APPENDIX B – SAMPLE DESIGN PROBLEM

The following is a sample design problem illustrating the design procedure described in Chapter 4. The hypothetical design case involves construction of a 2400-mm-tall (8-ft-tall) rockery with level back slope and toe slopes. A standard AASHTO vehicle surcharge is assumed to act behind the rockery. In order to simplify the analysis for the example problem, a temporary concrete traffic barrier (K-rail) was used instead of a guardrail. In addition, the following assumptions were made:

- The project geotechnical investigation has determined the rockery will retain medium dense clayey sand with a friction angle (ϕ) of 33º and no long-term cohesion.
- For short-term conditions, undrained cohesion will allow excavation of the rockery back cut at an inclination of 8V:1H.
- Passive pressure will be neglected at the toe of the rockery.
- Friction between the base rock and soil subgrade can be computed using the equation $\mu = \tan\phi$. Ultimate friction can be used because passive pressure is neglected.
- $FS_{OT} = 2.0$, $FS_{SL} = 1.5$, and $FS_{BC} = 2.5$.
- Inter-rock sliding will be satisfied through the plans and specifications, which will require the outermost bearing point to be within 150 mm (6 in) of the rockery face.
- The rockery face batter is 4V:1H.
- The site is located in Seismic Performance Category (SPC) C with an Acceleration Coefficient (A) of 0.25.

The design geometry and computation of the required base width and factors of safety follow:

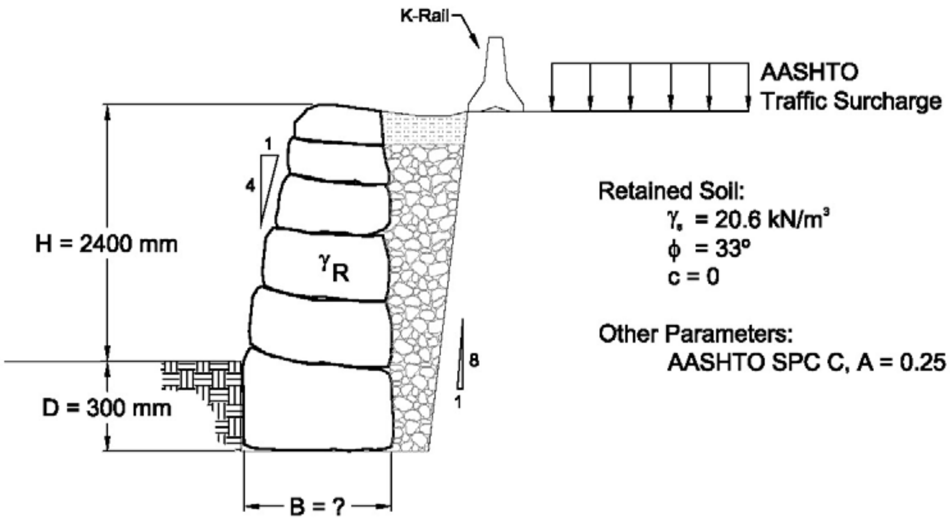


Figure 81. Graphic. Assumed Geometry for Example Problem—2400 mm (8 ft) rockery retaining medium dense clayey sand and subjected to a vehicle surcharge.

Parameters:

$\mathrm{H} = 2.7\mathrm{m}$ (total)

$\mathrm{H_R} = 2.4\mathrm{m}$ (exposed)

$\mathrm{D} = 0.3\mathrm{m}$

$\phi = 33°$

$\gamma_s = 20.6 \frac{\mathrm{kN}}{\mathrm{m}^3}$

$\gamma_R = 23.5 \frac{\mathrm{kN}}{\mathrm{m}^3}$

$\beta = 0$ (level backslope)

$\delta = \frac{2}{3}\phi = 22°$

$\alpha = \tan^{-1}(\frac{8}{1}) = 82.9°$

$\psi = 90° - \alpha = 7.13°$

$\mu = \tan\phi = 0.649$

Assume B = 1.2 m for initial analyses.

Lateral Earth Pressure Coefficient:

$$K_A = \frac{\cos^2(\psi+\phi)}{\cos^2(\psi)\cdot\cos(\delta-\psi)\cdot\left[1+\sqrt{\frac{\sin(\phi+\delta)\cdot\sin(\phi-\beta)}{\cos(\delta-\psi)\cdot\cos(-\psi-\beta)}}\right]^2}$$

$$K_A = 0.217$$

Surcharge:

$$q_s = \gamma_s(0.6m) = 12.36\tfrac{kN}{m^2}$$

Total Horizontal Force:

$$F_H = F_{A,H} + F_S = \tfrac{1}{2}\gamma_S K_A H^2 \cos\cdot(\delta - \psi) + q_S K_A H$$

$$F_H = 23.0\tfrac{kN}{m}$$

Wall Weight:

