# 3. Soil Improvement

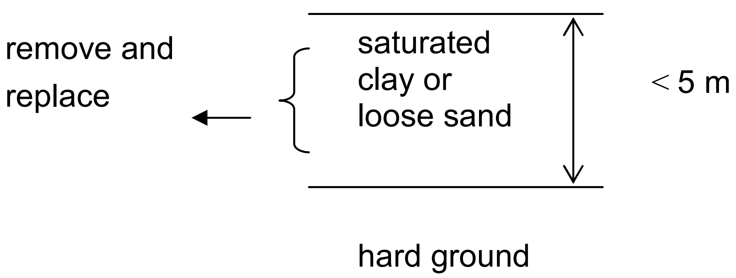
## 1) General

- Choices of foundation
  - → Shallow foundation
  - → In cases that shallow foundation does not work,
    - use deep foundation to transfer load to more competent stratum.
    - improve soil that causes the problem.

- Method of soil improvement
  1. Remove and replace
  2. Increase density in-place
     - compaction
     - vibroflotation
     - heavy tamping (dynamic compaction)
  3. Precompression
  4. Stone column or sand compaction pile
  5. Soil reinforcement

## 2) Remove and Replace (with compaction)

⇒ Economic considerations



## 3) Increase Density In-place

i) In-place compaction

- Generally compacted by rollers.
- Type of roller
  1. Smooth-wheel rollers
  2. Pneumatic rubber-tired rollers
  3. Sheepsfoot rollers
  4. Vibratory rollers
- Effective depth: 2~3m.
- Advantages
  - Increase $D_r$ , $\phi'$ and stiffness of clean cohesionless soils, effectively.
  - Very simple.
- Disadvantages: shallow treatment only.

ii) Vibroflotation

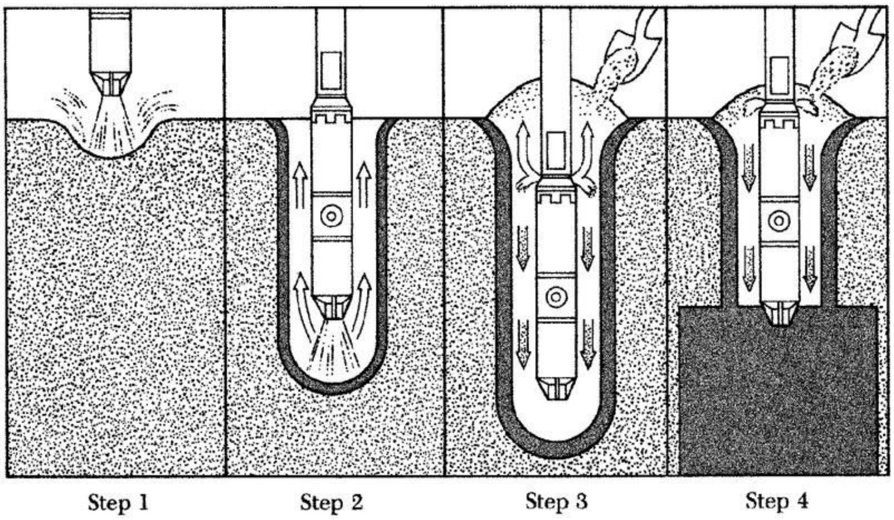



Fig 14.11 Compaction by the vibroflotation process (after Brown, 1977)

- Effective depth: 5~20m
  ( worked up to 30m depth )

- The capacity of densification depends upon grain size distribution of in-situ soil (Fig 14.13) and backfill material.

