SHALLOW FOUNDATIONS
SETTLEMENT

References:

1. Rajapakse, Ruwan. Geotechnical Engineering Calculations and Rules of Thumb.
2. Schroeder, W.L., Dickenson, S.E, Warrington, Don, C. Soils in Construction. Fifth Edition. Upper Saddle River, New Jersey; Prentice Hall, 2004.

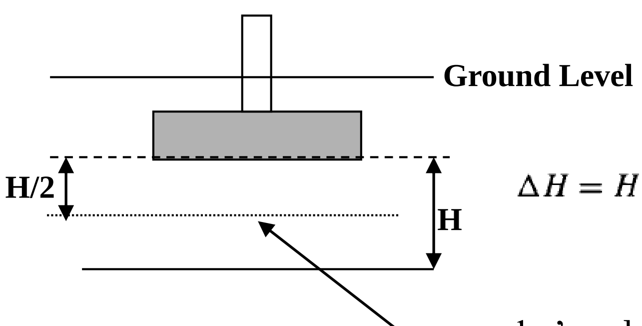
Learning objectives:

1. Design calculations for settlement depths in clays soils for normally consolidated, recompressed and in recompressed and virgin clays.
2. Calculations for the amount of time for settlement to occur in clay soils

This section is a continuation of the consolidation section in soil mechanics analysis. This section will give you formulas and quantitative example problems that you might see on the exam.

Learning objective #1: **Design calculations for settlement:**

- The first example we will look at is the settlement due to primary consolidation in normally consolidated clay. This is clay that has never been subject to a higher stress than what is being experience in situ.

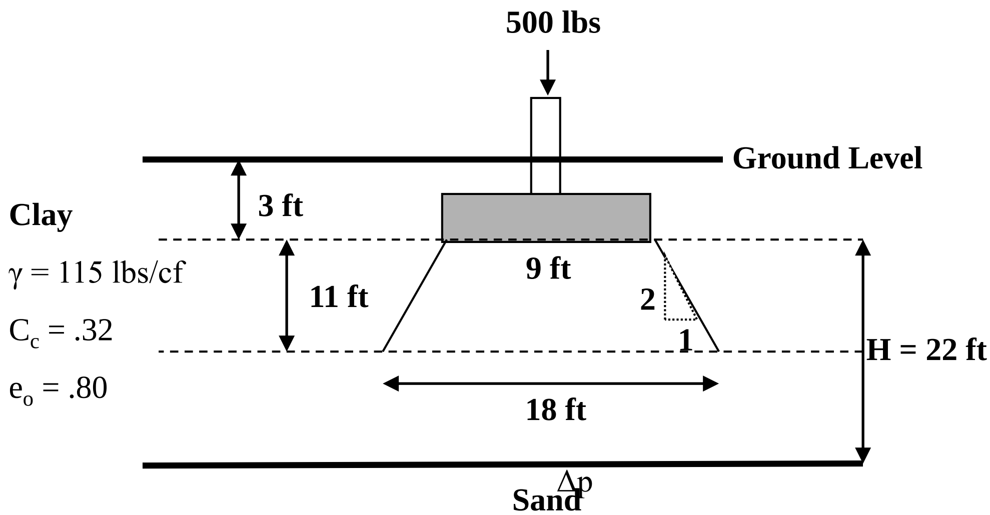


$$\Delta H = H \times C_c/(1+e_0) \times \log\left(\frac{(p'_0+\Delta p)}{p'_0}\right)$$

e_o and p'_o values are at H/2

Where:
ΔH = total primary consolidation settlement
H = thickness of the clay layer
C_c = Compression index of the clay layer
e_o = void ratio at H/2 prior to loading
p'_o = effective stress at H/2 prior to loading
Δp = increase of stress at H/2 due to loading

Example #1: Find the settlement due to consolidation of a 9 ft x 9 ft column foundation with a load of 500 lbs. The foundation is placed 3 ft below the top surface, and the clay layer is 25ft thick. There is a sand layer underneath the clay layer. The density of the clay layer is 115 lbs/cf, the compression index of the clay layer is .32, and the initial void ratio of the clay is .80. Assume that the pressure is distributed at a 2:1 ratio and the clay is normally consolidated.



