Settlement Analysis

STABILITY
DURING CONSTRUCTION

STAGED CONSTRUCTION:
TYPICALLY IN TWO TO THREE STAGES AND COMPLETED IN ONE OR TWO CONSTRUCTION SEASONS (REMEMBER THAT WE CANNOT INSTALL WICK DRAINS IF THE GROUND IS FROZEN AND WE USUALLY DO NOT PLACE FILL DURING THE WINTER)
STABILITY
DURING CONSTRUCTION

STAGED CONSTRUCTION:

TYPICAL STAGES IN CENTRAL AND NORTHERN ONTARIO:

• STAGE 1: 0 TO 8m, WAIT FOR 3 MONTHS
• STAGE 2: 8 TO 12m, WAIT FOR 3 MONTHS
• STAGE 3: 12 TO 14m, WAIT FOR 3 MONTHS BEFORE REMOVING SURCHARGE

Loaded Soil will Compress Due to:

1. Deformation of soil grains (elastic)
   Degree water saturation <1
2. Compression of air and water in voids
3. Squeezing out of water and air out of voids
4. Plastic flow (creep)
   Degree water saturation =1
5. Compression of water (very small)
6. Squeezing out of water out of voids
7. Plastic flow (creep)
For Load Problems Need to Answer

- How much settlement will occur due to an applied load?
  - Magnitude of consolidations
- How long will it take for settlement to occur?
  - Time rate of consolidation

EMBANKMENT SETTLEMENT

IMMEDIATE ("ELASTIC")

PRIMARY CONSOLIDATION (ASSOCIATED WITH DISSIPATION OF EXCESS PORE PRESSURES)

SECONDARY CONSOLIDATION (ASSOCIATED WITH REARRANGEMENT OF PARTICLES)

CREASEP (ASSOCIATED WITH SHEAR STRESS-STRAIN)
EMBANKMENT SETTLEMENT

IT IS IMPORTANT TO RECOGNIZE THE IMPACT OF DIFFERENT TYPES OF SETTLEMENTS ON THE PROJECT:

SETTLEMENTS THAT OCCUR DURING CONSTRUCTION (PRIOR TO DRIVING PILES AT THE BRIDGE ABUTMENTS AND PRIOR TO CONSTRUCTION OF THE BRIDGE)

POST CONSTRUCTION SETTLEMENTS (HAVE SERIOUS COST IMPLICATIONS: BRIDGE AND PAVEMENT PERFORMANCE)

EMBANKMENT SETTLEMENT

WE USUALLY DESIGN THE EMBANKMENT SO THAT:

IMMEDIATE SETTLEMENTS AND SETTLEMENTS DUE TO PRIMARY CONSOLIDATION OCCUR DURING CONSTRUCTION

AND SETTLEMENTS DUE TO SECONDARY CONSOLIDATION AND CREEP OCCUR AFTER THE END OF CONSTRUCTION
EMBANKMENT SETTLEMENT
IMMEDIATE SETTLEMENTS

USUALLY NOT A KEY ISSUE:

USE CLOSED FORM SOLUTIONS BASED ON THE THEORY OF ELASTICITY WITH CONSERVATIVE UNDRAINED SOILS PROPERTIES

ALTERNATIVELY, CARRY OUT NUMERICAL SIMULATION USING TOTAL STRESS ANALYSIS WITH UNDRAINED SOIL PROPERTIES

EMBANKMENT SETTLEMENT
PRIMARY CONSOLIDATION

TERZAGHI’S 1D THEORY OF CONSOLIDATION

KEY ASSUMPTIONS:
• CONSTANT VERTICAL TOTAL STRESS AND ELASTIC PROPERTIES DURING CONSOLIDATION
• VERTICAL DRAINAGE ONLY
• NO LATERAL STRAINING OF THE SOIL (OEDOMETER TESTING)
EMBANKMENT SETTLEMENT
PRIMARY CONSOLIDATION

