Appendix C

Diameter Analysis

Buckling

(A MathCad Model)

by

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The purpose of this calculation is to determine optimum outer diameters for the probe casings, to prevent buckling direct push and sonic load. This in not a formal analysis and need not follow MCP-2374 for format, checking, etc. The results of this analysis support using a 2.5" outer diameter for the Lysimeter, Tensiometer, and Vapor Port (Conesipper). In the case of the Soil Moisture Probe, where constrained to either 1.75" or 2" off-the-shelf probe casings, the 2" is better.

References:

1. J. Shigley & C. Mischke, Mechanical Engineering Design, Fifth Edition, McGraw-Hill Book Company, 1989, ISBN 0-07-056899-5.
2. ASTM A276, "Standard Specification for Stainless and Heat-Resisting Steel Bars and Shapes," 1992.
3. ASTM A36, "Standard Specification for Carbon Structural Steel," 1997.
4. Ryerson, "Stock List," Data Section.

Approach [1, Sections 3-14 & 3-15]:

1. Compute $\left(\frac{L}{k}\right)_l$ & $\left(\frac{L}{k}\right)_{actual}$ $\quad \left(\frac{L}{k}\right)_l = \sqrt{\frac{2 \cdot p^2 \cdot C_R \cdot E}{F_y}}$ [1, eqn 3-56]

2. If $\left(\frac{L}{k}\right)_l \geq \left(\frac{L}{k}\right)_{actual}$ => Euler Eqn $\frac{P_{cr}}{A} = \frac{C_R \cdot p^2 \cdot E}{\left[\left(\frac{L}{k}\right)_{actual}\right]^2} = \frac{F_y}{2}$ [1, eqn 3-55]

$$P_{cr} = \frac{C_R \cdot p^2 \cdot E \cdot I}{L^2}$$

3. If $\left(\frac{L}{k}\right)_l < \left(\frac{L}{k}\right)_{actual}$ => Johnson Eqn $\frac{P_{cr}}{A} = F_y - \left(\frac{F_y}{2 \cdot p}\right)^2 \cdot \frac{1}{C_R \cdot E} \cdot \left[\left(\frac{L}{k}\right)_{actual}\right]^2$ [1, eqn 3-58]

Materials: $\quad$ ORIGIN := 1 $\quad$ kip := 1000 lbf $\quad$ ksi := 1000 psi

$E_{sst} := 27.5 \cdot 10^6 \cdot psi$ Modulus of Elasticity for SST

$Fu_{sst} := 75 \cdot ksi$ $\quad Fy_{sst} := 30 \cdot ksi$ Ultimate & yield strength for 304/316 SST per ASTM A276 [2], used in ARA's instrument casing.

$E_{cs} := 30 \cdot 10^6 \cdot psi$ Modulus of Elasticity for CS

$Fu_{413} := 86 \cdot ksi$ $\quad Fy_{413} := 56 \cdot ksi$ Ultimate & yield strength for AISI 4130 [4], used in ARA's instrument casing, per Wes Bratton telecom (7-7-2000).

$Fu_{434} := 101 \cdot ksi$ $\quad Fy_{434} := 69 \cdot ksi$ Ultimate & yield strength for AISI 4340 [4], used in ARA's probe casing, per Wes Bratton telecom (7-7-2000).

$$E := \begin{bmatrix} E_{sst} \\ E_{cs} \\ E_{cs} \end{bmatrix} \quad E = \begin{bmatrix} 2.75 \cdot 10^7 \\ 3 \cdot 10^7 \\ 3 \cdot 10^7 \end{bmatrix} \cdot psi \quad F_y := \begin{bmatrix} Fy_{sst} \\ Fy_{413} \\ Fy_{434} \end{bmatrix} \quad F_y = \begin{pmatrix} 30 \\ 56 \\ 69 \end{pmatrix} \cdot ksi$$