Step 1: Write down the consolidation settlement equation:

$$\Delta H = H \times C_c/(1+e_0) \times \log\left(\frac{(p'_0 + \Delta p)}{p'_0}\right)$$

Step 2: Find the effective vertical stress at the midpoint:

p'_o = density of the clay x distance of the soil at the midpoint
$p'_o = \gamma$ x h = 115 lbs/cf x 14 ft = 1610 lbs/sf

Step 3: Find the increased effective vertical stress due to the footing at the midpoint:

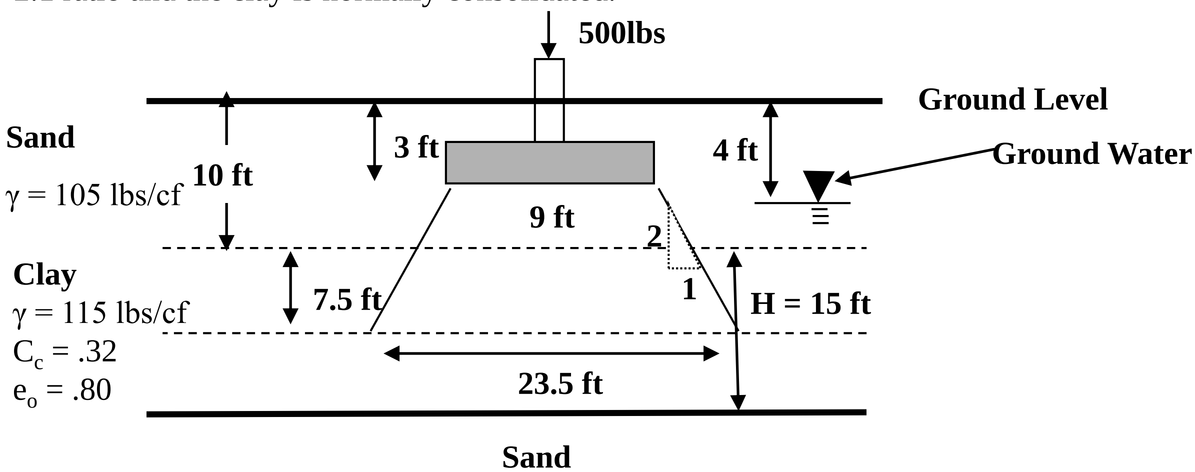
- It is key to recognize that 500lbs is distributed at a larger area at the midpoint of the clay layer. So the 500lbs is distributed by a (5.5ft + 9ft + 5.5) square area which is;
- Area distributed load = 20 ft x 20 ft = 400 sf
- Δp = 500 lbs/400 sf = 1.25 lbs/sf

Step 4: Solve the equation:

ΔH = 22 ft x .32/(1+.8) log (1610 lbs/sf + 1.25lbs/sf)/ 1610lbs/sf

ΔH = 22 ft x .1778 * .000337 = .0013 ft = **.016 in** → as you can see if the weight isn't that much there won't be a lot of settlement.

Example #2: Lets consider the same example as before but the only change is groundwater is present 4 ft below ground level, and a 10 ft sand layer is on top of the clay 15 ft layer. Find the settlement due to consolidation of a 9 ft x 9 ft column foundation with a load of 500 lbs. The foundation is placed 3 ft below the top surface, and the clay layer is 25ft thick. There is a sand layer underneath the clay layer. The density of the clay layer is 115 lbs/cf, the compression index of the clay layer is .32, and the initial void ratio of the clay is .80. Assume that the pressure is distributed at a 2:1 ratio and the clay is normally consolidated.



Step 1: Write down the consolidation settlement equation:

$$\Delta H = H \times C_c/(1+e_0) \times \log\left(\frac{(p'_0 + \Delta p)}{p'_0}\right)$$

Step 2: Find the effective vertical stress at the midpoint:

p'_o = density of the clay x distance of the soil at the midpoint

$p'_o = (\gamma_{sand} \text{ x } 4\text{ft}) + (\gamma_{sand} - \gamma_{water}) \text{ x } 6\text{ft} + (\gamma_{clay} - \gamma_{water}) \text{ x } 7.5\text{ft}$

= (105 lbs/cf x 4ft) + 6ft (105lbs/cf – 62.4 lbs/cf)+ 7.5 ft (115 – 62.4)