- In-situ soils

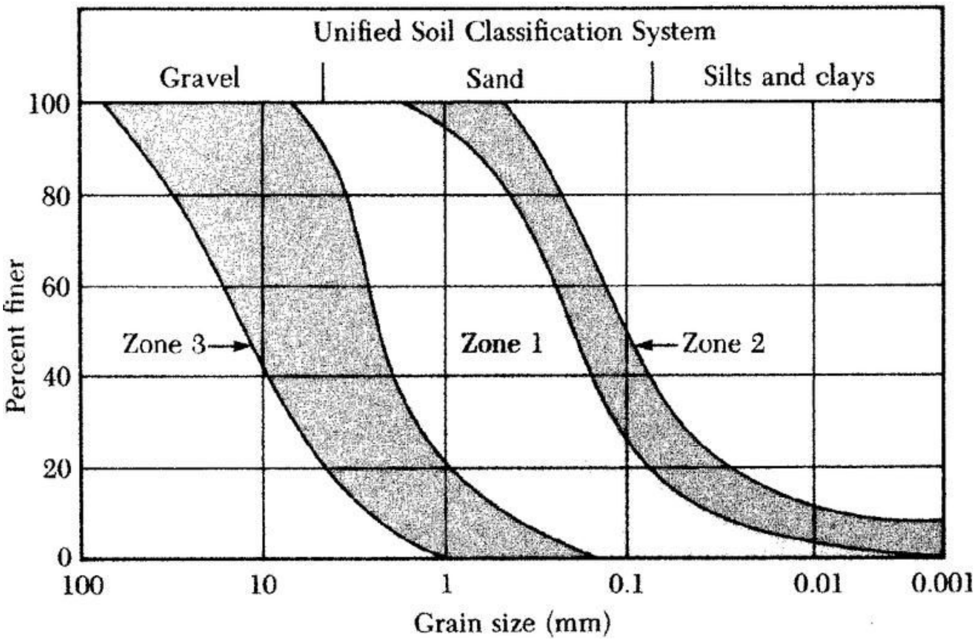



Fig 14.13 Effective range of grain-size distribution of soil for vibroflotation

Zone 1 → most suitable
Zone 2 (excessive amounts of fine materials )
→ the approximate lower limit.
Zone 3 (appreciable amounts of gravel)
→ slow rate of probe penetration.
→ can be uneconomical.

- Backfill materials

  Suitability number, $S_n = 1.7\sqrt{\frac{3}{(D_{50})^2} + \frac{1}{(D_{20})^2} + \frac{1}{(D_{10})^2}}$

  where $D_{50}$, $D_{20}$ and $D_{10}$ are the diameter (in mm) through which 50%, 20% and 10% repectively of the material is passing.

| Range of $S_N$ | Rating as backfill |
|---|---|
| 0–10 | Excellent |
| 10–20 | Good |
| 20–30 | Fair |
| 30–50 | Poor |
| >50 | Unsuitable |

- The zone of compaction depends on the type of vibroflot.
  - a radius of 6 ft. for 30-HP unit.
  - a radius of 10 ft. for 100-HP unit.

