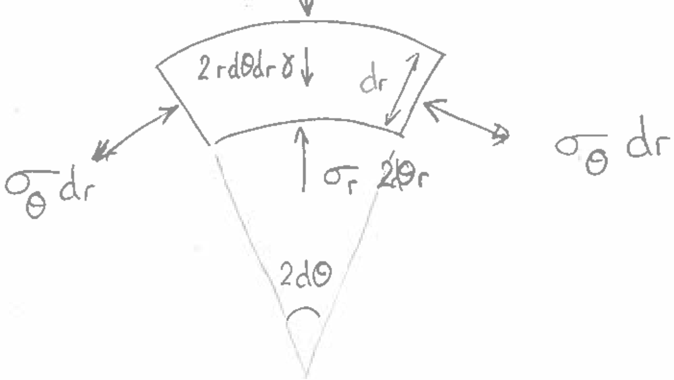
$$2d\theta\left[\sigma_r + dr\left(\frac{d\sigma_r}{dr}\right)\right](r+dr)$$



$$\uparrow \quad 2\sigma_\theta\, dr \overset{d\theta}{\{\cancel{\sin d\theta}\}} + 2r\sigma_r\, d\theta$$

$$=$$

$$2d\theta\,(r+dr)(\sigma_r + d\sigma_r)$$

$$=$$

$$2d\theta\left[r\sigma_r + r\,d\sigma_r + \sigma_r\,dr + \overset{0}{\cancel{dr\,d\sigma_r}}\right] + 2r\,d\theta\,dr\,\gamma$$

$$\sigma_\theta\,dr + \cancel{r\sigma_r} = \cancel{r\sigma_r} + r\,d\sigma_r + \sigma_r\,dr + r\,dr\,\gamma$$

$$r\frac{d\sigma_r}{dr} + (\sigma_r - \sigma_\theta) + \gamma r = 0$$

Plastic zone :

$$(\sigma_r - \sigma_\theta) = -2c_u$$

Elastic zone:

$$(\sigma_r - \sigma_\theta) = G\gamma_s$$

but at limit failure all plastic

$$\cancel{\gamma = \frac{\delta A}{\pi r^2}}$$

$$r\frac{d\sigma_r}{dr} - 2c_u + \gamma r = 0$$

$$\int_{\sigma_c}^{0} d\sigma_r = \int_{r}^{z} \frac{(2c_u - \gamma r)\,dr}{r}$$

$$-\sigma_c = \Big[2c_u \ln(r) - \gamma r\Big]_r^z$$

$$\sigma_c = -\left[2c_u \ln\left(\frac{z}{r}\right) - \gamma(z-r)\right]$$

$$= \gamma(z-r) - 2c_u \ln\left(\frac{z}{r}\right)$$

Frictional $\qquad \sigma_\theta = K_p \sigma_r$

$$r \frac{d\sigma_r}{dr} + \sigma_r (1 - K_p) + \gamma r = 0$$

$$d\sigma_r = \left((K_p - 1) \frac{\sigma_r}{r} - \gamma \right) dr$$

Let $\alpha = \frac{\sigma_r}{r} \Rightarrow r\,d\alpha + \alpha\,dr = d\sigma_r$

$$r\,d\alpha + \alpha\,dr = \left((K_p - 1)\alpha - \gamma \right) dr$$

$$r\,d\alpha = \left((K_p - 2)\alpha - \gamma \right) dr$$

$$\int_{\frac{\sigma_c}{r}}^{0} \frac{d\alpha}{(K_p - 2)\alpha - \gamma} = \int_{r}^{z} \frac{dr}{r}$$

$$\left[\frac{\ln\left[(K_p - 2)\alpha - \gamma \right]}{(K_p - 2)} \right]_{\frac{\sigma_c}{r}}^{0} = \ln\left(\frac{z}{r} \right)$$

$$= \frac{1}{(K_p - 2)} \left[\ln \left(\frac{(-\gamma)}{(K_p - 2)\frac{\sigma_c}{r} - \gamma} \right) \right] = \frac{1}{(K_p - 2)} \ln \left(\frac{\gamma}{\gamma - (K_p - 2)\frac{\sigma_r}{r}} \right)$$

$$\ln \left(\frac{\gamma}{\gamma - (K_p - 2)\frac{\sigma_r}{r}} \right) = (K_p - 2) \ln \left(\frac{z}{r} \right)$$