= 420 lbs/sf + 255.6 lbs/sf + 394.5 lbs/sf = 1070 lbs/sf

Step 3: Find the increased effective vertical stress due to the footing at the midpoint:

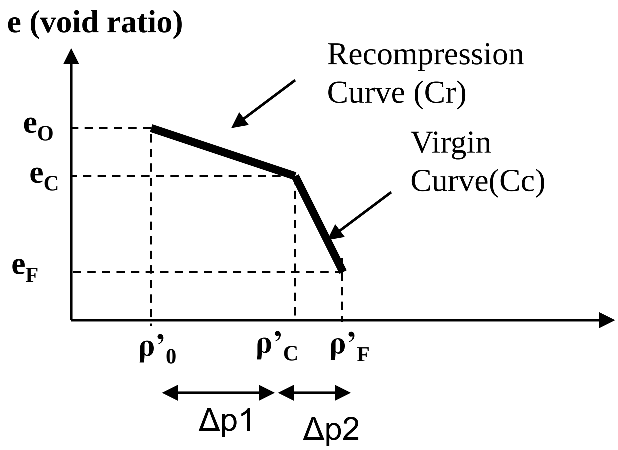
- It is key to recognize that 500lbs is distributed at a larger area at the midpoint of the clay layer. So the 500lbs is distributed by a (7.25ft + 9ft + 7.25) square area which is;
- Area distributed load = 23.5ft x 23.5 ft = 552.25 sf
- Δp = 500 lbs/552.25sf = .91 lbs/sf

Step 4: Solve the equation:

ΔH = 15 ft x .32/(1+.8) log (1070 lbs/sf + .91lbs/sf)/ 1070 lbs/sf

ΔH = 15 ft x .1778 * .00037 = .0009 ft = **.001 in** → Even though the effective stress was less due to the water, the load was distributed out more which accounts for less settlement.

- Now lets look at the settlement that occurs in over consolidated clay. The concept is the same however, you just need to remember that the void ratio changes at different stress rates depending if you are in the recompression portion or Virgin portion of the soil. Review below.



- Below is the equation to use when calculating the settlement in over consolidated clays.

$$\Delta H = \underbrace{H \times Cr/(1+e_o) \times \log((p'_o + \Delta p1)/p'_o)}_{\text{Settlement in the Recompression Curve}} + \underbrace{H \times Cc/(1+e_o) \times \log((p'_C + \Delta p2)/p'_C)}_{\text{Settlement in the Virgin Curve}}$$

Where:
ΔH = total primary consolidation settlement
H = thickness of the clay layer
Cr = Recompression index of the clay layer
C_c = Compression(virgin) index of the clay layer
e_o = void ratio at H/2 prior to loading
p'_o = effective stress at H/2 prior to loading
p'_C = overconsolidation or preconsolidated pressure
$\Delta p1 = p'_C - p'_o$
$\Delta p2 = p'_F - p'_C$
p'_F = pressure after the footing is placed $p'_o + \Delta p$

Clay Foundations: Secondary Compression (Consolidation) Settlement

Secondary consolidation occurs because particles within the clay layer are rearranged due to the applied load. Theoretically, secondary consolidation occurs after all of the excess pore water pressure due to the applied load has dissipated. In reality secondary compression occurs along with primary consolidation.

$S_s = [C_\alpha H / (1 + e_p)] \log (t / t_p)$

Where S_s = secondary consolidation settlement
C_α = coefficient of secondary consolidation
H = initial layer thickness before any consolidation occurs (use full layer regardless of single or double drainage)
e_p = void ratio at end of primary consolidation
t = time after start of primary consolidation that amount of secondary consolidation is wanted
t_p = time to end of primary consolidation = $(H_{dr})^2/c_v$

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Settlement in foundations built on sand

Settlement calculations of foundations built on sand are generally solved based on empirical methods and field tests. This is because it is practically impossible to obtain and transport undisturbed samples of sand to the lab and conduct meaningful tests.