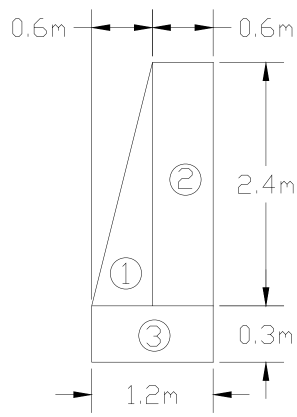
$$\gamma_R = 23.5\tfrac{kN}{m^3}$$

$$W_1 = \tfrac{1}{2}(0.6m)(2.4m)(23.5\tfrac{kN}{m^3}) = 16.9\tfrac{kN}{m}$$

$$W_2 = (0.6m)(2.4m)(23.5\tfrac{kN}{m^3}) = 33.8\tfrac{kN}{m}$$

$$W_3 = (0.3m)(1.2m)(23.5\tfrac{kN}{m^3}) = 8.46\tfrac{kN}{m}$$

$$\sum_i W_i = 59.2\tfrac{kN}{m}$$



Frictional Resistance:

$$F_\mu = \mu\cdot(W + F_{A,V}) = \mu\cdot\left(\sum_i W_i + \tfrac{1}{2}\gamma_S K_A H^2 \sin(\delta - \psi)\right)$$

$$F_\mu = 41.1\tfrac{kN}{m}$$

Factor of Safety against External Sliding:

$$FS_{SL} = \frac{F_\mu}{F_H} = 1.8 \quad \underline{\textbf{OK}}$$

Factor of Safety against External Overturning:

$$M_o = \tfrac{1}{2}\gamma_S K_A H^2 \cos(\delta - \psi)\left(\frac{H}{3}\right) + q_S K_A H\left(\frac{H}{2}\right)$$

$$M_o = 23.9\tfrac{kN\cdot m}{m}$$

$$M_r = \sum_i W_i x_i + \tfrac{1}{2}\gamma_S K_A H^2 \sin(\delta - \psi)\left(\frac{H}{3}\cdot\tan(\psi) + B\right)$$

$$\sum_i W_i x_i = (16.9\tfrac{kN}{m})(0.4m) + (33.8\tfrac{kN}{m})(0.9m) + (8.46\tfrac{kN}{m})(0.6m) = 42.3\tfrac{kN\cdot m}{m}$$

$$M_r = 47.8\tfrac{kN\cdot m}{m} \quad \therefore \quad FS_{OT} = \frac{M_r}{M_O} = 2.0 \quad \underline{\textbf{OK}}$$

Factor of Safety against Individual Rock Overturning:

$$\mathrm{H - H' = 1.2m}$$

$$\mathrm{W_1 = \tfrac{1}{2}(0.3m)(1.2m)(23.5\tfrac{kN}{m^3}) = 4.23\tfrac{kN}{m}}$$

$$\mathrm{W_2 = (0.6m)(1.2m)(23.54\tfrac{kN}{m^3}) = 16.9\tfrac{kN}{m}}$$

$$\mathrm{x_1 = 0.2m}$$

$$\mathrm{x_2 = 0.6m}$$

$$\mathrm{x' = 0.15m}$$

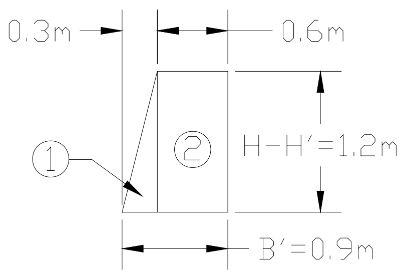
$$M_{o\_\mathrm{int}} = \tfrac{1}{2}\gamma_S K_A (H - H')^2 \cos(\delta - \psi)\left(\frac{H - H'}{3}\right) + q_S K_A (H - H')\left(\frac{H - H'}{2}\right)$$

$$M_{o\_\mathrm{int}} = 3.18\,\tfrac{kN\cdot m}{m}$$

$$M_{r\_\mathrm{int}} = \sum_i W_{i\_top}(x_i - x') + \tfrac{1}{2}\gamma_S K_A (H - H')^2 \sin(\delta - \psi)\left(\frac{H - H'}{3}\cdot \tan(\psi) + B'\right)$$

$$M_{r\_\mathrm{int}} = 8.60\,\tfrac{kN\cdot m}{m}$$

$$FS_{OT\_\mathrm{int}} = \frac{M_{r\_\mathrm{int}}}{M_{o\_\mathrm{int}}} = 2.7$$ **OK**