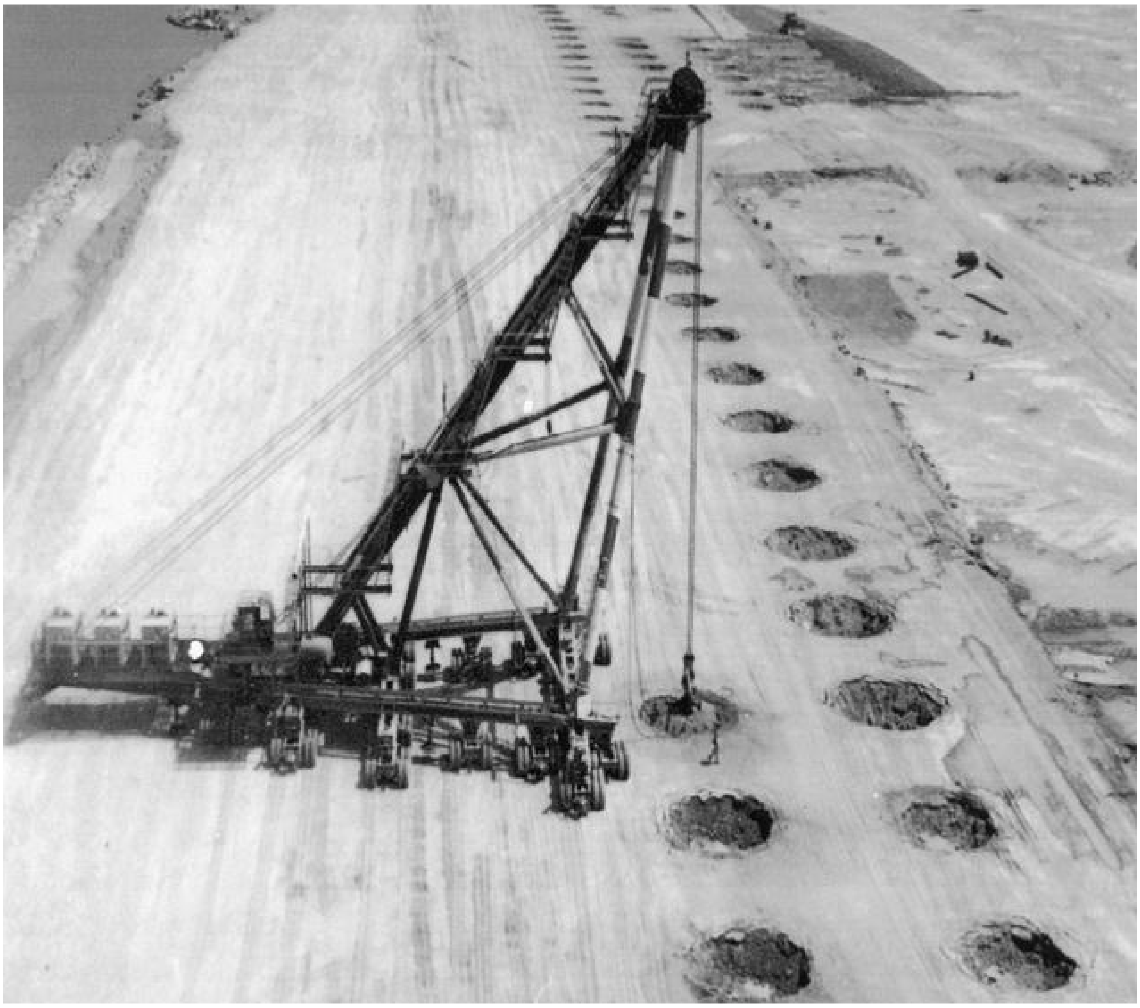
- Advantages
  i)
  ii)

- Limitations
  i)
  ii)
  iii)

iii) Heavy Tamping (Dynamic Compaction)

$$E = Wh$$

W: weight of pounder; h: drop height



- E = (150 ~ 500) t·m → typical
  = (1000 ~ 2000) t·m → highest

- Spacing = 5 ~ 15 m
- Effective depth = 20 m

- Advantages: (i) treats any type of non-plastic soils.
  (rockfills to organic silts)
  (ii) overall densification : reduce heterogeneity at site.
  (limit differential settlements)
  (iii) treats large areas.

- Limitations: (i) does not work in low-pervious, water-saturated, fine-grained soils such as clays and highly organic soils.
  (ii) water level below 1.5 ~ 3.0m from ground surface
  (iii) (30~70)m × (30~70) m clearance around site

