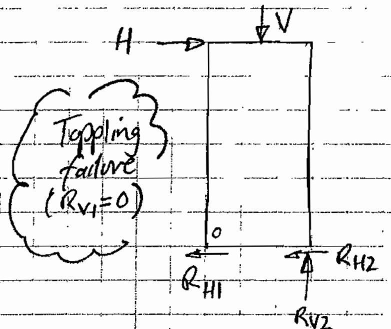
4D5 2006 crib : FOUNDATION ENGINEERING

1) Two-footed offshore structure, of weight V, under applied load, H.
Pinned feet, so not determinate, but we are told that H is equally distributed between feet.

a) Basic approach: ① Two failure modes possible: Toppling (upwind foot, $R_{V_1}=0$) or Bearing/sliding of downwind foot. ② Find H to cause toppling, then ③ compare load path and failure surface to find H to cause bearing/sliding.



$M)_o \Rightarrow \quad H.3a + V.\frac{a}{2} = R_{V2}.a$ — ①

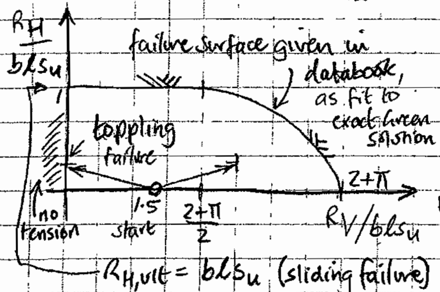
$R\uparrow \Rightarrow \quad R_{V2} = V$ — ②

Since $V = 3bls_u$, combining ①, ② ⇒

$$3aH = 3bls_u a - 3bls_u \frac{a}{2}$$

$$\Rightarrow \quad H = \frac{1}{2} bls_u \quad \text{(equally divided into } R_{H1}, R_{H2})$$

$R_{H1} = R_{H2} = \frac{bls_u}{4}$



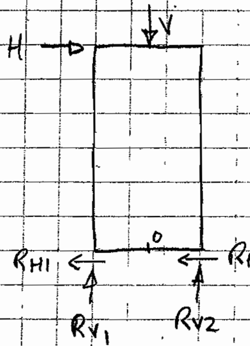
Check for bearing/sliding of downwind foot prior to toppling.
i.e. Does load point of downwind footing lie inside failure surface when upwind footing lifts off?

At toppling: $R_{H2}/R_{H2,ult} = 1/4 \Rightarrow R_{V2}/R_{V2,ult} = \frac{1}{2} + \frac{1}{2}\sqrt{1-\frac{1}{4}} = 0.933$ at bearing/sliding failure.

but $R_{V2}/R_{V2,ult} = 3/_{2+\pi} = 0.58$ at toppling failure, so this mode governs.

(Green solution fit on databook)

b) Free body diagram – used only to generate load paths towards failure

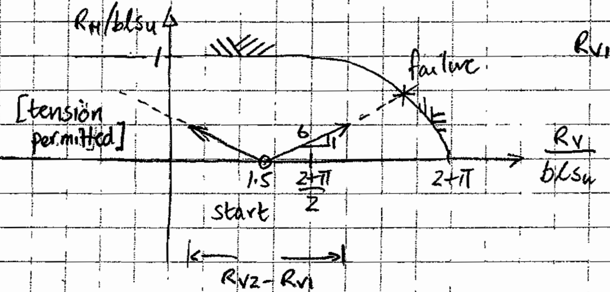


$M)_o \Rightarrow \quad 3aH = (R_{V2} - R_{V1})\frac{a}{2} \quad \Rightarrow \quad R_{V2} - R_{V1} = 6H$

$R\uparrow \Rightarrow \quad V = R_{V1} + R_{V2}$

(since $R_{H1} = R_{H2}$,

$R_{V1} - R_{V2} = 12 R_{H1}$
$= 12 R_{H2}$.



hence load paths are at gradient 1:6.

To find failure point, solve for downwind foundation load path and fit to failure surface (as given in databook): the two equations intersect at the failure point.

1 b) continued

Load path: $R_H = \frac{1}{6}(R_V - 1.5\, b l s_u)$

failure envelope: $\frac{R_H}{b l s_u} = 1 - \left(2 \frac{R_V}{(2+\pi) b l s_u} - 1\right)^2$ → curve fit to Green solution given in databook.