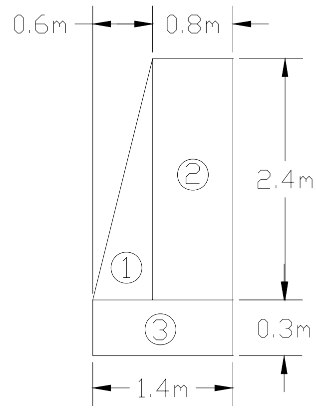
Factor of Safety against Bearing Capacity:

$$e = \frac{B}{2} - \frac{M_r - M_O}{W + \tfrac{1}{2}\gamma_S K_A H^2 \sin(\delta - \psi)}$$

$$e = 0.310$$

$$|e| \geq \frac{B}{6} = .200$$ **NO GOOD; USE B=1.4m**

Wall Weight for B=1.4m:



$$W_1 = 16.9\,\tfrac{\text{kN}}{\text{m}}$$
$$W_2 = (0.8\text{m})(2.4\text{m})(23.5\,\tfrac{\text{kN}}{\text{m}^3}) = 45.1\,\tfrac{\text{kN}}{\text{m}}$$
$$W_3 = (0.3\text{m})(1.4\text{m})(23.5\,\tfrac{\text{kN}}{\text{m}^3}) = 9.87\,\tfrac{\text{kN}}{\text{m}}$$
$$\sum_i W_i = 71.9\,\tfrac{\text{kN}}{\text{m}}$$

$$\bar{y} = \frac{16.9(0.3+0.8)+45.1(0.3+1.2)+9.87(0.15)}{71.9} = 1.22\text{m}$$

Factor of Safety against External Overturning:

$$M_o = \tfrac{1}{2}\gamma_S K_A H^2 \cos(\delta-\psi)\left(\frac{H}{3}\right) + q_S K_A H\left(\frac{H}{2}\right)$$
$$M_o = 23.9\,\tfrac{kN\cdot m}{m}$$
$$M_r = \sum_i W_i x_i + \tfrac{1}{2}\gamma_S K_A H^2 \sin(\delta-\psi)\left(\frac{H}{3}\cdot\tan(\psi)+B\right)$$
$$\sum_i W_i x_i = (16.9\,\tfrac{kN}{m})(0.4m)+(45.1\,\tfrac{kN}{m})(1.0m)+(9.87\,\tfrac{kN}{m})(0.7m) = 58.8\,\tfrac{kN\cdot m}{m}$$
$$M_r = 65.1\,\tfrac{kN\cdot m}{m} \quad \therefore \quad \text{FS}_{\text{OT}} = \frac{\text{M}_\text{r}}{\text{M}_\text{O}} = 2.7 \quad \underline{\textbf{OK}}$$

Factor of Safety against Bearing Capacity for B=1.4m:

$$e = \frac{B}{2} - \frac{M_r - M_O}{W + \tfrac{1}{2}\gamma_S K_A H^2 \sin(\delta-\psi)}$$
$$e = 0.158$$
$$|e| \le \frac{B}{6} = .233 \qquad \underline{\textbf{OK}}$$

$$q_{\max} = \frac{W + \tfrac{1}{2}\gamma_S K_A H^2 \sin(\delta-\psi)}{B}\cdot\left(1+\frac{6e}{B}\right)$$
$$q_{\max} = 91.1kPa$$

$$q_{ult} = cN_c + 0.5\lambda s B'' N_\lambda + qN_q$$ **From AASHTO Section 4.4.7.1**

Assume, $c = 0$ $B'' = B - 2e$ and $N_{\lambda 33^\circ} = 35.19$ **From AASHTO Table 4.4.7.1A**

$qNq = 0$ **(neglected)**

therefore, $q_{ult} = 0.5(20.6)(1.4 - 2(0.158))(35.19)$

$$q_{ult} = 393 kPa$$

therefore, $FS_{BC} = \dfrac{q_{ult}}{q_{max}} = 4.3$ **OK**

Seismic Earth Pressure Coefficient:

$$k_h = 0.5A = 0.125$$

$$k_v = 0$$

$$\theta = \tan^{-1}\left(\frac{k_h}{1 - k_v}\right) = 7.13$$

$$K_{AE} = \frac{\cos^2(\phi - \theta + \psi)}{\cos(\theta)\cdot\cos^2(-\psi)\cdot\cos(\delta - \psi + \theta)\cdot\left[1 + \sqrt{\dfrac{\sin(\phi + \delta)\cdot\sin(\phi - \theta - \beta)}{\cos(\delta - \psi + \theta)\cdot\cos(\beta + \psi)}}\right]^2}$$

$$K_{AE} = 0.295$$

Seismic Surcharge Pressure:

$$F_A = \tfrac{1}{2}\gamma_S K_A H^2 = 16.29\tfrac{kN}{m}$$

$$F_{AE} = \tfrac{1}{2}(1 - K_v)K_{AE}\gamma_S H^2 = 22.15\tfrac{kN}{m}$$

$$\Delta F_{AE} = F_{AE} - F_A = 5.86\tfrac{kN}{m}$$

Factor of Safety against Seismic Overturning:

$$M_{O,S} = M_O + \Delta F_{AE}\cos(\delta - \psi)\cdot 0.6H + k_h W\bar{y}$$
$$M_{O,S} = 44.0\,\tfrac{kN\cdot m}{m}$$

$$M_{r,s} = M_r + \Delta F_{AE}\sin(\delta - \psi)[(0.6H)\tan\psi + B]$$
$$M_{r,s} = 67.5\,\tfrac{kN\cdot m}{m}$$

$$FS_{OT,S} = \frac{M_{r,s}}{M_{O,S}} = 1.5$$ **OK**

Factor of Safety against Seismic Sliding:

$$F_{H,S} = F_{A,H} + F_S + \Delta F_{AE}\cos(\delta - \psi) + k_h W$$
$$F_{H,S} = 37.7\,\tfrac{kN}{m}$$

$$F_{R,S} = \mu\left(W + F_{A,V} + \Delta F_{AE}\sin(\delta - \psi)\right)$$
$$F_{R,S} = 50.4\,\tfrac{kN}{m}$$

$$FS_{SL,S} = \frac{F_{R,S}}{F_{H,S}} = 1.3$$ **OK**

Factor of Safety against Seismic Bearing Capacity:

$$e_S = \frac{B}{2} - \frac{M_{r,s} - M_{O,S}}{W + F_{AE}\sin(\delta - \psi)} = 0.397$$

$$q_{\max,S} = \frac{W + F_{AE}\sin(\delta - \psi)}{B}\cdot\left(1 + \frac{6e_S}{B}\right)$$
$$q_{\max,S} = 150kPa$$

$$FS_{BC} = \frac{q_{ult}}{q_{\max}} = 2.9$$ **OK**

Check seismic stability using the alternate approach by Richards and Elms:

Recompute k_h and K_{AE}

$$k_h = A_a\left(\frac{0.2A_v^{\,2}}{A_a\cdot\Delta}\right)^{0.25}$$

Assume Δ = 0.05B = 0.07m = 2.75 in

Estimate A_a, A_v :

$$a_{peak} = A = 0.25g$$

$$v_{peak} = 122 \tfrac{cm}{\sec \cdot g} \cdot a_{peak} = 30.5 \tfrac{cm}{s}$$

$$\alpha_A = 2.12$$

$$\alpha_V = 1.65$$

Calculate the Spectral Ordinates:

$$A^* = \alpha_A \cdot a_{peak} = 0.53g$$

$$V^* = \alpha_V \cdot v_{peak} = 50.3 \tfrac{cm}{s}$$

Calculate EPA and EPV:

$$EPA = A^* / 2.5 = 0.212g$$

$$EPV = V^* / 2.5 \tfrac{cm}{s} = 20.1 \tfrac{cm}{s}$$

Calculate Aa and Av:

$$A_a = EPA / g = 0.212$$

$$A_v = EPV / 76.2 \tfrac{cm}{s} = 0.264$$

therefore, $k_h = 0.083$

$$\theta = \tan^{-1}\left(\frac{k_h}{1-k_v}\right) = 4.74$$

$$K_{AE} = \frac{\cos^2(\phi - \theta + \psi)}{\cos(\theta) \cdot \cos^2(-\psi) \cdot \cos(\delta - \psi + \theta) \cdot \left[1 + \sqrt{\frac{\sin(\phi + \delta) \cdot \sin(\phi - \theta - \beta)}{\cos(\delta - \psi + \theta) \cdot \cos(\beta + \psi)}}\right]^2}$$

$$K_{AE} = 0.266$$

Factor of Safety against Wall Movement:

$$F_{AE} = \tfrac{1}{2}(1 - k_v) K_{AE} \gamma_S H^2 = 20.0 \tfrac{kN}{m}$$

$$C_{IE} = \frac{\cos(\delta - \psi) + \tan\phi \cdot \sin(\delta - \psi)}{(1 - k_v)(\tan\phi - \tan\theta)} = 2.00$$

$$W_{req} = F_{AE} \cdot C_{IE} = 40.0 \tfrac{kN}{m}$$

$$FS_{seismic} = \frac{W}{W_{req}} = 1.80 \quad \underline{\textbf{OK}}$$

Therefore, since $FS_{seismic} > 1.1$, there is at least a 90% probability that the observed movement following a design earthquake with the estimated level of shaking will be less than 70 mm

(2.75 in). Because the factor of safety is actually much greater than 1.1, the probability that the observed movement will not exceeded 70 mm (2.75 in) is likely greater than 95%.