CE464 Ground Improvement

Fall 2016
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PRELOADING without vertical drains

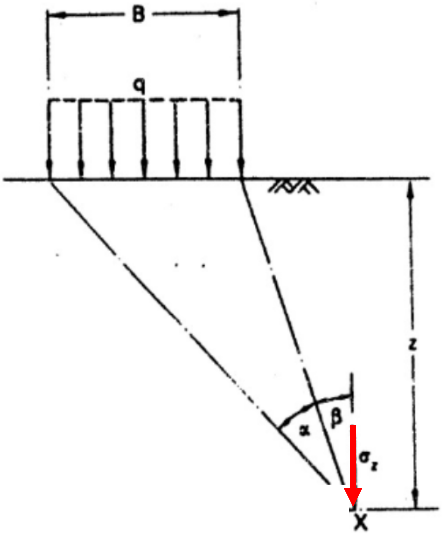
A Brief Review on Stress Distribution

Strip area carrying uniform pressure

The stresses at point X due to a uniform pressure q on a strip area of width B and infinite length are given in terms of the angles α and β

$$\boxed{\sigma_z = \frac{q}{\pi}\{\alpha + \sin\alpha\cos(\alpha + 2\beta)\}}$$

where, α and β are in radians.



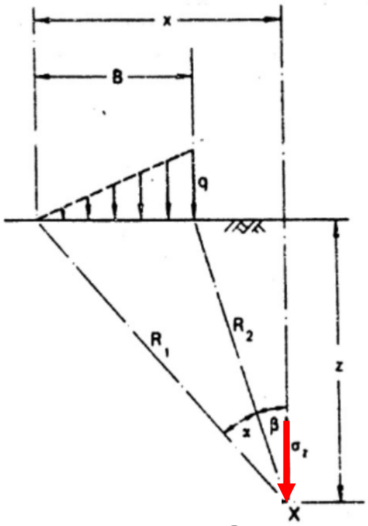
Boussinesq, 1885

Strip area carrying linearly increasing pressure

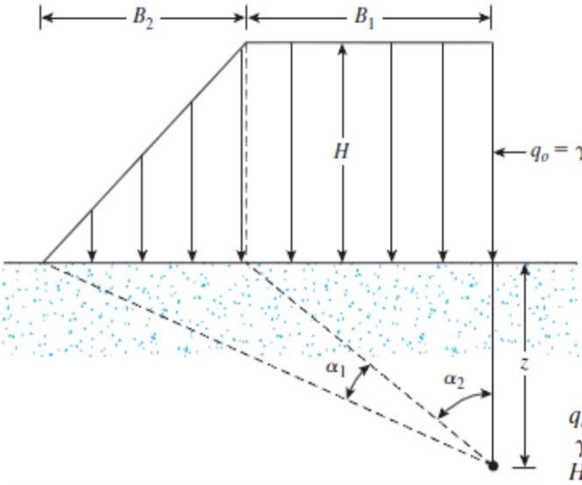
The stresses at point X due to pressure increasing linearly from zero to q on a strip area of width B are given in terms of the angles α and β and the lengths R_1 and R_2

$$\boxed{\sigma_z = \frac{q}{\pi}\left(\frac{x}{B}\alpha - \frac{1}{2}\sin 2\beta\right)}$$

where, α and β are in radians.



Boussinesq, 1885



$$\Delta\sigma = \frac{q_o}{\pi}\left[\left(\frac{B_1 + B_2}{B_2}\right)(\alpha_1 + \alpha_2) - \frac{B_1}{B_2}(\alpha_2)\right]$$

$q_o = \gamma H$
γ = unit weight of the embankment soil
H = height of the embankment

$$\alpha_1 = \tan^{-1}\left(\frac{B_1 + B_2}{z}\right) - \tan^{-1}\left(\frac{B_1}{z}\right)$$

$$\alpha_2 = \tan^{-1}\left(\frac{B_1}{z}\right)$$

(Note that α_1 and α_2 are in radians.)

Circular area carrying uniform pressure

The vertical stress at depth z under the centre of a circular area diameter D=2R carrying a uniform pressure q is given by:

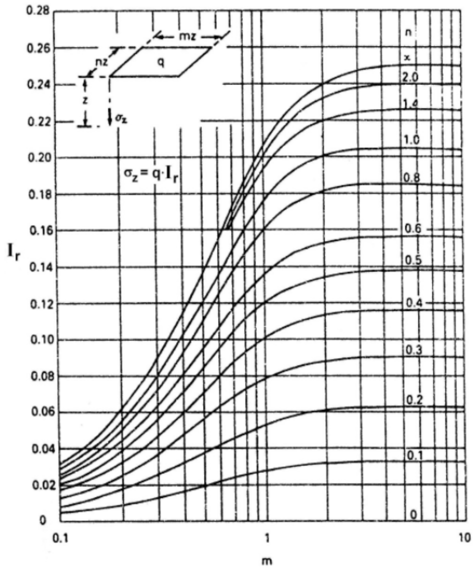
$$\sigma_z = q\left[1 - \left\{\frac{1}{1+(\frac{R}{z})^2}\right\}^{3/2}\right]$$

Boussinesq, 1885

Rectangular area carrying uniform pressure

A solution has been obtained for the vertical stress at depth z under a corner of a rectangular area dimensions mz and nz (Fig.1.6) carrying a uniform pressure q. The solution can be written in the form:

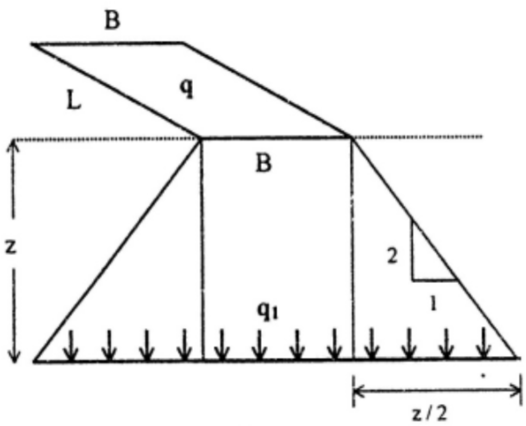
$$\sigma_z = q \cdot I_r$$



Boussinesq, 1885

2V:1H stress distribution

$$q_1 = \frac{q \cdot B \cdot L}{(B+z)(L+z)}$$



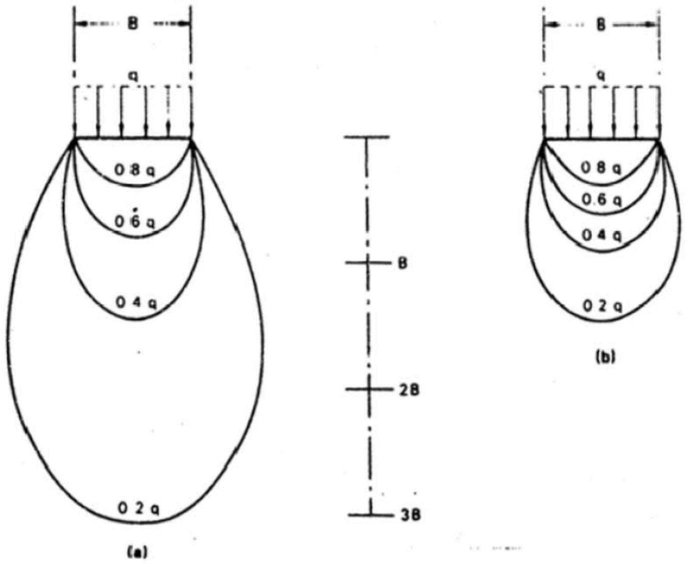


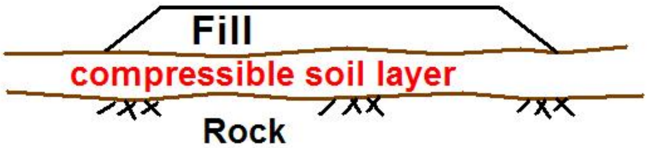
Figure 1.4 Contours of equal vertical stress: (a) under strip area, (b) under square area.

A Brief Review on Consolidation Settlement

One-Dimensional Consolidation

If the deformation and drainage boundary conditions of the soil are such that compression and water flow are in vertical direction, then we have one-dimensional consolidation.

Example of 1-D consolidation in the field:



If the fill width >> thickness of the compressible soil layer:
→ a soil element in the compressible layer is subjected to one-dimensional compression.

In one dimensional consolidation of soft clay deposits, we are interested in:

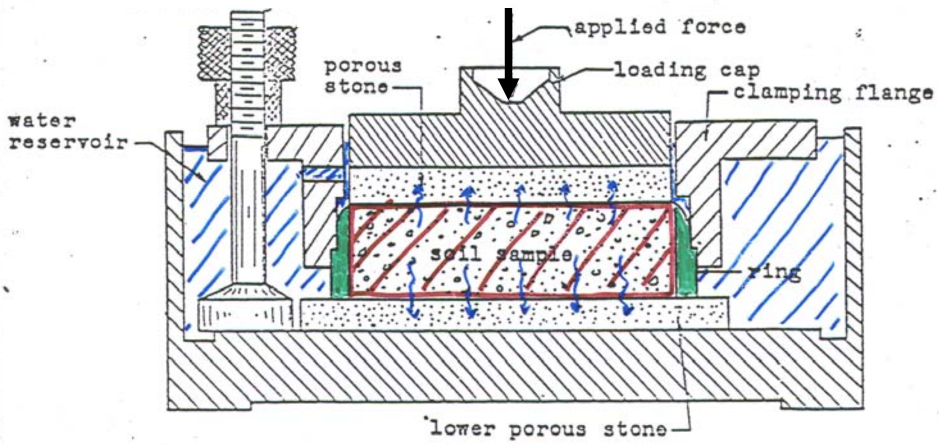
1) Magnitude of the settlement

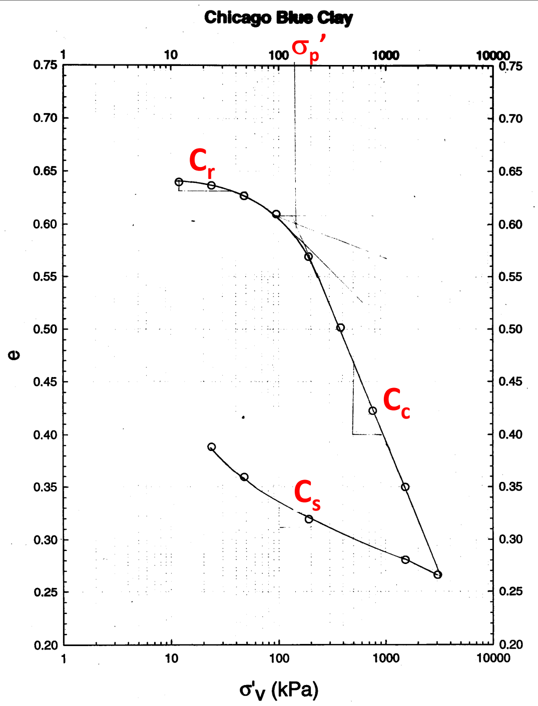
determined by compressibility and consolidation history of soils.

2) Rate of settlement

determined by compressibility and permeability of soils and drainage boundary conditions.