$C_R := 1.2$ Fixed-pinned condition

$Lki_{sst} := \sqrt{\frac{2 \cdot p^2 \cdot C_R \cdot E_{sst}}{Fy_{sst}}}$ $Lki_{sst} = 147.354$ Buckling Indice for Stainless Steel

$Lki_{413} := \sqrt{\frac{2 \cdot p^2 \cdot C_R \cdot E_{cs}}{Fy_{413}}}$ $Lki_{413} = 112.648$ Buckling Indice for AISI 4130 Carbon Steel (casing)

$Lki_{434} := \sqrt{\frac{2 \cdot p^2 \cdot C_R \cdot E_{cs}}{Fy_{434}}}$ $Lki_{434} = 101.483$ Buckling Indice for AISI 4340 Carbon Steel (instrument)

$$Lki := \begin{bmatrix} Lki_{sst} \\ Lki_{413} \\ Lki_{434} \end{bmatrix} \qquad Lki = \begin{pmatrix} 147.35 \\ 112.65 \\ 101.48 \end{pmatrix}$$

SST/CS Tube:

1-3/4" OD x 3/8" wall Tube

$od_{175} := 1.75in$ $id_{175} := 1.0 \cdot in$ $w_{175} := 5.507 \cdot \frac{lbf}{ft}$ 1.75"x0.375" thk tube

$t_{175} := \frac{od_{175} - id_{175}}{2}$ $t_{175} = 0.375 \cdot in$

$A_{175} := \frac{p}{4} \cdot \left(od_{175}^2 - id_{175}^2\right)$ $A_{175} = 1.62 \cdot in^2$ $I_{175} := \frac{p \cdot \left(od_{175}^4 - id_{175}^4\right)}{64}$ $I_{175} = 0.41 \cdot in^4$

$k_{175} := \sqrt{\frac{I_{175}}{A_{175}}}$ $k_{175} = 0.504 \cdot in$

2" OD x 3/8" wall Tube

$od_{20} := 2.0 \cdot in$ $id_{20} := 1.25in$ $w_{20} := 6.508 \frac{lbf}{ft}$ 2.0"x0.325" thk tube

$t_{20} := \frac{od_{20} - id_{20}}{2}$ $t_{20} = 0.375 \cdot in$

$A_{20} := \frac{p}{4} \cdot \left(od_{20}^2 - id_{20}^2\right)$ $A_{20} = 1.91 \cdot in^2$ $I_{20} := \frac{p \cdot \left(od_{20}^4 - id_{20}^4\right)}{64}$ $I_{20} = 0.67 \cdot in^4$

$k_{20} := \sqrt{\frac{I_{20}}{A_{20}}}$ $k_{20} = 0.59 \cdot in$

$P_{mast} := 37300\,lbf$ Peak dynamic load along probe for 30,000-lbf & 120 Hz input

$L_s := 1 \cdot ft$ Unbraced pipe buckling length $r := 1..rows(E)$

$$Ls175_r := root\left[\left[\left[Lki_r \geq \frac{L_s}{k_{175}}, \frac{C_R \cdot p^2 \cdot E_r \cdot I_{175}}{L_s^2}, \left[F_{y_r} - \left(\frac{F_{y_r}}{2 \cdot p}\right)^2 \cdot \frac{\left(\frac{L_s}{k_{175}}\right)^2}{C_R \cdot E_r}\right] \cdot A_{175}\right] - 1.0 \cdot P_{mast} L_s\right]\right]$$

$$Ls20_r := root\left[\left[\left[Lki_r \geq \frac{L_s}{k_{20}}, \frac{C_R \cdot p^2 \cdot E_r \cdot I_{20}}{L_s^2}, \left[F_{y_r} - \left(\frac{F_{y_r}}{2 \cdot p}\right)^2 \cdot \frac{\left(\frac{L_s}{k_{20}}\right)^2}{C_R \cdot E_r}\right] \cdot A_{20}\right] - 1.0 \cdot P_{mast} L_s\right]\right]$$

