P_{st}(H) - 0.4 \cdot P_v(H)$ $\qquad P_a = 12.339 \cdot psi$

Elephant Foot Buckling

$S_1 := \frac{R}{400 \cdot t_s}$ $\qquad S_1 = 2.4$

$\sigma_{ye} := \sigma_{ys}$ $\qquad \sigma_{ye} = 30 \cdot ksi$

$$\sigma_p := \frac{0.6 \cdot E_s}{\left(\frac{R}{t_s}\right)} \cdot \left[1 - \left(\frac{P_{cp} \cdot R}{\sigma_{ye} \cdot t_s}\right)^2\right] \cdot \left(1 - \frac{1}{1.12 + S_1^{1.5}}\right) \cdot \left(\frac{S_1 + \frac{\sigma_{ye}}{36 \cdot ksi}}{S_1 + 1}\right)$$

$\sigma_p = 9463 \cdot psi$ $\qquad C_{Be} := \sigma_p \cdot t_s$ $\qquad C_{Be} = 1774 \cdot \frac{lb}{in}$

Diamond Shape Buckling

$\phi := \frac{1}{16} \cdot \sqrt{\frac{R}{t_s}}$ $\qquad \phi = 1.936$

$\gamma := 1 - 0.73 \cdot \left(1 - e^{-\phi}\right)$ $\qquad \gamma = 0.375$ $\qquad \frac{P_{cm}}{E_s} \cdot \left(\frac{R}{t_s}\right)^2 = 0.468$

$\Delta\gamma := 0.19$ Manually from Figure Figure 6 of NASA SP-8007 based on Pc-

$$\sigma_{cb} := (0.6 \cdot \gamma + \Delta\gamma) \cdot \frac{E_s}{\left(\frac{R}{t_s}\right)}$$

$C_{Bd} := \sigma_{cb} \cdot t_s$ $\qquad C_{Bd} = 2295 \cdot \frac{lb}{in}$

$C_B := 0.72 \cdot \min x\left(C_{Be}, C_{Bd}\right)$ $\qquad C_B = 1278 \cdot \frac{lb}{in}$

Fluid Hold Down Force

$P := P_{st}(H) - 0.09 \cdot P_{sh}(H) - 0.4 \cdot P_v(H)$ Average pressure for fluid hold-down calculation

$P = 12.156 \cdot psi$

$\kappa := \sqrt{\frac{R}{t_s} \cdot \sqrt{3 \cdot (1 - \nu^2)}}$ $\kappa = 39.62$

$K := \frac{E_s \cdot t_s^3}{12 \cdot (1 - \nu^2)}$ $K = 1454 \cdot lb \cdot ft$

$K_s := \frac{2 \cdot K \cdot \kappa}{R}$ $K_s = 7680 \cdot lb$

$M_F := \frac{R \cdot t_s}{\sqrt{12 \cdot (1 - \nu^2)}} \cdot \left(1 - \frac{R}{H \cdot \kappa}\right) \cdot P$ $M_F = 124 \cdot lb$

$L := 1 \cdot in, 2 \cdot in .. 30 \cdot in$

$F(L) := 1 + \frac{K_s \cdot L}{2 \cdot E_s \cdot I_b}$

$T_e(L) := \left[\frac{L}{2} + \frac{1}{F(L)} \cdot \left(\frac{K_s \cdot L^2}{12 \cdot E_s \cdot I_b} + \frac{M_F}{P \cdot L}\right)\right] \cdot P$

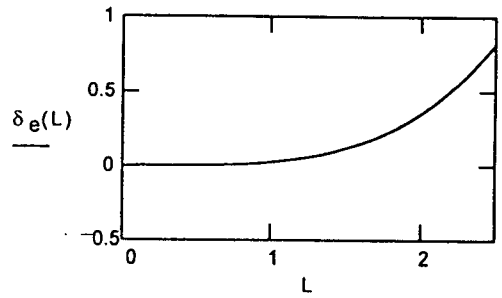
$M_e(L) := \left(\frac{1}{F(L)}\right) \cdot \left(\frac{K_s \cdot L^3}{12 \cdot E_s \cdot I_b} + \frac{M_F}{P}\right) \cdot P$

$\delta_e(L) := \left[\frac{L^4}{24} - \frac{1}{F(L)} \cdot \left(\frac{K_s \cdot L^5}{72 \cdot E_s \cdot I_b} + \frac{M_F}{P} \cdot \frac{L^2}{6}\right)\right] \cdot \frac{P}{E_s \cdot I_b}$