Laboratory One dimensional consolidation (oedometer) test

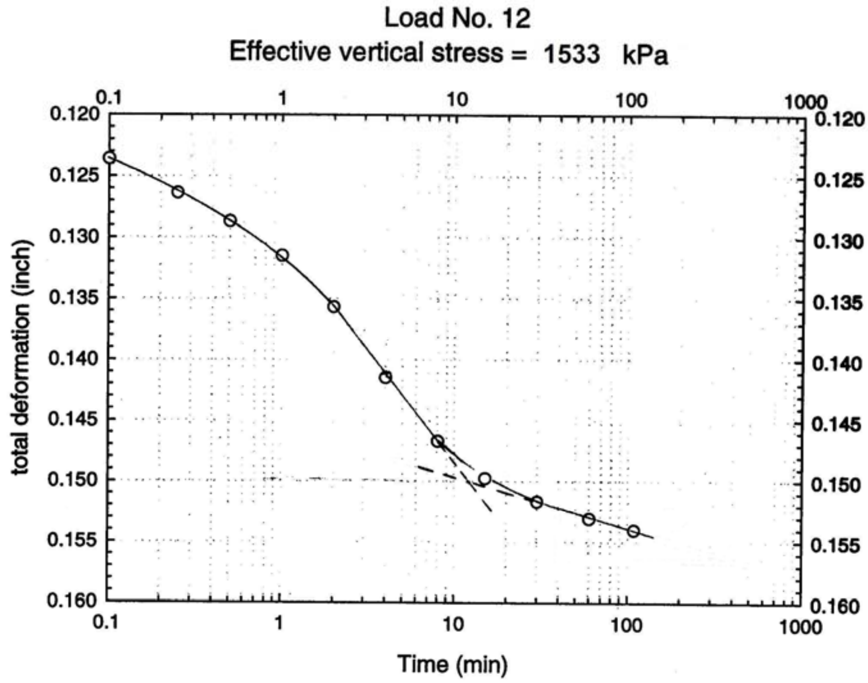


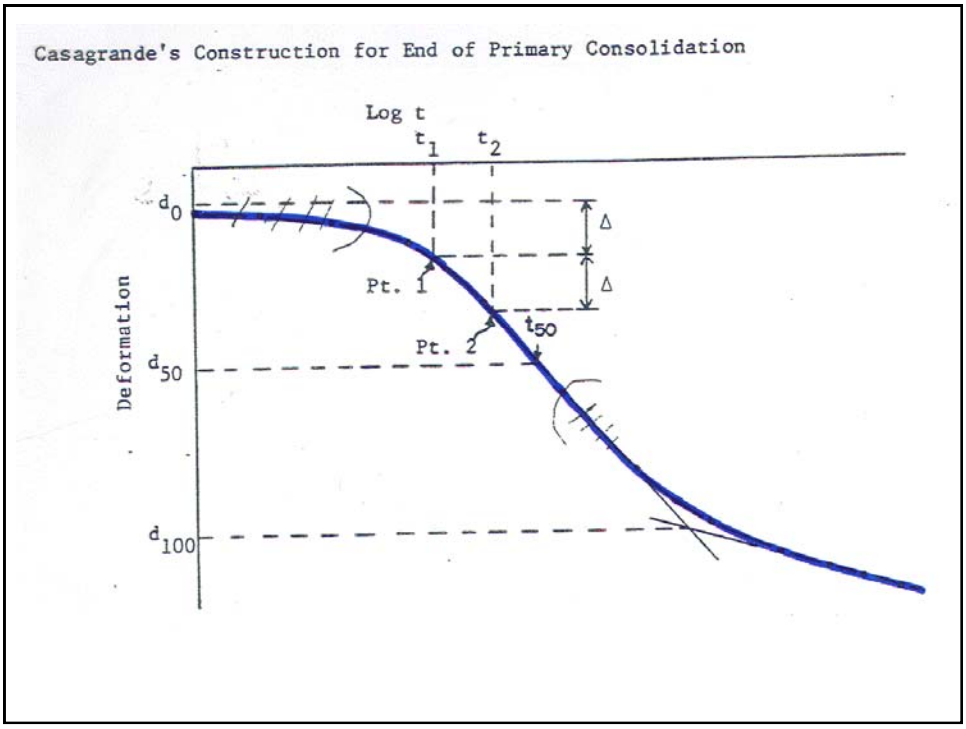


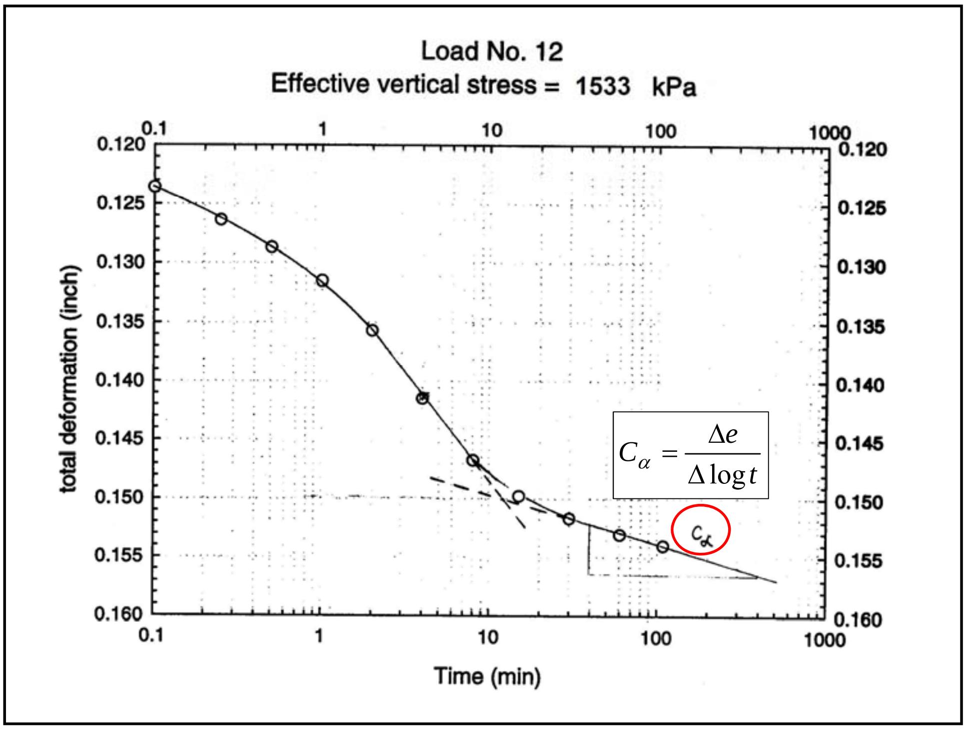
Each load increment is kept on the sample for 24 hours and vertical compression is recorded

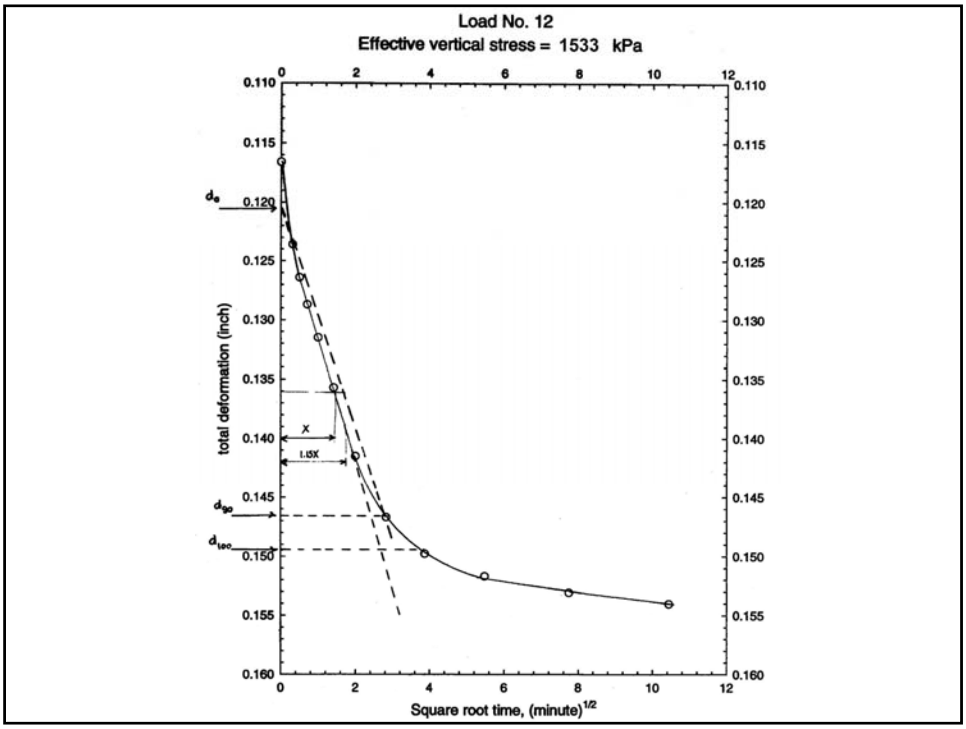
At each load increment deformation versus time data is used to determine the time (t_{100}) and deformation (d_{100}) at the end-of-primary consolidation settlement:

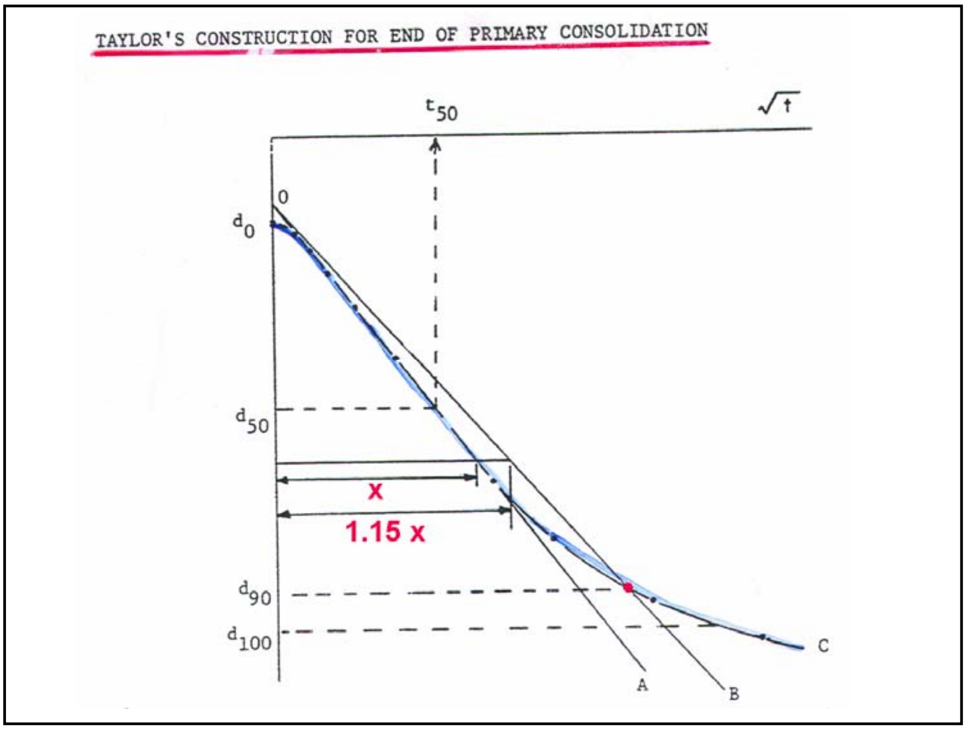
1) Casagrande's d-log t method
2) Taylor's d-$\sqrt{t}$ method

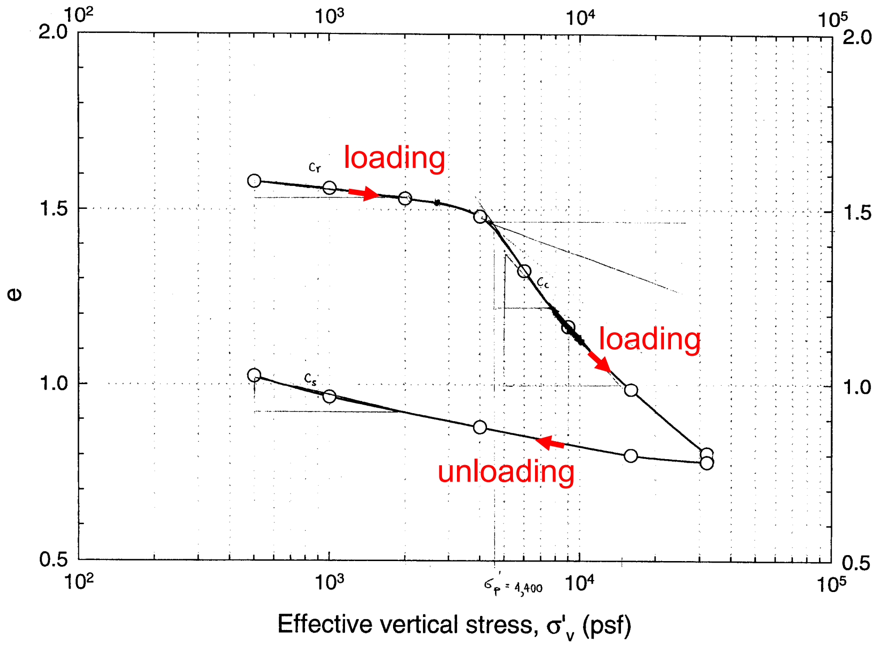



Casagrande's Construction for End of Primary Consolidation
Log t
t1
t2
d0
Δ
Δ
Pt. 1
Pt. 2
t50
d50
d100
Deformation


Load No. 12
Effective vertical stress = 1533 kPa
0.1
1
10
100
1000
0.120
0.125
0.130
0.135
0.140
0.145
0.150
0.155
0.160
total deformation (inch)
Time (min)
$C_\alpha = \dfrac{\Delta e}{\Delta \log t}$
C_α


Load No. 12
Effective vertical stress = 1533 kPa
total deformation (inch)
Square root time, (minute)^1/2
d90
d100
x
1.15X


TAYLOR'S CONSTRUCTION FOR END OF PRIMARY CONSOLIDATION
t50
√t
O
d0
d50
x
1.15 x
d90
d100
A
B
C



Overconsolidation ratio: $OCR = \frac{\sigma_p'}{\sigma_{vo}'}$

Compression index: $C_c = \frac{\Delta e}{\Delta \log \sigma'_v}$ $\left(C_r = \frac{\Delta e}{\Delta \log \sigma'_v}\right)$

C_r / C_c ratio typically = 0.1 to 0.2

Coefficient of consolidation:

$$c_v = \frac{k_v}{m_v \cdot \gamma_w} \qquad T_v = \frac{c_v \cdot t}{d^2}$$

Secondary compression index

$$C_\alpha = \frac{\Delta e}{\Delta \log t}$$

Degree of consolidation at a depth, at a given time, U_z

$$U_z = \frac{u_{ie} - u_e}{u_{ie}} = \frac{\sigma' - \sigma'_o}{\sigma'_f - \sigma'_o}$$

u_{ie} = initial excess pore water pressure

u_e = excess pore water pressure at that point, at that time

Average degree of consolidation of the layer, U

$$S_{at\ time\ t} = S_f \cdot U_{at\ time\ t} \qquad U = \frac{S_{at\ time\ t}}{S_f}$$