$$\gamma = \left(\gamma - (K_p - 2)\frac{\sigma_r}{r} \right) \left(\frac{z}{r} \right)^{K_p - 2}$$

$$\sigma_r = \frac{r\gamma\left[1-\left(\frac{z}{r}\right)^{2-K_p}\right]}{(K_p-2)}$$

$$\frac{\partial}{\partial x} \sin(2x) = \frac{\partial}{\partial(2x)} \sin(2x) \; \frac{\partial(2x)}{\partial x}$$

$$= 2 \cancel{\sin} \cos(2x).$$

$$\frac{\partial}{\partial x} \ln(ax - b) = \frac{\partial}{\partial(ax-b)} \ln(ax-b) \quad a$$

$n = 9 \times 1.5 = 13.5$ kPa/m

Short pile:

$$\frac{L}{D} = \frac{20.5}{5} \sim 4$$

$$\frac{e}{D} = \frac{20}{5} = 4$$

$$\frac{H_{ult}}{nD^3} = 0.9 \qquad H_{ult} = 0.9 \times 13.5 \times 5^3$$

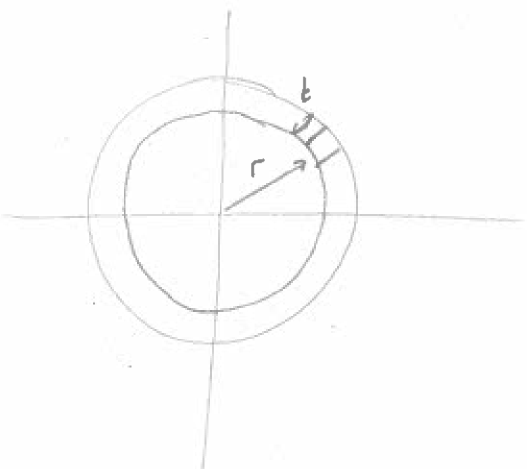
$$= \underline{\underline{1519 \text{ kN}}}$$

fail

$\frac{H_{ult}}{nD^3}$ needs to be $\frac{2000}{13.5 \times 125} = 1.2$

$$\frac{L}{D} \approx 4.3$$

$$L \sim \underline{\underline{21.5\,m}}$$



$$M_p = 4\int_0^{\frac{\pi}{2}} r\sin\theta \; rt\,d\theta \;\; \sigma_y$$

$$= 4r^2 t\sigma_y \left[-\cos\theta\right]_0^{\frac{\pi}{2}}$$

$$= 4r^2 t\sigma_y$$

$$= 4 \times 2.5^2 \times 0.05 \times 400$$

$$= 500 \text{ MNm}$$

Long failure $\frac{M_p}{nD^4} = \frac{500000}{13.5 \times 5^4} = 60$

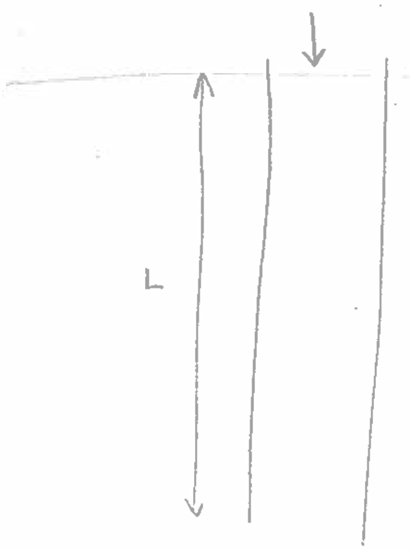
$\frac{H_u}{nD^3} \sim 8.5 \qquad H_u = 8.5 \times 13.5 \times 125 = 14$ MN

OK

$C_u = 1.5z \qquad \gamma' = 6\ \text{kN/m}^3$

$$\frac{\tau}{S_u} = 0.5 \max\left\{\left(\frac{\sigma'_{vo}}{S_u}\right)^{0.5}, \left(\frac{\sigma'_{vo}}{S_u}\right)^{0.25}\right\}$$

$$\frac{\sigma'_{vo}}{C_u} = 4, \quad \text{so } \left(\frac{\sigma'_{vo}}{S_u}\right)^{1/2} = 2 \text{ is bigger}$$



