Calculations according to "Design of soil steel composite bridges" by Lars Pettersson and Håkan Sundquist

Report 112, 5th Edition 2014

Project name: **Ojaäärse I**

Date: **2025-10-13**

Structure: **RA7**

Input parameters

Partial coefficients

Safety class: $\gamma_d := 1.0$

Serviceability limit state: $\varphi\gamma_{s.s} := \begin{bmatrix} 1 \\ 1 \end{bmatrix}$ $\varphi\gamma_{t.s} := \begin{bmatrix} 1 \\ 0 \end{bmatrix}$

Ultimate limit state: $\varphi\gamma_{s.u} := \begin{bmatrix} 1.35 \\ 1 \end{bmatrix}$ $\varphi\gamma_{t.u} := \begin{bmatrix} 1.35 \\ 0 \end{bmatrix}$

Partial factors: $\gamma_{M0} := 1.00$

$\gamma_{M1.steel} := 1.10$

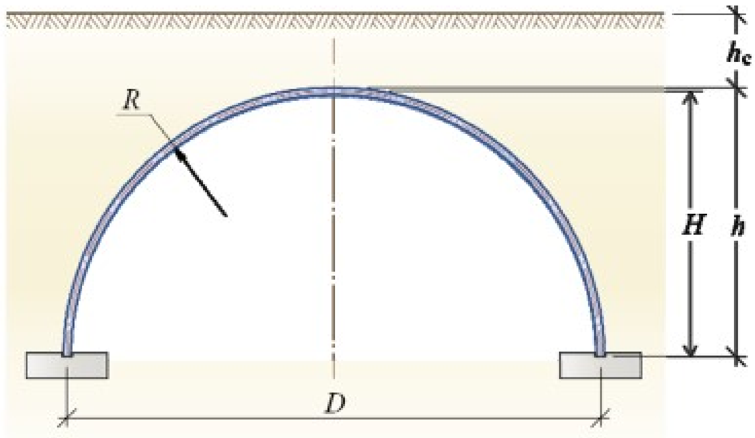
$\gamma_{M2} := 1.25$

$\gamma_{Ff} := 1.00$

$\gamma_{Mf} := 1.15$

Adjustment factor for LM1: $\alpha_Q := 1.00$ $\alpha_q := 1.0$

Profile geometry



Profile E. Pipe-arch (defined by three radii) $profile := \text{“B”}$

Possible values are "A", "B",..., "G" corresponding to the figures on the previous page.

The following parameters are defined in the figures on the previous page. For profiles A and B, all radii should be set equal to R. For profiles C and D, R_c should be set equal to R_s. For profile E, R_s should be set equal to R_t. For profile F, R_b should be set equal to R_c. For profile G, R_b and R_c should be set equal to R_t.

$H := 1.48 \cdot m$ $D := 3.246 \cdot m$ $R_t := 1.630 \cdot m$ $R_s := R_t$ $R_c := R_t$ $R_b := R_t$

Height of soil cover: $h_c := 2.85 \cdot m$

Height of cover at the position of the bolted connections: $h_f := h_c$

R_{check} is a vector with the different radii to be checked in the lower part of the culvert (R_b and R_c): $R_{check} := \begin{bmatrix} R_b \\ R_c \end{bmatrix}$

Corrugated steel plate parameters

Thickness of the plate: $t := 3.00 \cdot mm$

Corrugation wave length: $c_{val} := 200 \cdot mm$

Corrugation wave height: $h_{corr} := 55 \cdot mm$

Radii of curvature: $R := 53 \cdot mm$

Young modulus: $E := 206 \cdot GPa$

Yield stress and ultimate stress: $f_{yk} := 355 \cdot MPa$ $f_{uk} := 470 \cdot MPa$

Bolted connection parameters

Bolt diameter: $d_{bolt} := 20 \cdot mm$

Cross sectional area: $A_{s.b} := 245 \cdot mm^2$

Bolt ultimate stress: $f_{u.bolt.k} := 800 \cdot MPa$

Number of bolts per meter in each row: $n. := \begin{bmatrix} 0.0001 & 5 & 5 \end{bmatrix}^T$

Distance from the edge of the sheet to the center of each row of bolt: $a. := \begin{bmatrix} 0.0001 & 40 & 90 \end{bmatrix}^T \cdot mm$

Length of the pressure zone: $p_{zone} := 10 \cdot mm$

Distance from the center of a hole to a free edge or to the center of an adjacent hole measured in the direction of force. It should never exceed 3*d: $e_1 := 3 \cdot d_{bolt}$