Denote: $r_h = R_H / b l s_u$; $r_v = R_V / b l s_u$

Combine equations:

$$r_h = \frac{1}{6}(r_v - 1.5) = 1 - \left(\frac{2}{2+\pi} r_v - 1\right)^2$$

$$\Rightarrow \quad -0.25 + 0.17 r_v - 1 + (0.39 r_v - 1)^2 = 0$$

$$\Rightarrow \quad 0.15 r_v^2 - 0.61 r_v - 0.25 = 0$$

Solving quadratic: $r_v = \frac{0.61 \pm \sqrt{0.61^2 + 4 \times 0.15 \times 0.25}}{0.3}$

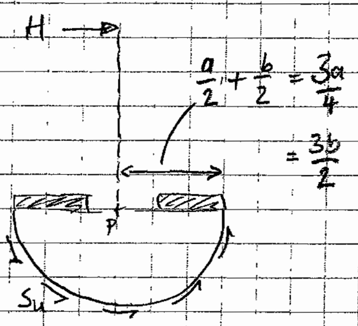
$$r_v = \frac{0.61 \pm 0.72}{0.3} = 4.44$$

$$\Rightarrow \quad r_h = \frac{1}{6}(4.44 - 1.5) = 0.49$$

$$\Rightarrow \quad R_{H1} = R_{H2} = 0.49\, b l s_u$$

Hence, horizontal load at failure, $H = R_{H1} + R_{H2} = 0.98\, b l s_u$

c) Structure and foundation fail as single rigid body, so equilibrium equation is equivalent to work equation over increment of collapse



$M) \Rightarrow \quad H \cdot \cancel{3a} = \pi \frac{3b}{2} \frac{\cancel{3a}}{4} l s_u$

$H = 1.18\, b l s_u$

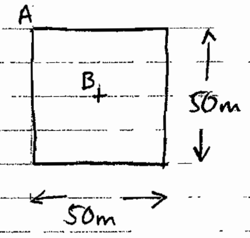
$H = 1.18\, b l s_u$

→ higher than part (b), shallow individual foundation failures.

d) If s_u is reduced at depth, shallower mechanisms through the stronger soil will become less favarable.
Hence (b) might become harder than (c),

(3)

2) a) Ignoring stiffness $\Rightarrow$ assume fully flexible.



Immediate settlement $\Rightarrow$ $\nu = 0.5$, $G = 20$ MPa.

Centre settlement (point B) –

superpose corner settlement of 4 25x25 regions.

$$w_B = 4\left[\frac{(1-\nu)}{G}\frac{qB}{2}I_{rect}\right] = 4\left[\frac{(1-0.5)}{20}\times\frac{250\times 25}{2}\times 0.561\right]$$

Elastic solution – databook

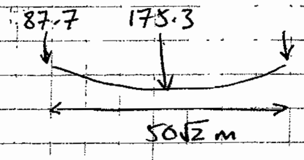
0.561 for L/B = 1

$$w_B = 175.3\,\text{mm}$$

Corner settlement (point A) –

$$w_A = \frac{1-\nu}{G}\frac{qB}{2}I_{rect} = \frac{0.5}{20}\times\frac{250\times 50}{2}\times 0.561$$

$$w_A = 87.7\,\text{mm}$$



Deflection ratio across diagonal of building:

$$\text{Defl}^n \text{ ratio} = \frac{175.3 - 87.7}{50\sqrt{2}\times 1000} = 0.00124 \sim 1/800$$

$\rightarrow$ acceptable for non-masonry structures

b) Rigid raft:

databook

~ 0.9 for $\frac{L}{B} = 1$

$$w_r = \frac{(1-\nu)}{G}\times\frac{q_{avg}\sqrt{BL}}{2}\times I_{rigid} = \frac{1-0.5}{20}\times\frac{250\times 50}{2}\times 0.9$$

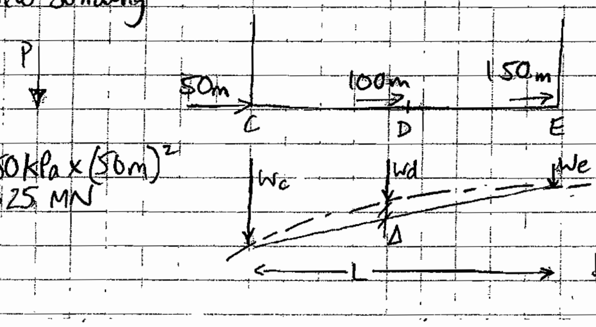
$$w_r = 140.7\,\text{mm}$$

Note: alternative is superposition of uniformly loaded rectangles, $w = \frac{1-\nu}{G}\frac{qB}{2}I_{rect}$ (databook)

This gives: $w_C = 51.6$, $w_D = 25.0$, $w_E = 16.7$ mm

c) – Model new building as point load
– Consider points at ends and middle of existing building to estimate distortion.