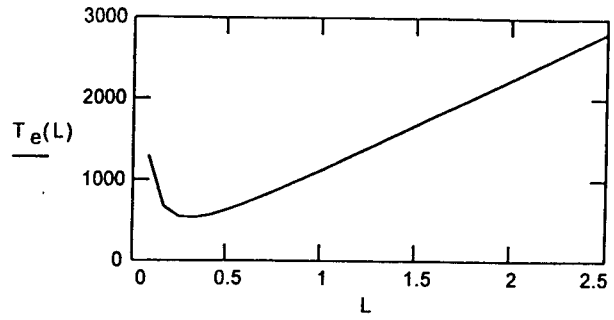
$M_{pb} := \min x\left(\sigma_{us} \cdot \frac{t_s^2}{4}, \sigma_{ub} \cdot \frac{t_b^2}{4}\right)$ $M_{pb} = 0.659 \cdot \frac{kip \cdot in}{in}$

$F_H := \frac{\sigma_{ye} \cdot t_s}{2 \cdot \kappa} + \frac{M_{pb} \cdot \kappa}{R}$ $F_H = 0.216 \cdot \frac{kip}{in}$

$T_m(L) := \sqrt{4 \cdot M_{pb} \cdot P} \cdot \sqrt{1 + \frac{F_H \cdot \delta_e(L)}{2 \cdot M_{pb}}}$



$\frac{L}{in}$	$\frac{\delta_e(L)}{in}$	$\frac{T_e(L)}{\frac{lb}{in}}$	$\frac{T_m(L)}{\frac{lb}{in}}$
1	-0.001	108.031	179.018
2	-0.003	56.426	178.989
3	-0.005	45.536	178.963
4	-0.005	44.586	178.959
5	-0.002	47.5	178.998
6	0.005	52.288	179.105
7	0.019	58.116	179.306
8	0.041	64.574	179.631
9	0.074	71.44	180.113
10	0.12	78.584	180.788
11	0.183	85.925	181.692
12	0.264	93.409	182.865
13	0.368	101.002	184.349
14	0.497	108.677	186.182
15	0.656	116.418	188.408
16	0.848	124.21	191.065
17	1.077	132.044	194.192
18	1.348	139.912	197.825
19	1.666	147.809	201.995
20	2.034	155.729	206.732
21	2.459	163.669	212.06
22	2.945	171.626	218
23	3.498	179.597	224.568
24	4.125	187.581	231.776
25	4.829	195.576	239.631
26	5.619	203.581	248.137
27	6.501	211.593	257.297
28	7.48	219.614	267.109
29	8.564	227.64	277.568
30	9.761	235.673	288.67



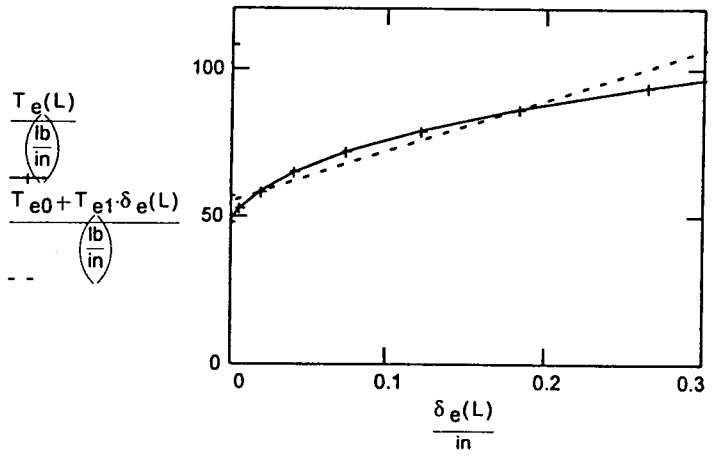
$i := 0..35$

$\delta_i := \delta_e(0.2 \cdot i \cdot in + 5 \cdot in)$

$T_i := T_e(0.2 \cdot i \cdot in + 5 \cdot in)$

$T_{e0} := intercept(\delta, T)$ $\qquad T_{e0} = 54.744 \cdot \frac{lb}{in}$

$T_{e1} := slope(\delta, T)$ $\qquad T_{e1} = 170.817 \cdot \frac{lb}{in^2}$



Compute Capacity

$h_a := 27 \cdot in$ $\quad \delta_{e0} := 0.01 \cdot (h_a)$ $\quad \delta_{e0} = 0.27 \cdot in$