$Ws175_r := w_{175} \cdot Ls175_r$ $Ws20_r := w_{20} \cdot Ls20_r$

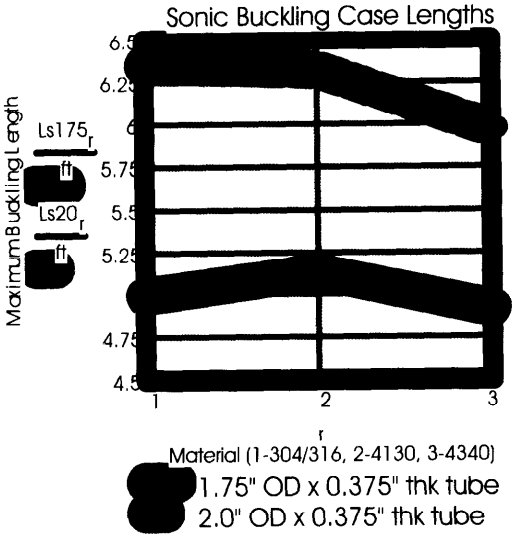
$Ls175^T = (4.99\ \ 5.13\ \ 4.92) \cdot ft$ $Ls20^T = (6.353\ \ 6.321\ \ 5.974) \cdot ft$ Sonic Peak Load Lengths

$Ls175^T = (59.93\ \ 61.6\ \ 59.03) \cdot in$ $Ls20^T = (76.233\ \ 75.851\ \ 71.685) \cdot in$

$s_{s175} := \frac{P_{mast}}{A_{175}}$ $s_{s175} = 23.026 \cdot ksi$ $s_{s20} := \frac{P_{mast}}{A_{20}}$ $s_{s20} = 19.484 \cdot ksi$

$\frac{s_{s175}}{Fy_{sst}} = 0.768$ $\frac{s_{s20}}{Fy_{sst}} = 0.649$

$Ws175 = \begin{pmatrix} 27.502 \\ 28.268 \\ 27.09 \end{pmatrix} \cdot lbf$ 304 SST 4130 CS 4340 CS $Ws20 = \begin{pmatrix} 41.34 \\ 41.14 \\ 38.88 \end{pmatrix} \cdot lbf$



$P_{push} := 11000\,lbf$ Direct push load magnitude

$L_p := 1 \cdot ft$ Unbraced pipe buckling length $r := 1..rows(E)$

$$Lp175_r := root\left(\left(\left(Lki_r \geq \frac{L_p}{k_{175}}, \frac{C_R \cdot p^2 \cdot E_r \cdot I_{175}}{L_p^2}, \left(F_{y_r} - \left(\frac{F_{y_r}}{2 \cdot p}\right)^2 \cdot \frac{\left(\frac{L_p}{k_{175}}\right)^2}{C_R \cdot E_r}\right) \cdot A_{175}\right) - 1.25 P_{push} \cdot L_p\right)\right)$$

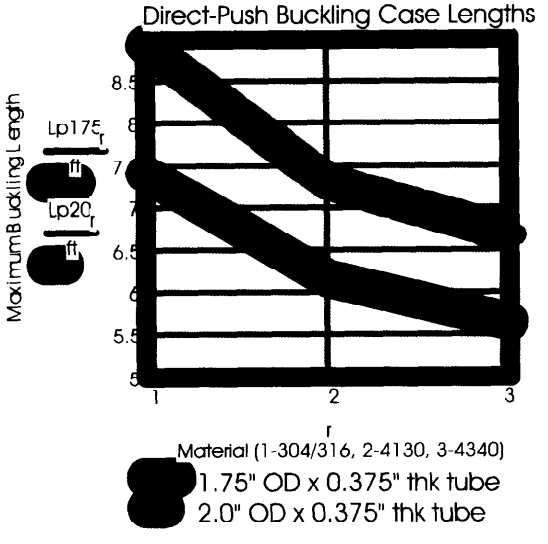
$$Lp20_r := root\left(\left(\left(Lki_r \geq \frac{L_p}{k_{20}}, \frac{C_R \cdot p^2 \cdot E_r \cdot I_{20}}{L_p^2}, \left(F_{y_r} - \left(\frac{F_{y_r}}{2 \cdot p}\right)^2 \cdot \frac{\left(\frac{L_p}{k_{20}}\right)^2}{C_R \cdot E_r}\right) \cdot A_{20}\right) - 1.25 P_{push} \cdot L_p\right)\right)$$