Live Load parameters

Live load model LM 1 from EN 1991-2. Live load model 1 consists form 3 lanes with axle load 300kN, 200kN and 100kN. And distributed load

Soil parameters

Degree of compaction, the standard Proctor value RP: $RP := 98$

Tangent modulus calculation method. Meth=1 for the simplified method (Method A) or Meth=2 for the more precise method (Method B): $Meth := 2$

Soil parameters for Method B:

Optimal soil density: $\rho_{opt} := 20.6 \cdot \frac{kN}{m^3}$ $\qquad \rho_{cv} := \frac{RP}{100} \cdot \rho_{opt}$

Soil density: $\rho_1 := \rho_{cv}$

Average soil density: $\rho_2 := \rho_{cv}$

Soil particle size distribution: $d_{10} := 3.1 \cdot mm$

$d_{50} := 20 \cdot mm$

$d_{60} := 31 \cdot mm$

Partial coefficient: $\gamma_{m.soil} := 1.3$

Calculations

Soil tangent modulus

The choice of method to calculate tangent soil modulus is done in the input section. The calculations are made in functions containing the formulas from the handbook. Before you can calculate the tangent modulus with Method B, you need to calculate the arching coefficient for the soil. It is done in the function called arch(). It uses equations (4.d) through (4.g) and (b2.f) in the handbook. The function used for calculating the tangent modulus is called soil(). It uses equations (b2.a) through (b2.i) in the handbook.

$S_{ar} = 0.8182$

$E_{s.k} := soil\left(Meth, RP, h_c, H, 1, 1, d_{soil}, \rho_{opt}, \rho_{cv}, \rho_2, S_{ar}\right)$

$E_{s.k} = 47.49\ MPa$

$f_5 := 1.5$

$E_{sk.SLS.Traffic} := f_5 \cdot E_{s.k} = 71.2\ MPa$

$f_6 := 1.5 \cdot 1.5$

$E_{sk.Fatigue} := f_6 \cdot E_{s.k} = 106.9\ MPa$

Culvert profile section parameters

The sectional properties of the culvert profile are calculated according to equation (b1.a) in the handbook.

$$A_s = 3.6\ \frac{mm^2}{mm} \qquad I_s = 1334.1\ \frac{mm^4}{mm} \qquad W_s = 46\ \frac{mm^3}{mm} \qquad Z_s = 62.9\ \frac{mm^3}{mm} \qquad \frac{Z_s}{W_s} = 1.4$$

Corrugated steel profile stiffness parameter

The stiffness parameter is calculated according to equation (4.p) in the handbook.

$$\lambda_f := \frac{E_{s.k} \cdot D^3}{\gamma_{m.soil} \cdot E \cdot I_s} \qquad \lambda_f = 4547$$

$$\lambda_{f.SLS.Traffic} := \frac{E_{sk.SLS.Traffic} \cdot D^3}{\gamma_{m.soil} \cdot E \cdot I_s} = 6820 \qquad \lambda_{f.Fatigue} := min\left(50000, \frac{E_{sk.Fatigue} \cdot D^3}{\gamma_{m.soil} \cdot E \cdot I_s}\right) = 10230$$

Profile crown rise

The crown rise is calculated according to equation (b3.b) in the handbook.

$$\delta_{crown} := cRise\left(h_c, D, H, \lambda_f, \rho_1, E_{s.k}, profile\right) \qquad \delta_{crown} = 0\ mm$$

The reduced depth of cover is calculated according to equation (4.a) in the handbook.

$$h_{c.red} := h_c - \delta_{crown} \qquad h_{c.red} = 2.85\ m$$

$$0.015 \cdot D = 48.7\ mm$$

Dynamic amplification factor

There are two different cases when it comes to the dynamic factor.