$h_c := 13.5 \cdot in$ Assumed, not sensitive

$\Delta T_e := T_{e1} \cdot \delta_{e0}$

$$W_{te} := (W_H + W_s) \cdot \left(1 - 0.4 \cdot \frac{Scale \cdot A_v}{g}\right) \qquad W_{te} = 28 \cdot kip$$

$$C_1(\beta) := \frac{1 + \cos(\beta)}{\sin(\beta) + (\pi - \beta) \cdot \cos(\beta)} \qquad C_2(\beta) := \frac{\sin(\beta) \cdot \cos(\beta) + \pi - \beta}{1 + \cos(\beta)}$$

$$C_3(\beta) := \frac{\sin(\beta) - \beta \cdot \cos(\beta)}{\sin(\beta) + (\pi - \beta) \cdot \cos(\beta)} \cdot \frac{1 + \cos(\beta)}{1 - \cos(\beta)} \qquad C_4(\beta) := \frac{\beta - \sin(\beta) \cdot \cos(\beta)}{1 - \cos(\beta)}$$

$\beta 1 := 2.1$ Initial Guess

$N_b := 18$

$i := 1, 2 .. N_b$

$A_b := 2.41 \cdot in^2$

$\alpha_i := i \cdot \frac{360}{N_b} \cdot deg$

$T_{BC} := 19.7 \cdot kip$

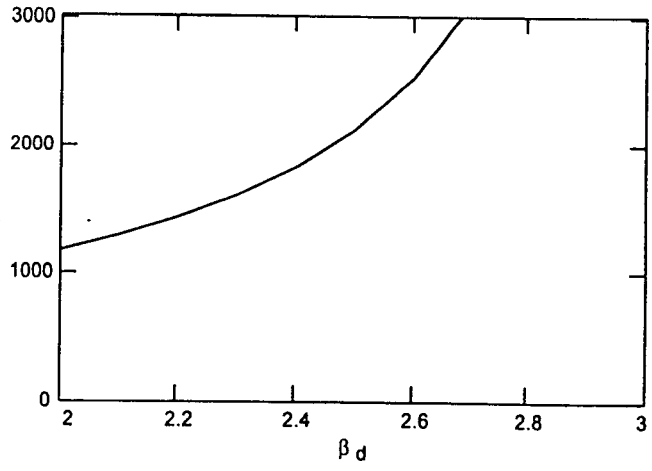
$$\delta_{e_i} := \delta_{e0} \cdot \frac{\cos(\alpha_i) - \cos(\beta 1)}{1 - \cos(\beta 1)}$$

$$K_b := \frac{A_b \cdot E_s}{h_a}$$

$$T_{b_i} := maxx\left(minx\left(\delta_{e_i} \cdot K_b, T_{BC}\right), 0 \cdot kip\right)$$

$\beta_d := 2.0, 2.1 .. 3$

$$\frac{\left(\frac{W_{te} + \sum_i T_{b_i}}{2 \cdot R} + T_{e0} \cdot \beta_d\right) \cdot C_1(\beta_d) + \Delta T_e \cdot C_3(\beta_d)}{\left(\frac{lb}{in}\right)}$$



$$\beta := \mathrm{root}\left[\left(\frac{W_{te} + \sum_i T_{b_i}}{2 \cdot R} + T_{e0} \cdot \beta 1\right) \cdot C_1(\beta 1) + \Delta T_e \cdot C_3(\beta 1) - \mathrm{minx}\left[\frac{E_s \cdot t_s \cdot \left(\delta_{e0} \cdot \frac{1 + \cos(\beta 1)}{1 - \cos(\beta 1)}\right)}{h_c}, C_B\right], \beta 1\right]$$

$\beta = 2.104$

$$\delta_c := \delta_{e0} \cdot \frac{1 + \cos(\beta)}{1 - \cos(\beta)}$$

$$C_m := \mathrm{minx}\left(\frac{E_s \cdot t_s \cdot \delta_c}{h_c}, C_B\right) \qquad C_m = 1278 \cdot \frac{lb}{in}$$

$$M_{sc} := C_m \cdot C_2(\beta) \cdot R^2 + \sum_i T_{b_i} \cdot R \cdot \cos(\alpha_i) + T_{e0} \cdot R^2 \cdot 2 \cdot \sin(\beta) + \Delta T_e \cdot C_4(\beta) \cdot R^2$$

$M_{sc} = 6238 \cdot kip \cdot ft$

$COF := 0.55$

$W_{ve} := W_{te} + P_a \cdot \pi \cdot R^2$

$V_{sc} := COF \cdot W_{ve} \qquad V_{sc} = 706 \cdot kip$

$$Factor_of_Safety := \mathrm{minx}\left(\frac{M_{sc}}{M_{sh}}, \frac{V_{sc}}{V_{sh}}\right) \qquad Factor_of_Safety = 0.992$$

Capacity: $S_{Al} = 0.418 \cdot g$