$Wp175_r := w_{175} \cdot Lp175_r$ $Wp20_r := w_{20} \cdot Lp20_r$

$Lp175^T = (7.41\ \ 6.16\ \ 5.64) \cdot ft$ $Lp20^T = (8.93\ \ 7.308\ \ 6.675) \cdot ft$ Direct-Push Load Lengths

$Lp175^T = (88.92\ \ 73.94\ \ 67.72) \cdot in$ $Lp20^T = (107.158\ \ 87.701\ \ 80.096) \cdot in$

$$Wp175 = \begin{pmatrix} 40.806 \\ 33.932 \\ 31.079 \end{pmatrix} \cdot lbf \qquad \begin{matrix} 304\ SST \\ 4130\ CS \\ 4340\ CS \end{matrix} \qquad Wp20 = \begin{pmatrix} 58.12 \\ 47.56 \\ 43.44 \end{pmatrix} \cdot lbf$$



Summary:
Sonic Loading Safety Factor = 1.0 based on Fy (Material Yield Strength for minimum ASTM)
Direct-Push Loading Safety Factor = 1.25 based on Fy (Material Yield Strength - average)

Sonic Peak Load

Lengths SST 4130 4340

$Ls175^T = (4.99 \quad 5.13 \quad 4.92)\cdot ft$

$Ls175^T = (59.93 \quad 61.6 \quad 59.03)\cdot in$

Direct-Push Load

Lengths SST 4130 4340

$Lp175^T = (7.41 \quad 6.16 \quad 5.64)\cdot ft$

$Lp175^T = (88.92 \quad 73.94 \quad 67.72)\cdot in$

$\frac{s_{s175}}{Fy_{sst}} = 0.768$ Maximum compression/tension stress OK

Rings Inst. Casing

$Ls20^T = (6.353 \quad 6.321 \quad 5.974)\cdot ft$

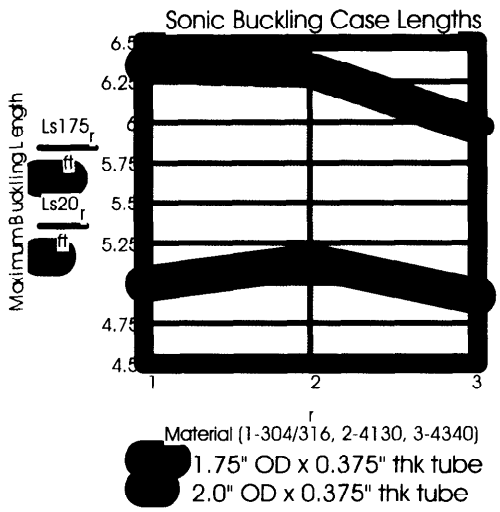
$Ls20^T = (76.233 \quad 75.851 \quad 71.685)\cdot in$

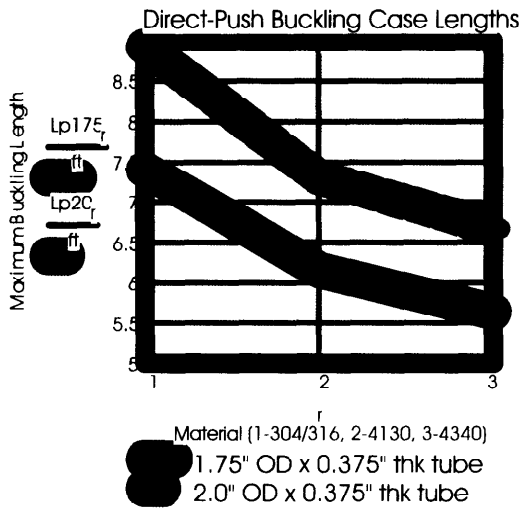
Rings Inst. Casing

$Lp20^T = (8.93 \quad 7.308 \quad 6.675)\cdot ft$

$Lp20^T = (107.158 \quad 87.701 \quad 80.096)\cdot in$

$\frac{s_{s20}}{Fy_{sst}} = 0.649$





Length Evaluation:

$L_{inst} := 3 \cdot in + 6.5 \cdot in + 12 \cdot in$ $\quad L_{inst} = 21.5 \cdot in$ Approximate length of SMR instrument (3"-tip/lower, 6.5"-rings, 12"-upper casing) constructed from 304/316 SST and 4130 CS.

$L_{ad} := 16 \cdot in$ Length of 4130 CS adapter

$L_{ext} := 1 \cdot m$ Length of 4340 casing extension

$L_{stage1} := L_{inst} + L_{ad} + L_{ext}$ $\quad L_{stage1} = 6.406 \cdot ft$ Length of 1st stage to be put into ground

$\frac{L_{stage1}}{mir(Ls175)} = 1.302$ NG $\quad \frac{L_{stage1}}{mir(Ls20)} = 1.072$ Marginal - recommend reduce adapter length.

$mir(Ls175) = 4.919 \cdot ft$ 4340 CS casing weak link $\quad mir(Ls20) = 5.974 \cdot ft$ 4340 CS casing weak link $\quad$ SONIC

$\frac{L_{stage1}}{mir(Lp175)} = 1.135$ NG $\quad \frac{L_{stage1}}{mir(Lp20)} = 0.96$ OK

$mir(Lp175) = 5.644 \cdot ft$ 4340 CS casing weak link $\quad mir(Lp20) = 6.675 \cdot ft$ 4340 CS casing weak link $\quad$ DIRECT PUSH

$L_{stop} := 2 \cdot ft$ Length above ground probe is pushed to by RSI rig - could be varied by procedure.

$L_{stage2} := L_{stage1} + L_{stop}$ $\quad L_{stage2} = 8.406 \cdot ft$

$\frac{L_{stage2}}{mir(Ls175)} = 1.709$ NG $\quad \frac{L_{stage2}}{mir(Ls20)} = 1.407$ NG

$mir(Ls175) = 4.919 \cdot ft$ 4340 CS casing weak link $\quad mir(Ls20) = 5.974 \cdot ft$ 4340 CS casing weak link $\quad$ SONIC

$\frac{L_{stage2}}{mir(Lp175)} = 1.489$ NG $\quad \frac{L_{stage2}}{mir(Lp20)} = 1.259$ NG

$mir(Lp175) = 5.644 \cdot ft$ 4340 CS casing weak link $\quad mir(Lp20) = 6.675 \cdot ft$ 4340 CS casing weak link $\quad$ DIRECT PUSH

Let => $L_{stage2} := L_{stage1} + L_{stop} - L_{ext}$ $\quad L_{stage2} = 5.125 \cdot ft$

$\frac{L_{stage2}}{mir(Ls175)} = 1.042$ Marginal $\quad \frac{L_{stage2}}{mir(Ls20)} = 0.858$ OK

$mir(Ls175) = 4.919 \cdot ft$ 4340 CS casing weak link $\quad mir(Ls20) = 5.974 \cdot ft$ 4340 CS casing weak link $\quad$ SONIC

$\frac{L_{stage2}}{mir(Lp175)} = 0.908$ OK $\quad \frac{L_{stage2}}{mir(Lp20)} = 0.768$ OK

$mir(Lp175) = 5.644 \cdot ft$ 4340 CS casing weak link $\quad mir(Lp20) = 6.675 \cdot ft$ 4340 CS casing weak link $\quad$ DIRECT PUSH

Length Summary: ARA's 4340 CS casing is weak link of each length. Recommend that 2" OD is used so that more options for length (adapter, stop, etc.) can be addressed. The 1.75" OD is too limiting.