The function dyn() handles both cases the sub function redFac() to calculate the reduction factor according to equation (3.a) in the handbook. If the dynamic effect is not included, it uses the sub function dynFac() to calculate the dynamic amplification factor according to equation (b6.a) in the handbook.

$$r_d := dyn\left(D, h_c, h_{c.red}, inc\right) \qquad r_d = 0.96$$

Axial forces

Axial forces from Dead Load

Equation (4.c) in the handbook is used to calculate the normal forces in the culvert due to the load from the surrounding soil.

$$\begin{bmatrix} N_{s.surr} \\ N_{s.cover} \end{bmatrix} := N_{s.f}\left(H, D, R_s, \rho_1, h_{c.red}, S_{ar}, \rho_{cv}, profile\right) \qquad N_s := N_{s.surr} + N_{s.cover}$$

$$N_{s.surr} = 19.4\ \frac{kN}{m} \qquad N_{s.cover} = 102.7\ \frac{kN}{m} \qquad N_s = 122.1\ \frac{kN}{m}$$

Manually check a point:

The result for the manually selected point:

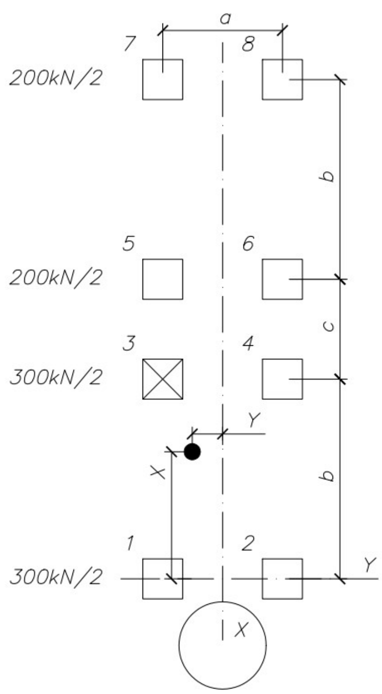
$$P14 := P_{LM1_{0,0}} \cdot 2 \cdot \alpha_Q \qquad P14 = 300\ kN \qquad h_c = 2.85\ m$$

$$P58 := P_{LM1_{4,0}} \cdot 2 \cdot \alpha_Q \qquad P58 = 200\ kN$$

$$a := 1.2\ m$$

$$b := 2.0\ m$$

$$c := 1.0\ m$$



The equivalent line load is calculated according to equation (4.k) in the handbook.

$$h_{c.red} = 2.85\ m \qquad \max\left(\sigma_v\right) = 30.144\ kPa \qquad \max\left(\sigma_{v.fatigue}\right) = 30.144\ kPa$$

$$p_{traffic} := \frac{\pi \cdot h_{c.red}}{2} \cdot \max\left(\sigma_v\right) \qquad p_{traffic} = 134.949 \ \frac{kN}{m}$$

The normal force in the culvert due to live load is calculated according to equations (4.I’) through (4.I’”).

$h_{c.red} = 2.85\ m$ $\qquad D = 3.25\ m$ $\qquad q = 9\ kPa$ $\qquad p_{traffic} = 135\ \frac{kN}{m}$

$$N_t := N_{t.f}\left(h_{c.red}, D, q, p_{traffic}\right) \qquad N_t = 82.1\ \frac{kN}{m}$$

Design axial forces

Serviceability limit state

$\varphi\gamma_{t.s} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$ $\qquad N_t = 82.1\ \frac{kN}{m}$

$$N_{d.s} = N_{s.d.s.all} + \varphi\gamma_{t.s} \cdot N_t \cdot \left\| \begin{array}{l} \text{if } \frac{R_t}{R_s} > 1.0 \\ \quad \left\| \left(\frac{R_t}{R_s}\right)^{0.25} \right. \\ \text{else} \\ \quad \left\| 1.0 \right. \end{array} \right. \qquad N_{d.s} = \begin{bmatrix} 204.2 \\ 122.1 \\ 204.2 \\ 122.1 \\ 204.2 \\ 122.1 \\ 204.2 \\ 122.1 \end{bmatrix} \frac{kN}{m}$$

Ultimate limit state

$\varphi\gamma_{t.u} = \begin{bmatrix} 1.35 \\ 0 \end{bmatrix}$

$$N_{d.u} = \gamma_d \cdot \left(N_{s.d.u.all} + \varphi\gamma_{t.u} \cdot N_t\right) \qquad N_{d.u} = \begin{bmatrix} 275.6 \\ 164.8 \\ 268.8 \\ 158.0 \\ 239.7 \\ 128.9 \\ 232.9 \\ 122.1 \end{bmatrix} \frac{kN}{m}$$

Bending moments

Bending moments from Dead Load and Live Load

$M_{s.surr} = -1\ \frac{kN \cdot m}{m}$ $\qquad M_{s.cover} = 1.6\ \frac{kN \cdot m}{m}$ $\qquad M_t = 2.2\ \frac{kN \cdot m}{m}$ $\qquad M_{t.SLS} = 1.8\ \frac{kN \cdot m}{m}$