New building



$P = 250\,\text{kPa} \times (50\,\text{m})^2$
$= 625$ MN

@C: $w_C = \frac{1}{2\pi}\,\frac{1-0.5}{20}\,\frac{625}{50} = 49.7\,\text{mm}$

@D: $w_D = $ —"— $\frac{}{100} = 24.9\,\text{mm}$

@E: $w_E = $ —"— $\frac{}{150} = 16.6\,\text{mm}$

$$\text{Tilt} = (w_C - w_E)/L \simeq 1/3000.$$

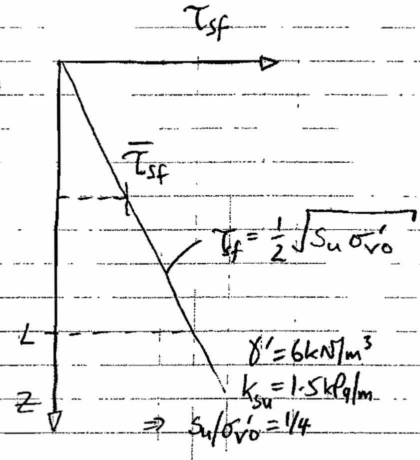
$$\text{Defl}^n \text{ ratio} = \frac{\Delta}{L} \simeq 1/12000.$$

e) – Stiffness of 1m overburden was ignored.
– Soil stiffness reduces with strain level – deformation will be more local than elastic predictions, and given value of G may be unrepresentative
– Stiffness of the building may restrain movement
– Building may be founded on piles, which restrain or isolate building from surface settlements

d) Building is deforming in hogging mode.
Tension cracks in upper storeys, especially at stress concentration points such as windows, are the likely first sign of distress

3) a) Vertical capacity from API method

$s_u < \sigma'_{vo} \Rightarrow \tau_{sf} = \frac{1}{2}\sqrt{s_u \sigma'_{vo}}$ (i.e. $\alpha = 1$)



Shaft resistance:

$$Q_{sf} = (\pi D L)\,\bar{\tau}_{sf} = (\pi D L)\,\bar{\tau}_{sf}\Big|_{z=\frac{L}{2}}$$

$$= (\pi D L)\,\frac{1}{2}\sqrt{1.5\frac{L}{2}\,6\frac{L}{2}} \quad (kN)$$

$$= \frac{3}{4}\pi D L^2$$

$$Q_{sf} = 3\pi L^2 \quad (kN)$$

Base resistance:

$$Q_{bf} = N_c s_u A_b = 9 \cdot 1.5 \frac{\pi D^2}{4} L$$

$$= \frac{27\pi D^2}{8} L = 54\pi L \quad (kN)$$

Pile weight (assumes, since the pile is plugged, a solid cylinder with the density of soil):

$$W_p = \pi \frac{D^2}{4} L \gamma' = 24\pi L$$

Design vertical load = 6000 kN

$$F = Q_{sf} + Q_{bf} - W_p$$

$$\Rightarrow 6000 = 3\pi L^2 + 54\pi L - 24\pi L$$

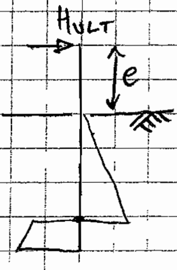
$$L = \frac{-30\pi \pm \sqrt{(30\pi)^2 + 4 \times 3\pi \times 6000}}{6\pi} = 20.7m$$

Say, $\underline{L = 21m}$

b) Use design charts for linearly-increasing soil resistance with depth

Resistance gradient, $n = 9 k_{su} = 9 \times 1.5 = 13.5$ kPa/m

Only short pile mechanism need be considered



$$H_{ULT}/nD^3 = \frac{1000}{13.5 \times 4^3} = 1.16$$

$$e/D = 10/4 = 2.5$$

$\Rightarrow$ from design chart: $L/D = 4-5$

$\Rightarrow \underline{L \simeq 16-20m}$ ✓ OK, compared to part a).

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3) c) Equivalent pile has same cross-sectional area

$$\Rightarrow \quad \frac{\pi D_{eq}^2}{4} = \pi D t \qquad \text{(assuming } t \ll D\text{)}$$

$$D_{eq} = 2\sqrt{Dt} = 2\sqrt{4 \times 0.05}$$

$$D_{eq} = 0.89\,m$$

After 90% consolidation:

$$T_{eq} = \frac{c_h t}{D_{eq}^2} \approx 10$$

$$\Rightarrow \quad t = \frac{10 D_{eq}^2}{c_h} = \frac{10 \times 0.89^2}{15} = 0.533 \text{ years}$$

$$= 195 \text{ days}$$

d) Result a) unchanged

Result b) unchanged since pile does not fail structurally

– Note, capacity of long pile failure mechanisms would change

Result c) would change: larger equivalent diameter, more dissipation required, longer set-up period.