THE THEORY IS COMMONLY USED BECAUSE:
• IT IS SIMPLE (IT CAN EASILY BE INCORPORATED IN A FINITE DIFFERENCE FORMULATION)
• IT PROVIDES REASONABLE PREDICTION OF SETTLEMENT OF WIDE EMBANKMENTS FOUNDED ON RELATIVELY THIN CLAY LAYER

Spring Analogy to Soil Consolidation
Soil Vertical Stress

\[ q = \frac{P}{A} \]

\[ \Delta \sigma'_v \]

Spring Analogy to Soil Consolidation

Immediate settlement

Valve (size is analogous to permeability)

\[ \Delta \sigma_v + \text{overburden load} \]

Note: porewater pressure increased by \( \Delta u = u_e \)

(b) Under load, \( \Delta \sigma \).

Note increased pore water pressure and water flow.
Spring Analogy

$S_{\text{max}}$ occurs when $\Delta u = 0$

Change in volume in container = volume of water removed if $S_{rw}=1$

(c) At equilibrium under $\sigma_s + \Delta \sigma$. Note settlement $s$.

Fig. 8.2 Spring analogy as applied to consolidation.

Oedometer Test

$\Delta \sigma = \frac{P}{A}$

$t=0, u_e=0\%$, $t=\infty$

$h_w = \frac{\Delta \sigma}{\gamma_w}$

$t=1, u_e=100\%$

$t=2, u_e=50\%$

Record for each stress increment ($\Delta \sigma$):
Change in height of specimen with time

Figure 7.2 Consolidometer
Typical Stress Increment Test Data

Casagrande Log Time Method

\[ U = \text{degree of pore water pressure dissipated} \]

- \( u_e = 50\%, U = 50\% \)
- \( u_e = 100\%, U = 0\% \)
- \( u_e = 0\%, U = 100\% \)

Fig. 9.6: Deformation-time curves for data from Table 9.3: (a) linear scale; (b) log time scale; (c) square root of time scale.

Fig. 9.7: Determination of \( t_0 \) by the Casagrande method; data from Table 9.2.
Casagrande Log Time Method

Fig. 9.8 Terzaghi consolidation theory and a typical experimental curve used to define $t_p$.

Root Time Method

Fig. 9.9 Determination of $c_u$ using Taylor's square root of time method; data from Table 9.2.
Settlement Calculations

Consolidation Settlement Calculations

\[ \varepsilon_v = \frac{\Delta H}{H_0} = \frac{s}{H_0} = \frac{\Delta e}{1+e_0} \]

\[ s = \varepsilon_v H_0 = (\Delta e/1+e_0) H_0 \]

Note: Want settlement @ \( U=100\% \)

100% dissipation of excess porewater pressure
**U\textsubscript{100} Data for Stress Increments**

**Coefficient of Volume Change (m\textsubscript{v})**

\[
m\textsubscript{v} = \frac{\Delta e}{\Delta \sigma'}
\]

**Coefficient of Compressibility (a\textsubscript{v})**

\[
a\textsubscript{v} = -\frac{\Delta e}{\Delta \sigma'}
\]

**Compression Index (C\textsubscript{c})**

\[
c\textsubscript{c} = \frac{\Delta e}{\log \sigma_2' - \log \sigma_1'}
\]

If \(\sigma_2' = \sigma_1' + \Delta \sigma\)

\[
c\textsubscript{c} = \frac{\Delta e}{\log \left(\frac{(\sigma_1' + \Delta \sigma)}{\sigma_1'}\right)}
\]

\(e_1 = 2.4, \ e_2 = 1.4, \ \Delta e = 1.0\)

\(\sigma_1' = 7.1, \ \sigma_2' = 49\)

\[c\textsubscript{c} = \frac{1.0}{\log 49 - \log 7.1} = 1.19\]
Settlement Equation in Terms of $m_v$

\[ S = \varepsilon_v H_o \]

\[ m_v = \frac{\Delta \varepsilon_v}{\Delta \sigma'} \quad (1/\text{kPa} = \text{m}^2/\text{kN}) \]

\[ S = \int_0^H m_v \Delta \sigma' dz \]