Design bending moments

Serviceability limit state

$$\max\left(\varphi\gamma_{t.s}\right)=1$$

$$M_{td.s}:=\begin{bmatrix}\max\left(\varphi\gamma_{t.s}\right)\cdot M_{t.SLS}\\ \max\left(\varphi\gamma_{t.s}\right)\cdot\left(\dfrac{-M_{t.SLS}}{2}\right)\end{bmatrix}\qquad M_{td.s}=\begin{bmatrix}1.8\\-0.9\end{bmatrix}\dfrac{kN\cdot m}{m}$$

$$\varphi\gamma_{s.s.1}=\begin{bmatrix}1\\1\\1\\1\end{bmatrix}\qquad \varphi\gamma_{s.s.2}=\begin{bmatrix}1\\1\\1\\1\end{bmatrix}$$

$$M_{s.d.s.all}:=\varphi\gamma_{s.s.1}\cdot M_{s.surr}+\varphi\gamma_{s.s.2}\cdot M_{s.cover}$$

$$M_{s.d.s.all}=\begin{bmatrix}0.5\\0.5\\0.5\\0.5\end{bmatrix}\dfrac{kN\cdot m}{m}$$

$$M_{sd.s}=M_{s.d.s.all}+M_{td.s}$$

$$M_{sd.s}=\begin{bmatrix}2.4\\-0.4\\2.4\\-0.4\\2.4\\-0.4\\2.4\\-0.4\end{bmatrix}\dfrac{kN\cdot m}{m}$$

Ultimate limit state

$$\max\left(\varphi\gamma_{t.u}\right)=1.35$$

$$M_{td.u}:=\begin{bmatrix}\max\left(\varphi\gamma_{t.u}\right)\cdot M_{t}\\ \max\left(\varphi\gamma_{t.u}\right)\cdot\left(\dfrac{-M_{t}}{2}\right)\end{bmatrix}\qquad M_{td.u}=\begin{bmatrix}3\\-1.5\end{bmatrix}\dfrac{kN\cdot m}{m}$$

$$\varphi\gamma_{s.u.1}=\begin{bmatrix}1.35\\1\\1.35\\1\end{bmatrix}\qquad \varphi\gamma_{s.u.2}=\begin{bmatrix}1.35\\1.35\\1\\1\end{bmatrix}$$

$$M_{s.d.u.all}:=\varphi\gamma_{s.u.1}\cdot M_{s.surr}+\varphi\gamma_{s.u.2}\cdot M_{s.cover}$$

$$M_{s.d.u.all} = \begin{bmatrix} 0.7 \\ 1.1 \\ 0.2 \\ 0.5 \end{bmatrix} \frac{kN \cdot m}{m}$$

$$M_{sd.u} = \gamma_d \cdot \left(M_{s.d.u.all} + M_{td.u}\right)$$

$$M_{sd.u} = \begin{bmatrix} 3.7 \\ -0.8 \\ 4 \\ -0.4 \\ 3.1 \\ -1.3 \\ 3.5 \\ -1 \end{bmatrix} \frac{kN \cdot m}{m}$$

$$M_{d.u.bolt} = max\left(\gamma_d \cdot \left(M_{s.d.u.all} + \frac{h_{c.red}}{h_f} \cdot M_{td.u}\right)\right)$$

$$M_{d.u.bolt} = 4 \frac{kN \cdot m}{m}$$

BEARING CAPACITY DESIGN CHECK

Ensuring safety against the onset of yielding in the serviceability limit state

$f_{yk} = 355\ MPa$ $\qquad f_{yd} := \frac{f_{yk}}{\gamma_{M0}}$ $\qquad f_{yd} = 355\ MPa$

$$\sigma := \frac{N_{d.s}}{A_s} + \frac{\overrightarrow{\left|M_{sd.s}\right|}}{W_s}$$

$$\sigma = \begin{bmatrix} 107.7 \\ 42.3 \\ 107.7 \\ 42.3 \\ 107.7 \\ 42.3 \\ 107.7 \\ 42.3 \end{bmatrix} MPa$$

$$\max\left(\varphi\gamma_{s.s}\right) \cdot \left(\frac{N_{s.surr}}{A_s} + \frac{\left|M_{s.surr}\right|}{W_s}\right) = 28.15\ MPa$$