S_f (settlement at end-of-primary consolidation) is at U = 95%

Relation between average degree of consolidation, U, and Time factor, T_v

U (%)	T_v
0	0
5	0.002
10	0.008
15	0.018
20	0.031
25	0.049
30	0.071

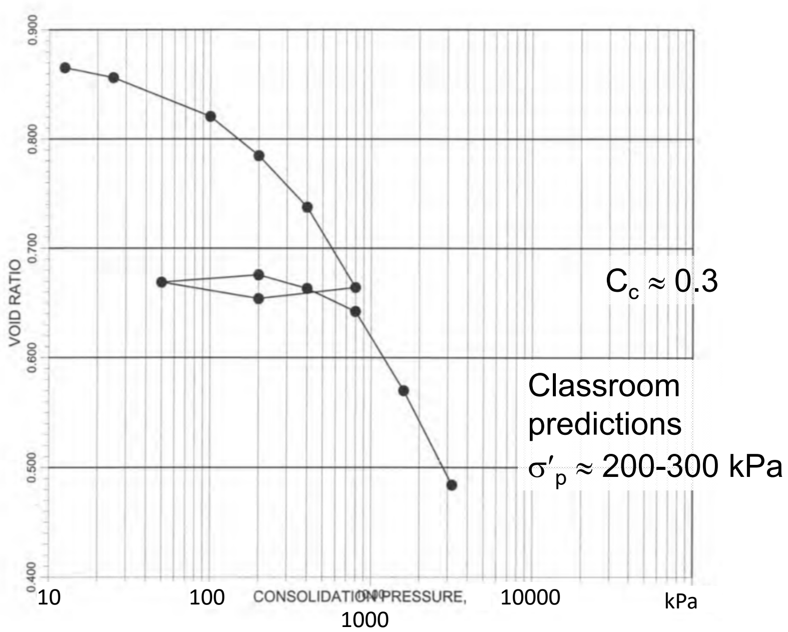
U (%)	T_v
35	0.096
40	0.126
45	0.159
50	0.195
55	0.239
60	0.286
65	0.340

U (%)	T_v
70	0.403
75	0.477
80	0.567
85	0.684
90	0.848
95	1.129

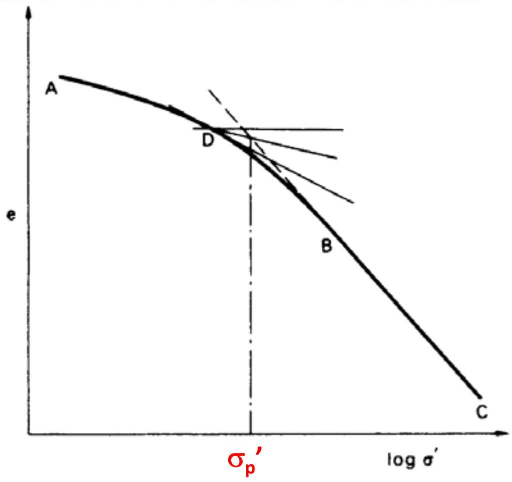
Time Factor T_v for U = 95% consolidation is T_v = 1.129

$$\text{For constant } u_{ie} \text{ with depth}: \begin{cases} \text{for U} < 60\%,\ T_v = \dfrac{\pi}{4} \cdot U^2 \\ \text{for U} > 60\%,\ T_v = -0.933 \cdot \log(1-U) - 0.085 \end{cases}$$

Example: find preconsolidation pressure and compression index



1. Produce back the straight-line part (BC) of the curve.
2. Determine the point (D) of maximum curvature on the recompression part (AB) of the curve.
3. Draw the tangent to the curve at D and bisect the angle between the tangent and the horizontal through D.
4. The vertical through the point of intersection of the bisector and CB produced gives the approximate value of the preconsolidation pressure.



Primary consolidation settlement

$$S = \frac{C_r}{1+e_o} L_o \log \frac{\sigma'_p}{\sigma'_{vo}} + \frac{C_c}{1+e_o} L_o \log \frac{\sigma'_{vf}}{\sigma'_p}$$

$$S = \frac{C_c}{1+e_o} L_o \log \frac{\sigma'_{vf}}{\sigma'_p}$$

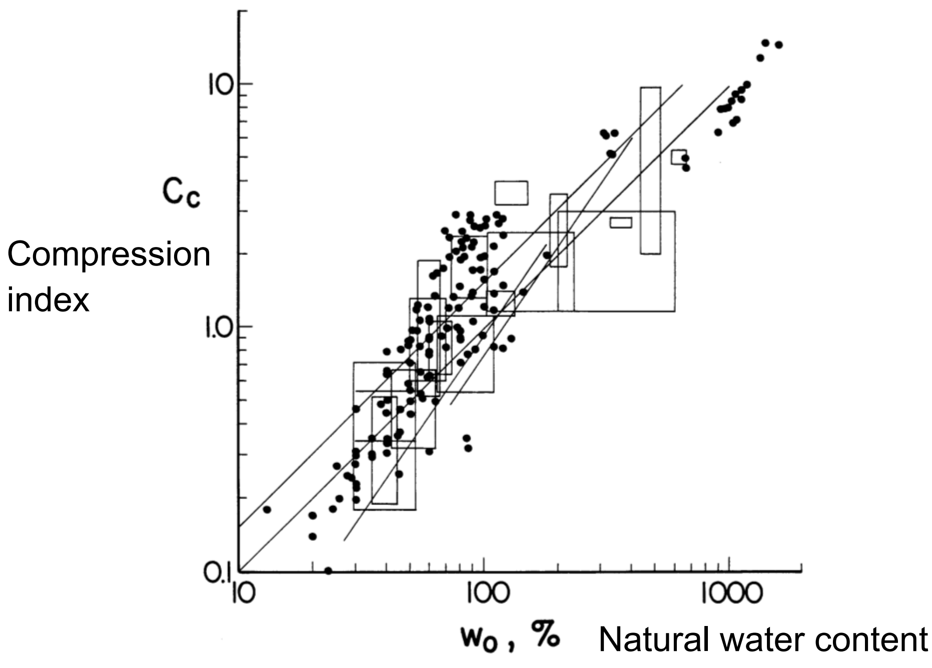
Subdivide the clay if it is thicker than 6 m