If $m_v$ and $\Delta \sigma'$ are assumed constant with depth then \[ S = m_v \Delta \sigma' H \]

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Settlement Equation in Terms of $a_v$

\[ S = \varepsilon_v H_o = \frac{\Delta e}{1 + e_o} H \]

\[ a_v = \frac{\Delta e}{\Delta \sigma'} \quad (1/\text{kPa} = \text{m}^2/\text{kN}) \]

\[ S = \int_0^H \frac{a_v}{1 + e_o} \Delta \sigma' dz \]

If $a_v$ and $\Delta \sigma'$ are assumed constant with depth then \[ S = \frac{a_v}{1 + e_o} \Delta \sigma' H = m_v \Delta \sigma' H \]

Therefore \[ m_v = \frac{a_v}{1 + e_o} \]
Settlement Equation in Terms of $c_c$

$$S = \varepsilon e H_o = \frac{\Delta e}{1 + e_o} H$$

$$c_c = \frac{\Delta e}{\log \frac{\sigma_2'}{\sigma_1'}}$$  \text{Note: } c_c = 0.009(\text{LL-10})$$

$$S = \frac{c_c H \log \frac{\sigma_2'}{\sigma_1'}}{1 + e_o} = \frac{c_c H \log \left(\frac{\sigma_1' + \Delta \sigma}{\sigma_1'}\right)}{1 + e_o}$$

Settlement due to $\Delta \sigma$

$$S_{total} = S_r + S_c$$

$$S_r = S_{\text{rebound}} = \frac{C_r}{1 + e_o} H_0 \log \left(\frac{\sigma_2'}{\sigma_1'}\right) = \frac{C_r}{1 + e_o} H_0 \log \left(\frac{\sigma_c'}{\sigma_1'}\right)$$

\text{note: for this case } \sigma_1' = 0$$

$$S_c = \frac{C_c}{1 + e_o} H_0 \log \left(\frac{\sigma_2'}{\sigma_1'}\right) = \frac{C_c}{1 + e_o} H_0 \log \left(\frac{\sigma_c' + \Delta \sigma}{\sigma_c'}\right)$$
Over Consolidation Ratio (OCR)

$$OCR = \frac{\sigma'_c}{\sigma'}$$

where:
OCR = Over Consolidation Ratio
$\sigma'_c$ = preconsolidation pressure of a specimen
$\sigma'$ = present (field) effective overburden pressure
Determination of $\sigma_c'$

See Das for procedure
Note $\sigma_c'$ is not a distinct point

Over Consolidation Ratio (OCR)

- If $\text{OCR} \leq 1.2 \quad \sigma_c' \sim \sigma'$ then soil is normally consolidated

- If $\text{OCR} \geq 1.2$ then soil over consolidated

Figure 7.8
Graphic procedure for determining preconsolidation pressure
EMBANKMENT SETTLEMENT
PRIMARY CONSOLIDATION

1D THEORY OF CONSOLIDATION TIME-INDEPENDENT ANALYSIS

\[ \Delta H = \frac{H \cdot C}{1 + e_0} \]

\[ \log \left( \frac{\sigma_f'}{\sigma_i'} \right) \]

Compression Index

Log Effective Stress

Preconsolidation Pressure (pc)

Compressibility

Initail Stress

Final Stress

Void Ratio

Log Total Stress
EMBANKMENT SETTLEMENT
PRIMARY CONSOLIDATION

1D THEORY OF CONSOLIDATION TIME-DEPENDENT ANALYSIS

INITIAL STRESS

LOG TOTAL STRESS

FINAL STRESS

UNDRAINED LOADING:
- PORE PRESSURE GENERATION
- NO CHANGE IN EFFECTIVE STRESSES
- NO SETTLEMENT

DRAINED LOADING:
- PORE PRESSURE DISSIPATION
- INCREASE IN EFFECTIVE STRESSES
- SETTLEMENT