Calculation of bending moment capacity

Local buckling reduction factor

$$M_{ucr} := \left(1.429 - 0.156 \cdot \ln\left(\left(\frac{m_t}{t}\right) \cdot \left(\frac{f_{yk}}{227 \cdot MPa}\right)^{0.5}\right)\right) \cdot \left(\frac{\left(f_{yk} \cdot Z_s\right)}{\gamma_{M1.steel}}\right) = 20.4 \ \frac{kN \cdot m}{m}$$

$$\alpha_{red} := min\left(1.0, \frac{M_{ucr}}{f_{yk} \cdot Z_s}\right) = 0.91$$

$$M_{y.Rk} := \alpha_{red} \cdot f_{yk} \cdot Z_s = 20.4 \ \frac{kN \cdot m}{m}$$

Calculation of normal force capacity

$$N_{Rk} := f_{yk} \cdot A_s = 1280.1 \ \frac{kN}{m}$$

Check against the building of a plastic hinge in the crown

$$N_{cr.1} = 1033.7 \ \frac{kN}{m}$$

$$\left(\frac{N_{d.u}}{N_{cr.1}}\right)^{\alpha_{c.1}} \le 1.0$$

$$\left(\frac{N_{d.u}}{N_{cr.1}}\right)^{\alpha_{c.1}} = \begin{bmatrix} 0.11 \\ 0.05 \\ 0.11 \\ 0.04 \\ 0.09 \\ 0.03 \\ 0.08 \\ 0.03 \end{bmatrix}$$

$$N_{cr.2} = 1033.7 \ \frac{kN}{m} \qquad N_{cr.el} = 2602.4 \ \frac{kN}{m} \qquad k_{yy} = \begin{bmatrix} 1.04 \\ 1.02 \\ 1.04 \\ 1.02 \\ 1.03 \\ 1.02 \\ 1.03 \\ 1.02 \end{bmatrix}$$

$$Utilization = \frac{N_{d.u}}{\chi_y \cdot \frac{N_{Rk}}{\gamma_{M1.steel}}} + k_{yy} \cdot \frac{\overrightarrow{\left|M_{sd.u}\right|}}{\frac{M_{y.Rk}}{\gamma_{M1.steel}}} \le 1.0$$

$$Utilization = \begin{bmatrix} 0.473 \\ 0.202 \\ 0.487 \\ 0.175 \\ 0.406 \\ 0.197 \\ 0.42 \\ 0.171 \end{bmatrix}$$

Bolted connection calculations

Forces in bolted connection

Tension in last row of bolted connection:

$$F_{t.ULS} := F\left(M_{d.u.bolt}, n., a_n\right) = 8.8\ \boldsymbol{kN}$$

Shear in last row of bolted connection:

$$F_{v.ULS} := \frac{\max\left(N_{d.u}\right)}{\frac{\sum n.}{\boldsymbol{m}}} = 27.6\ \boldsymbol{kN}$$

Capacity of the bolted connection

Shear capacity in ULS:

$$F_{b.Rd} := \frac{2.5 \cdot f_{uk} \cdot d_{bolt} \cdot t}{\gamma_{M2}} = 56.4\ \boldsymbol{kN}$$

$$F_{v.Rd} := \frac{0.6 \cdot f_{u.bolt.k} \cdot A_{s.b}}{\gamma_{M2}} = 94.08\ \boldsymbol{kN}$$

Tension capacity in ULS:

$$F_{t.Rd} := \frac{0.9 \cdot f_{u.bolt.k} \cdot A_{s.b}}{\gamma_{M2}} = 141.12\ \boldsymbol{kN}$$

Ensuring safety against exceeding the capacity of the bolted connections

Shear:

$$\frac{F_{v.ULS}}{min\left(F_{v.Rd}, F_{b.Rd}\right)} \le 1.00$$

$$\frac{F_{v.ULS}}{min\left(F_{v.Rd}, F_{b.Rd}\right)} = 0.49$$

Tension:

$$\frac{F_{t.ULS}}{F_{t.Rd}} \le 1.00$$

$$\frac{F_{t.ULS}}{F_{t.Rd}} = 0.063$$

Interaction of shear and tension:

$$\frac{F_{v.ULS}}{min\left(F_{v.Rd}, F_{b.Rd}\right)} + \frac{F_{t.ULS}}{1.4 \cdot F_{t.Rd}} \le 1.00$$

$$\frac{F_{v.ULS}}{min\left(F_{v.Rd}, F_{b.Rd}\right)} + \frac{F_{t.ULS}}{1.4 \cdot F_{t.Rd}} = 0.53$$