4) a) Assume that anchor length $L << z_{final}$, so anchor can be modelled as a single point, acted on by submerged weight, shaft resistance and end bearing.

S_u at depth $z = k_{su} z$

$= z$ (kPa)

Equation of motion:

Assume resistance acts on front and rear of anchor, although it is also reasonable to assume gap remains open (water-filled) at rear, but this gives high (unconservative) estimate of embedment and therefore pullout capacity.

$$F = ma$$

$$m\ddot{z} = \underbrace{W'}_{\text{Submerged weight}} - \underbrace{2N_c k_{su} z A_{end}}_{\text{End resistance}} - \underbrace{\alpha k_{su} z A_{shaft}}_{\text{Shaft resistance}}$$

Submerged weight = Dry weight − Buoyancy force

$$W' = mg - \gamma'_w \left(\pi \frac{D^2}{4} L\right)$$

Approximate anchor volume.

$$W' = 30000 \times 9.81 - 9.81 \times \pi \frac{0.75^2}{4} 10 \times 1000$$

$$W' = 251 \text{ kN}$$

(compared to a dry weight of $30000 \times 9.81 = 294$ kN.)

b) Equation of motion shown above:

$$\ddot{z} = \underbrace{\frac{W'}{m}}_{f_1} - \underbrace{\left(\frac{2N_c k_{su} A_{end} + \alpha k_{su} A_{shaft}}{m}\right)}_{f_2} z$$

Substitute

$$\ddot{z} = \dot{z}\left(\frac{d\dot{z}}{dz}\right) \qquad \left[a = \frac{d^2 z}{dt^2} = \frac{dv}{dt} = \frac{dz}{dt}\frac{dv}{dz} = v\frac{dv}{dz}\right.$$

Separating variables: $\dot{z}\, d\dot{z} = (f_1 - f_2 z)\, dz$

$$\Rightarrow \dot{z}^2 = 2f_1 z - f_2 z^2 + \text{const}$$

When $z = 0$, $\dot{z} = V_{impact}$ $\Rightarrow$ $\dot{z}^2 = 2f_1 z - f_2 z^2 + V_{impact}^2$

At final embedment, $\dot{z} = 0$ $\Rightarrow$ $f_2 z_{final}^2 - 2f_1 z_{final} - V_{impact}^2 = 0$

$\rightarrow$ quadratic in z_{final}.

(8)

4)b, continued:

$$z_{final} = \frac{2f_1 \pm \sqrt{4f_1^2 + 4f_2 V_{impact}^2}}{2f_2}$$

$$z_{final} = \frac{2\frac{W'}{m} \pm \sqrt{4\frac{W'^2}{m^2} + 4\frac{(2N_c k_{su} A_{end} + \alpha k_{su} A_{shaft})}{m} V_{impact}^2}}{2\frac{(2N_c k_{su} A_{end} + \alpha k_{su} A_{shaft})}{m}}$$

$$z_{final} = \frac{W' \pm \sqrt{W'^2 + m V_{impact}^2 k_{su}(2N_c A_{end} + \alpha A_{shaft})}}{k_{su}(2N_c A_{end} + \alpha A_{shaft})}$$

$$z_{final} = \frac{245 \pm \sqrt{245^2 + 30000 \times 40^2 \times 0.8(2\times 9 \times 0.44 + 0.3 \times 23.6)/1000}}{0.8(2 \times 9 \times 0.44 + 0.3 \times 23.6)}$$

(bracket = 15

$$A_{end} = \pi \frac{0.75^2}{4} = 0.44\,m^2$$

$$z_{final} = \frac{1042}{12} = \underline{87m}$$

$$A_{shaft} = \pi D L = 23.6\,m^2$$

c) To calculate pullout capacity, assume strength at depth z_{final} acts along entire shaft. Ignore reverse end bearing – suction may dissipate under sustained load.

$$F_{pullout} = \underbrace{N_c A_{end}\, k_{su} z_{final}}_{\text{end bearing on top of anchor}} + \underbrace{\alpha A_{shaft}\, k_{su} z_{final}}_{\text{shaft resistance}} + \underbrace{W'}_{\text{submerged weight}}$$

$$F_{pullout} = 9 \times 0.44 \times 0.8 \times 87 + 0.3 \times 23.6 \times 0.8 \times 87$$

$$= 275 + 493 + 251$$

$$= 1019\,kN$$

$$\Rightarrow \text{Efficiency} = \frac{F_{pullout}}{mg} = \frac{1019000}{30000 \times 9.81} = \underline{\underline{3.46}}$$

DJW.
May 2006.