<u>Empirical Methods</u>

- Based on penetration resistance (SPT N or CPT q_c)
- Net allowable pressure to limit settlement to 1 inch (typically)
- $q_{net(all)} = q_{(all)} - \gamma' D_f$
  - γ' = the effective unit weight of the soil above the bottom of the footing
  - D_f = depth from the top of the soil to the bottom of the footing
- Relations vary: examples

$q_{net(all)}$ (ksf) = $(N_1 / 2.5)\, F_d\, S_e$ (B < 4ft)

$q_{net(all)}$ (ksf) = $(N_1 / 4)\, [(B + 1) / B]^2\, F_d\, S_e$ (B > 4ft)

N_1 = the corrected SPT blow count at the depth of the bottom of the footing (correction adjusts for overburden effects)
S_e = tolerable settlement in inches
F_d = depth factor = $1 + 0.33\,(D_f/B)$
B = the width of the footing (width is the smallest dimension of the contact area)

<u>Plate Load Tests</u>

Plate load tests are conducted by pressing a metal plate into the soil with the same contact pressure that is anticipated in the final footing. The test plates are generally much smaller than the final size of the footings. Plates that are too small may provide inaccurate data. The results of the load tests are "scaled up" by the following formula:

$$S_F = S_P\, [\, 2B_F / (B_F + B_P)]^2$$

Learning Objective #2: Calculations for the amount of time for settlement to occur in clay soils

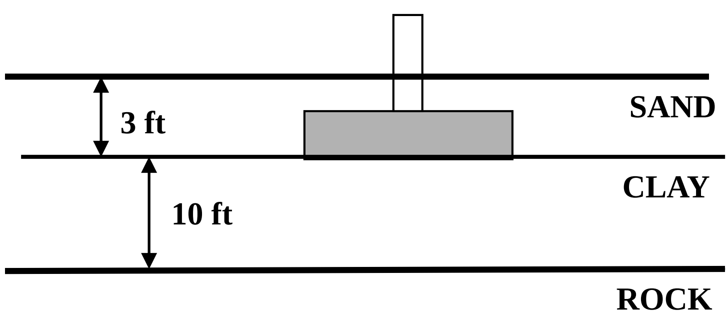
In this section we are going to find out how to calculate the time required for primary consolidation within the clay soil. The equation for this calculation is below.

$$t = \frac{H^2 \times T_V}{c_V}$$

Where:
t = time taken for the consolidation process
H = thickness of the drainage layer (drainage layer discussed below)
T_V = time coefficient (chart should be given)
c_V = consolidation coefficient (this should be given)

The thickness of the drainage layer is the longest distance the water molecule has to travel in order to drain out of the clay layer into a highly permeable soil. For example water CANNOT drain freely into a rock surface, but CAN drain freely into sand.

Example #4: Review the below example, What is the thickness of the drainage layer?

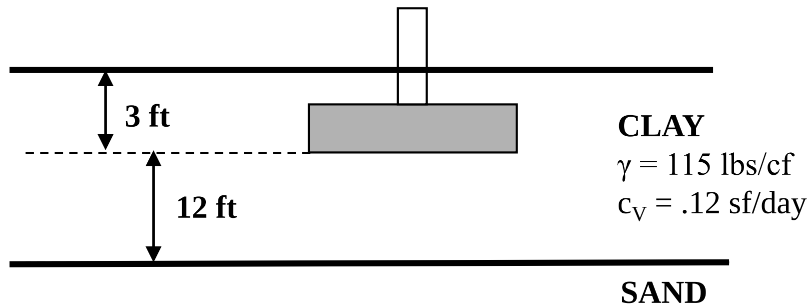


Solution: Since the water can't drain into rock the longest path is into the sand on the top, so the water molecule at the bottom of the clay layer will have to travel the 10 ft to the sandy soil. **H = 10 ft.**

* Important note: If the ROCK layer was SAND instead the water molecule could drain from both the top and bottom. Which would make the thickness of the drainage layer **(H) = 5 ft.**

Example #5: Find the approximate time taken for 90% consolidation using the chart and diagram
below.

Percent Consolidation (U%)	T_v
0	0
10	0.05
20	0.092
30	0.12
40	0.23
50	0.3
60	0.39
70	0.5
80	0.67
90	0.97



Step 1: Write the formula:
$t = (H^2 \times T_v)/ c_v$

Step 2: Find the variables:
H = since the water can go up or down to hit a drainage path, H = 12ft /2 = 6 ft
T_v = Using the chart for 90% consolidation the time coefficient = .97
c_v = is given as .12 sf/day

Step 3: Solve equation:
$t = (H^2 \times T_v)/ c_v = (6^2 \times .97)/ .12$ sf/day = **291 days**