- Based on case records, the depth of compaction,

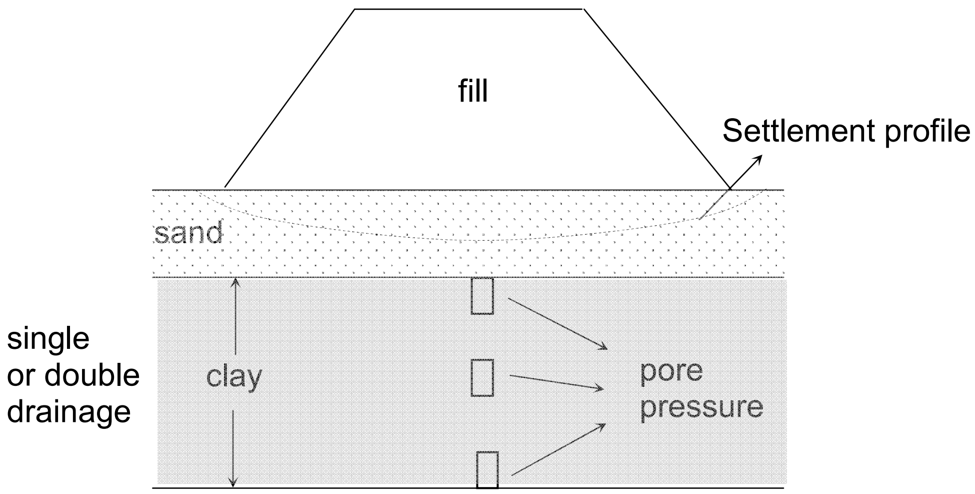
$$d_{cp} = n\sqrt{Wh} \quad n = 0.3 \sim 1.0$$

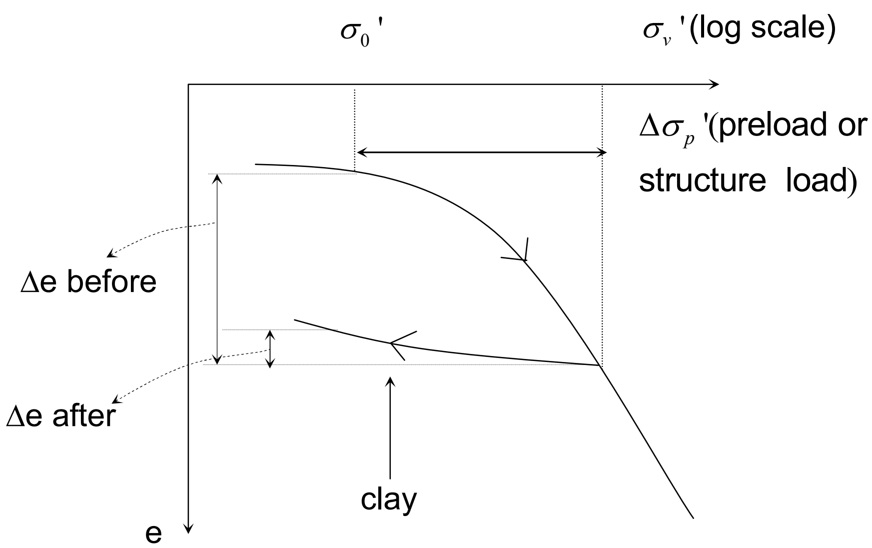
For cohesionless soils, n=0.5~1.0
0.5 : very coarse grained soils
For clayey and silty soils, n=0.3~0.5

**4) Preload (Precompression)**

- Static loads to densify soil (highly compressible, NC or lightly OC clayey soils)

① Add fill.
② Measure settlements and pore water pressures with time.
③ When consolidation under preload is complete, remove the fill.
④ Construct the structure.