$$S_{oed} = \sum H \cdot m_v \cdot \Delta\sigma'$$

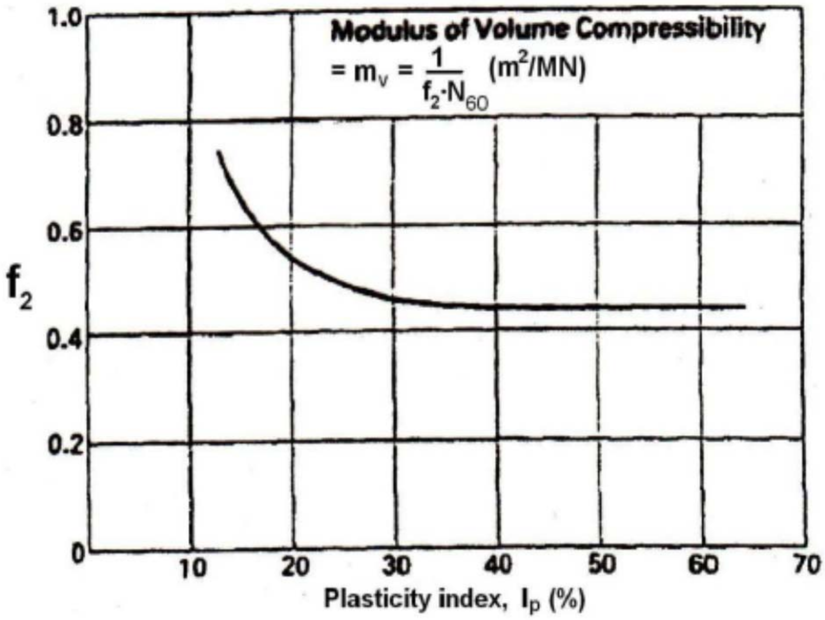
Secondary consolidation settlement

$$S = \frac{C_\alpha}{1+e_o} L_o \log \frac{t}{t_p}$$

Material	C_α / C_c
Inorganic clays and silts	0.04 ± 0.01
Organic clays and silts	0.05 ± 0.01



Coefficient of volume compressibility, m_v



Skempton-Bjerrum correction is applied to calculated settlements. This is because definition of compressibility parameters is one-dimensional. Skempton and Bjerrum observed that actual consolidation settlement of the structures were generally less than the values computed based on oedometer tests. They proposed the following expression:

$$S_c = \mu \, . \, S_{oed} \qquad (3.5)$$

where μ is coefficient which depends on the type of clay and the shape of the foundation and thickness of the clay layer. (See, Craig, Fig.7.12, 5th ed.). For practical purposes the values in Table 3.3 may be used:

Table 3.3 The Skempton and Bjerrum correction factor

Type of clay	μ
Sensitive clays, soft alluvial clays	1.0-1.2
Normally consolidated clays	0.7-1.0
Overconsolidated clays	0.5-0.7
Heavily overconsolidated clays	0.2-0.5

PRELOADING
without vertical drains

PRELOADING IS SURCHARGING THE GROUND WITH A UNIFORMLY DISTRIBUTED SURFACE LOAD PRIOR TO THE CONSTRUCTION OF THE INTENDED STRUCTURE (BUILDINGS, BRIDGE FOUNDATIONS, EMBANKMENTS, RUNWAYS, TANKS ETC.).

THE PURPOSE IS TO TAKE UP THE SETTLEMENTS UNDER THE STRUCTURES BEFORE THEY ARE BUILT.

WITH PRELOADING (SURCHARGE) THE CONSOLIDATION SETTLEMENTS TAKE PLACE, THEN THE LOAD IS REMOVED AND THEN THE BUILDING IS CONSTRUCTED.

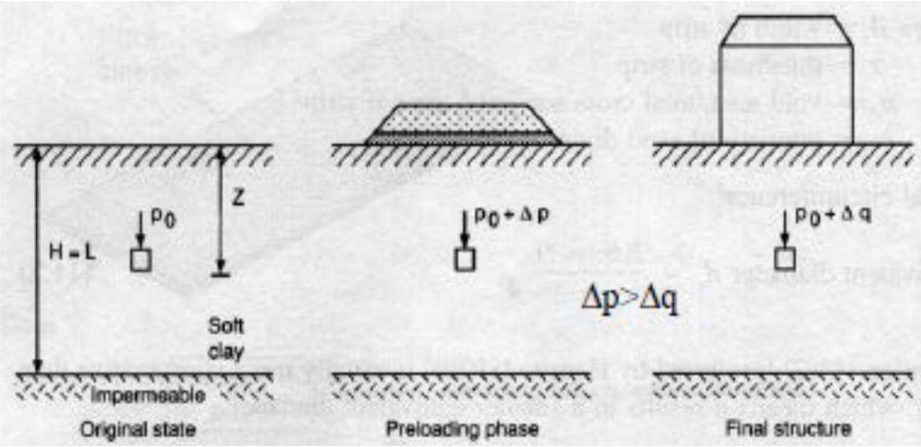
SOILS SUITABLE FOR PRELOADING: COMPRESSIBLE SOFT TO MEDIUM SOFT SATURATED CLAYS AND SILTS, ORGANIC CLAYS, PEATS.

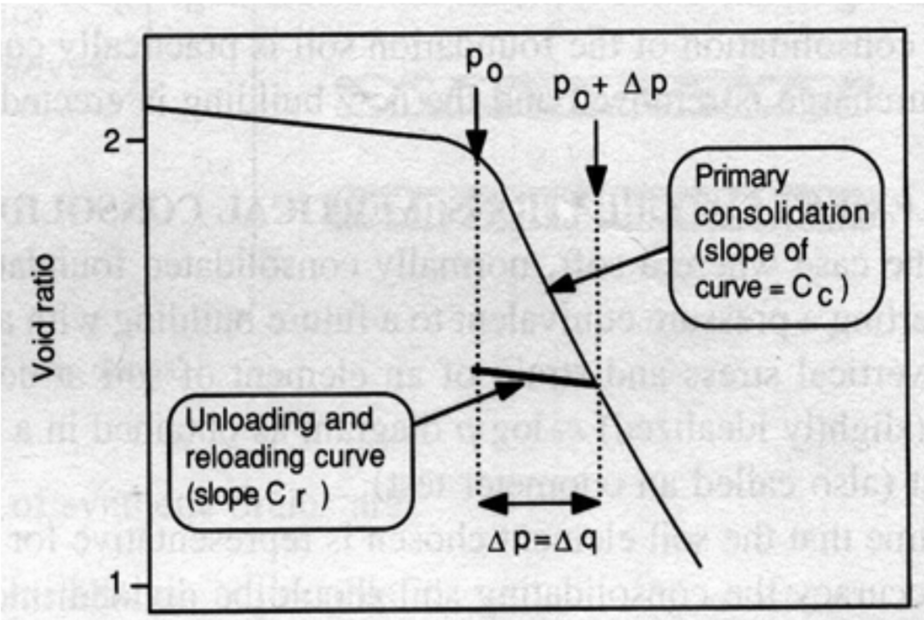
TYPES OF PRELOADS:

- EARTH FILLS (MOST COMMON),
- WATER IN TANKS OR POOLS,
- VACUUM APPLICATION UNDER A MEMBRANE,
- GROUNDWATER LOWERING

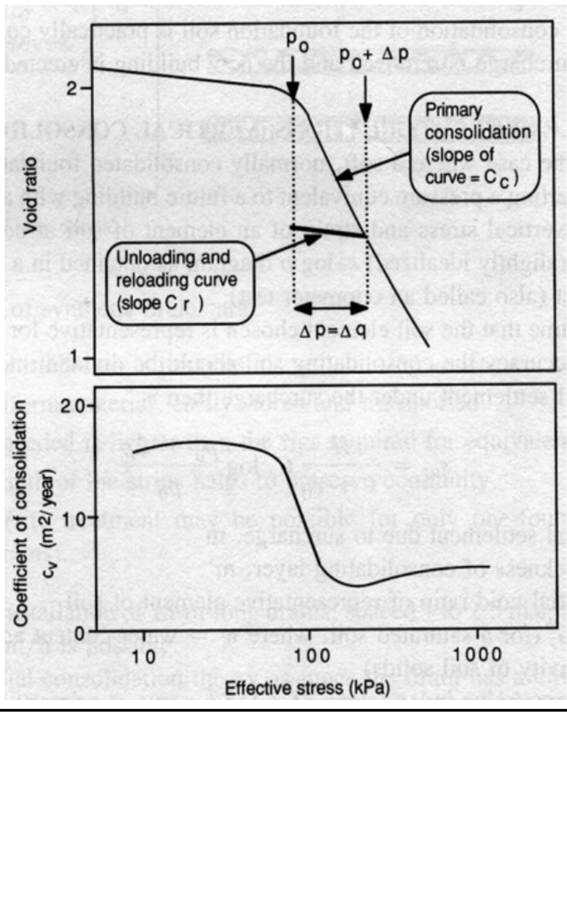
THE SURCHARGE RESULTS IN;

•PRIMARY CONSOLIDATION SETTLEMENT
•SECONDARY CONSOLIDATION SETTLEMENT
•INCREASE IN THE UNDRAINED SHEAR STRENGTH OF THE SOIL.





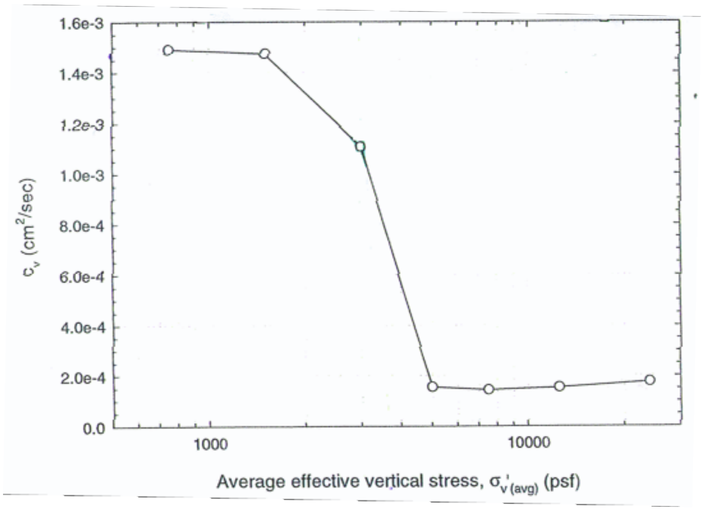
p_o
$p_o + \Delta p$
2
1
Void ratio
Primary consolidation (slope of curve = C_c)
Unloading and reloading curve (slope C_r)
$\Delta p = \Delta q$



p_o
$p_o + \Delta p$
2
1
Void ratio
Primary consolidation (slope of curve = C_c)
Unloading and reloading curve (slope C_r)
$\Delta p = \Delta q$
20
10
0
Coefficient of consolidation
c_v (m^2/year)
10
100
1000
Effective stress (kPa)

c_v in recompression range is = 5 to 10 times c_v in compression range

$$T_v = \frac{c_v \cdot t}{d^2}$$

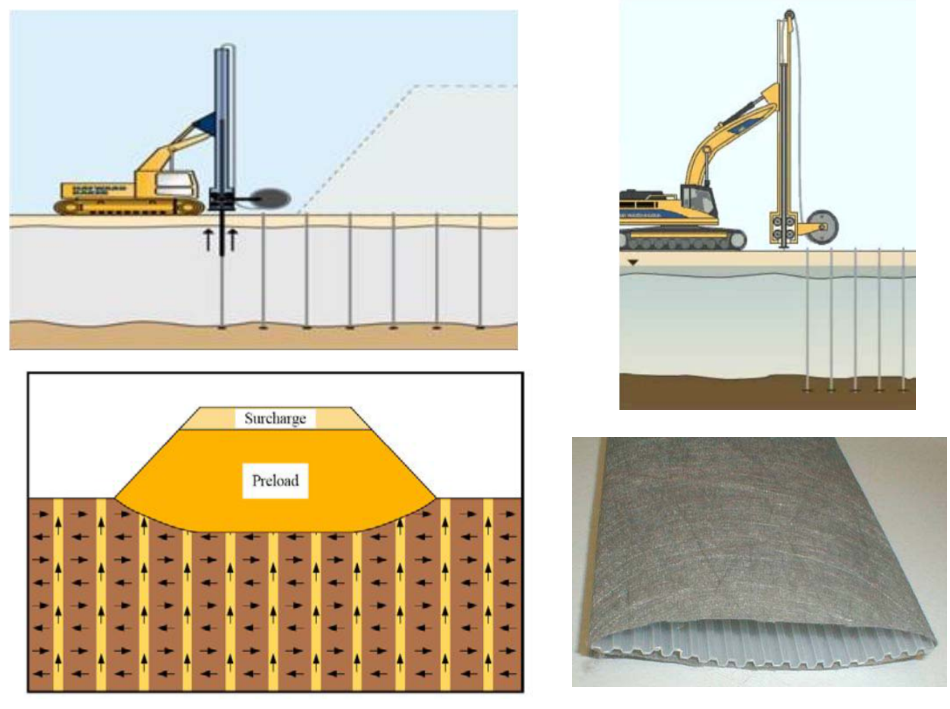


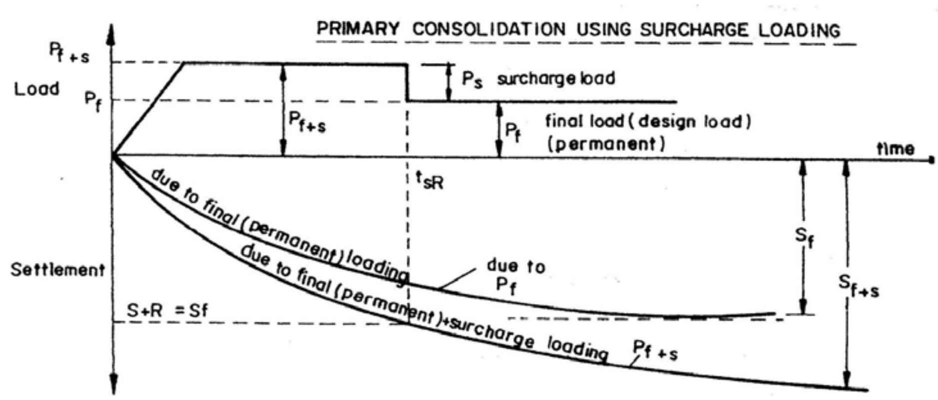
100 psf = 4.8 kPa

SURCHARGE LOADS AND VERTICAL DRAINS ARE FREQUENTLY USED TOGETHER WITH THE PRELOADING TECHNIQUE.