Plugged:

$$F = \pi D L \times 1.5\frac{L}{2} + \frac{\pi D^2}{4} \times 9 \times 1.5L - \frac{\gamma' \pi D^2 L}{4}$$

$$= \frac{\pi D L}{4}\left(\frac{3L}{\cancel{4}} + 13.5D - 6D\right)$$

$$= \frac{\pi D L}{4}(3L + 7.5D)$$

$$8000 = \frac{\pi \times 5}{4}(3L^2 + 37.5L)$$

$L = 20.5\text{m}$

Unplugged

$$F = \cancel{2}\pi D L \times 1.5\frac{L}{\cancel{2}}$$

$$= 1.5\pi D L^2$$

$$= 9950\ \text{kN}$$

Plugged governs

d) $T_{eq} = C_h t / D_{eq}^2$

$$\frac{\cancel{\pi} D_{eq}^2}{4} = \cancel{\pi} D t$$

$$D_{eq}^2 = 4Dt = 4 \times 5 \times \frac{1}{20} = 1\,m^2$$

$$10 = \frac{15}{1} \times t \qquad \underline{\underline{t = 2/3 \text{ year}}}$$

3. a) Design of shallow foundations is based on closed form plasticity solutions which have exact (or almost exact) answers, whereas pile foundation design is based on more empirical data.

Shallow foundations use soil close to the surface whose properties can be easily investigated whereas piles average over a large depth.

Piles tend to be used as repeated units within a design and so testing one has benefits for the design of others. Shallow foundations tend to be unique..

b) Maintained Load test. Add load to a pile and hold until movement ceases and then increase. Gold standard test for capacity and stiffness but slow and expensive requiring dead weight as reaction

Constant rate of penetration test: Rate effects affect data but quicker and hence cheaper than MLT.

Dynamic testing. Instrumented hammer applies a blow to the top of the pile and reflected stress waves are measured. These can be correlated against soil and pile properties. Cheap and non-destructive but only gives a second-hand measure of strength.

Statnamic test. An explosion is used to throw a counterweight upwards giving a downward load on the pile. Load and displacement are measured. Very high strain rate can affect data but much quicker than MLT.

c) As the pile tip approaches soil vertical stresses increase massively and horizontal stresses increase in sympathy. The soil element moves out round the pile toe, relaxing vertical stresses but at high horizontal stress. Cyclic Driving of the pile then leads to compaction of soil around the pile shaft in the process of friction fatigue which reduces horizontal stresses, hence reducing the shear stress on the pile surface.

d) Increasing stresses during pile driving lead to changes in water pressures due to both shear and compression. For a stiff OC clay, shear leads to dilation (-ve pp) and compression leads to positive pp, so the effects somewhat cancel. For soft clays both compression and shear give +ve pore pressures. Because installation is undrained friction fatigue is less important that for sands. Post-installation the pore pressures dissipate tending to lead to a reduction in pp and an increase in effective stress, hence giving set-up (increase in pile capacity). This process is complex as during consolidation both total stress and pore pressures change.

The API unit shaft resistance change reflects the difference in behaviour between NC and OC clays in terms of the pore pressure generation due to shear.

4. a) For a tunnel to be constructed with an open face the face must be stable without support. Stability is enhanced by strong soils (i.e. cu) and low depths of tunnelling. Stability will be reduced if the tunnel progresses a substantial distance in from t of the lining, as shown by the graph in the databook.

b) From databook p.20, if C/D=3 and Nc=C*gamma/su=6, P/D=2.

Tunnel can progress 10m in front of lining.

c) Forepoling involves inserting rods into the ground ahead of the tunnel above the top of the tunnel construction. This temporary roof increases the distance that the tunel can progress in front of the lining.

d) An EPB tunnelling machine is used when the ground is unstable for open face tunnelling. It consists of a bulkhead ahead of which is a cutter wheel surrounded by spoil which supports the tunnel face. As the TBM advances, the spoil is removed at an appropriate rate to maintain stability of the face and minimise ground movements using a screw conveyer. Behind the TBM, tunnel lining is assembled from segments with hydraulic jacks reacting against the lining to advance the TBM.

e) Settlements due to tunnelling typically have a Gaussian shape with the maximum settlement above the tunnel dissipating with width as given on p.21 of the databook. This leads to sagging of structures above the tunnel and hogging to the sides. Typically the bases of buildings are held together by strong foundation slabs whereas masonry walls are very badly affected by tension. Hogging thus tends to be more damaging than sagging behaviour.

Rotation and settlement of buildings can be an issue, but typically bending is more damaging. Stiff buildings will bridge the soil's deformed shape and have low bending and hence damage, whereas flexible buildings will follow the ground and crack.