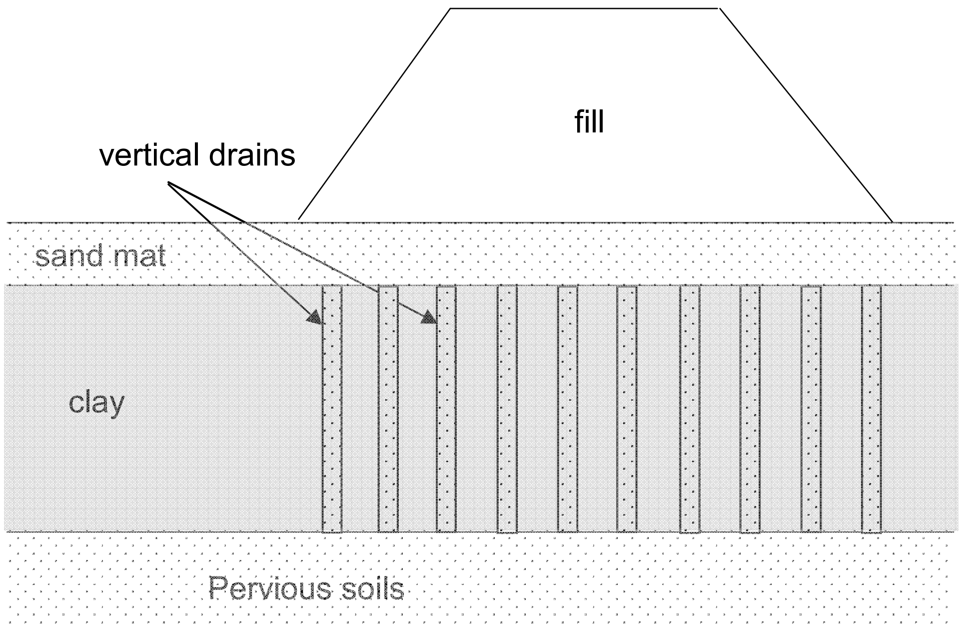



- To accelerate drainage :

  Use vertical drains.

  (drains → sand drains, pack drains, prefabricated vertical drains (PVD, plastic board drains, wick drains))

  ⇒ shortening drainage paths and inducing horizontal flow ( $k_h > k_v$ ).



- Preload ($\Delta\sigma'_{(p)}$) and Surcharge($\Delta\sigma'_{(f)}$)
  - Surcharge is load in excess of the anticipated structural load. (effective for reducing construction time)