SURCHARGE LOADS (LOADS IN EXCESS OF THOSE TO BE APPLIED BY A PERMANENT FILL OR STRUCTURE) CAN BE USED TO ACCELERATE THE PROCESS FOR A PERIOD OF TIME T_SR. TERZAGHI'S ONE-DIMENSIONAL CONSOLIDATION THEORY CAN BE USED.

WHEN THE ANTICIPATED TIME OF COMPRESSION IS EXCESSIVE, VERTICAL DRAINS MAY BE USED TO SHORTEN THE TIME REQUIRED





Primary Consolidation By Using Surcharge Loading

USE OF SURCHARGE LOADING (EXTRA P_S) AND DURATION OF ITS APPLICATION IS TO REDUCE THE MAGNITUDE OF SETTLEMENT AFTER CONSTRUCTION. IT IS USUALLY AIMED AT EITHER;

1)

TO DETERMINE THE MAGNITUDE OF SURCHARGE (P_S , OR $P_S + P_F$) REQUIRED TO ENSURE THAT THE TOTAL SETTLEMENT ANTICIPATED UNDER THE FINAL PRESSURE (P_F) WILL BE COMPLETED (OR MOSTLY COMPLETED) IN A GIVEN LENGTH OF TIME.

2)

TO DETERMINE THE LENGTH OF TIME REQUIRED TO ACHIEVE A GIVEN AMOUNT OF SETTLEMENT UNDER A GIVEN SURCHARGE LOAD.

$$S_f = \frac{C_c}{1+e_o} \cdot L_o \cdot \log \frac{\sigma'_o + P_f}{\sigma'_o}$$

$$S_{f+s} = \frac{C_c}{1+e_o} \cdot L_o \cdot \log \frac{\sigma'_o + (P_f + P_s)}{\sigma'_o}$$

$$U = \frac{S_F}{S_{F+S}}$$

Example:

A soil profile consists of 3 m of gravel (γ = 19 kN/m^3) over 5 m or clay (γ = 18 kN/m^3, e_o = 0.9, C_c = 0.7, σ'_p/σ'_{vo} = 1.0 and c_v = 0.36 m^2/month) over impervious bedrock. The water table is at the ground surface. A 12 m x 12 m square foundation slab carrying 10 MN will be placed at 1.5 below the ground surface. Use 2V:1H stress distribution. Compute settlement at the center of the slab resulting from:

a) Primary consolidation settlement of the clay
b) Time required to complete primary consolidation settlement (no preloading)
c) What surcharge is required to eliminate primary consolidation settlement in 9 months?

a) Primary consolidation settlement of the clay

Net foundation pressure at 1.5 m depth:

= 10000 kN / (12 x 12) – (1.5 x 19) = 40.9 kPa

At the mid-depth of clay layer:

σ'_{vo} = 3 x (19-10) + 2.5 x (18-10) = 47 kPa

σ'_p = 47 kPa

$\sigma'_f = \sigma'_{vo} + \Delta\sigma'_v$

$\Delta\sigma'_v$ = (40.9 x 12 x 12) / ((12 + 4) x (12 + 4)) = 23 kPa

$\sigma'_f = \sigma'_{vo} + \Delta\sigma'_v$ = 47 + 23 = 70 kPa

$$S = \frac{C_c}{1+e_o} \cdot H_o \cdot \log\frac{\sigma'_f}{\sigma'_o} = \frac{0.7}{1+0.9} \cdot 5 \cdot \log\frac{70}{47} = 0.32\ \mathrm{m}$$

$$(S = S_{oed} \cdot \mu = 0.32 \cdot 0.85 = 0.27\ \mathrm{m})$$

b) Time required to complete primary consolidation settlement (no preloading)

"complete primary consolidation" : Average degree of consolidation, U = 95%

T_v = 1.129

$$T_v = \frac{c_v \cdot t}{d^2} = 1.129 = \frac{(0.36\, m^2 / mo) \cdot t}{(5)^2}$$

t = 78.4 months = 6.5 years

Total consolidation settlement is 32 cm (not acceptable!), and this 32 cm will occur in 6.5 years. To eliminate the settlement, preloading is considered:

c) What surcharge is required to eliminate primary consolidation settlement in 9 months?

$$T_v = \frac{c_v \cdot t}{d^2} = \frac{(0.36\, m^2 / mo) \cdot 9 \text{ months}}{(5)^2} = 0.1296$$

U (%)	T_v
35	0.096
40	0.126
45	0.159
50	0.195
55	0.239
60	0.286
65	0.340

Linearly interpolate from table values, or use the equations below:

$$U = 40.6\%$$

$$\begin{cases} \text{for U} < 60\%,\ T_v = \dfrac{\pi}{4} \cdot U^2 \\ \text{for U} > 60\%,\ T_v = -0.933 \cdot \log(1-U) - 0.085 \end{cases}$$

$$U = 40.6\%$$

$$U = \frac{S_{\text{due to } final \text{ building pressure}}}{S_{\text{due to } preloading}} \qquad 40.6\% = \frac{0.32 \text{ m}}{S_{preloading}}$$

$$S_{preloading} = 0.788 \text{ m}$$

$$S = \frac{C_c}{1+e_o} \cdot H_o \cdot \log\frac{\sigma'_f}{\sigma'_o} = \frac{0.7}{1+0.9} \cdot 5 \cdot \log\frac{x?}{47} = 0.788 \text{ m}$$

$$x? = 125.9 \text{ kPa}$$

$$x? = \sigma'_o + \Delta\sigma'_v$$

$$125.9 = 47 + \Delta\sigma'_v$$

$$\Delta\sigma'_v = 78.9 \ kPa$$

Consider a wide fill (with γ = 20 kN/m^3) is to be placed at ground surface as a surcharge. Required height of fill: 3.95 m (use 4 m fill)

$\Delta\sigma'_v$ = constant with depth for wide fill