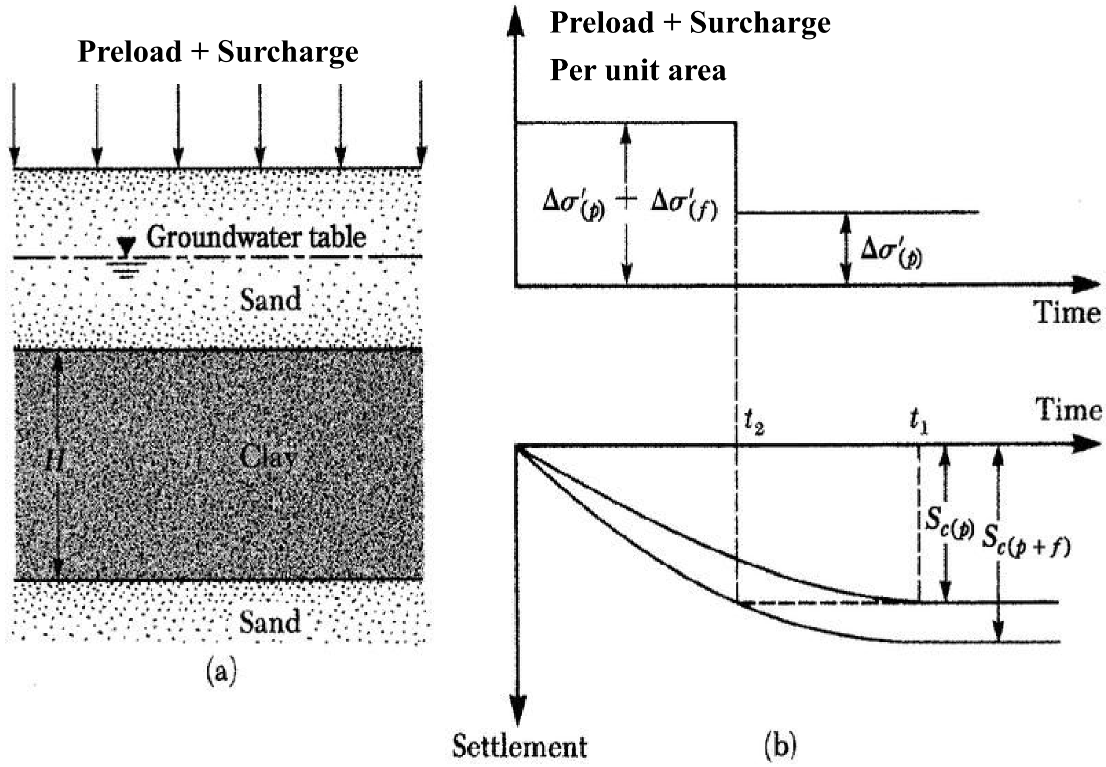



Fig 14.18 Principles of precompression

  - Consolidation time to reach the desired effective stress (or the expected settlement by structural load only) can be shorten by loading with preloading + surcharge.

- Compute time( $t_2$ ) that preload + surcharge ( $\Delta\sigma'_{(p)} + \Delta\sigma'_{(f)}$ ) must be left in place.

  - Average degree of consolidation U$_{ave}$ at time $t_2$ ,

$$U_{ave} = \frac{S_{(p)}}{S_{(p+f)}}$$ for NC soils,

$$U_{ave} = \frac{\frac{C_c}{1+e_0} H \log \frac{\sigma'_0 + \Delta\sigma'_{(p)}}{\sigma'_0}}{\frac{C_c}{1+e_0} H \log \frac{\sigma'_0 + \Delta\sigma'_{(p)} + \Delta\sigma'_{(f)}}{\sigma'_0}}$$

$$= \frac{\log \frac{\sigma'_0 + \Delta\sigma'_{(p)}}{\sigma'_0}}{\log \frac{\sigma'_0 + \Delta\sigma'_{(p)} + \Delta\sigma'_{(f)}}{\sigma'_o}}$$

or U$_{ave}$ can be determined with Fig 14.19.

  - Time Factor, T$_v$ can be computed from Fig 1.24, or by equations as below,

$$T_v = \frac{\pi}{4}\left[\frac{U_{ave}(\%)}{100}\right]^2 \qquad \text{(for } U_{ave} = 0 \sim 60\%\text{)}$$

$$T_v = 1.781 - 0.933\log(100 - U_{ave}(\%)) \qquad \text{(for } U_{ave} \geq 60\%\text{)}$$

  - t$_2$ ( $= \frac{T_v H^2}{C_v}$ ) can be computed.

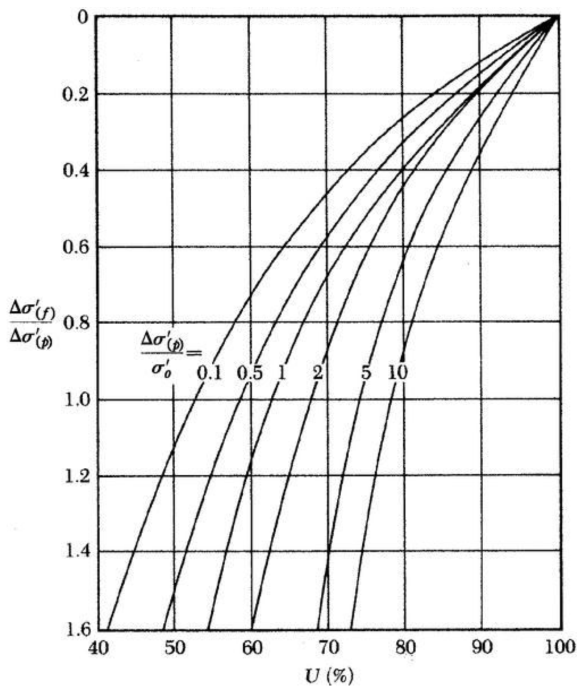



Fig 14.19 Plot of $\Delta\sigma'_{(f)} / \Delta\sigma'_{(p)}$ against U for various values of $\Delta\sigma'_{(p)} / \sigma'_0$ - Eq. (14.11)

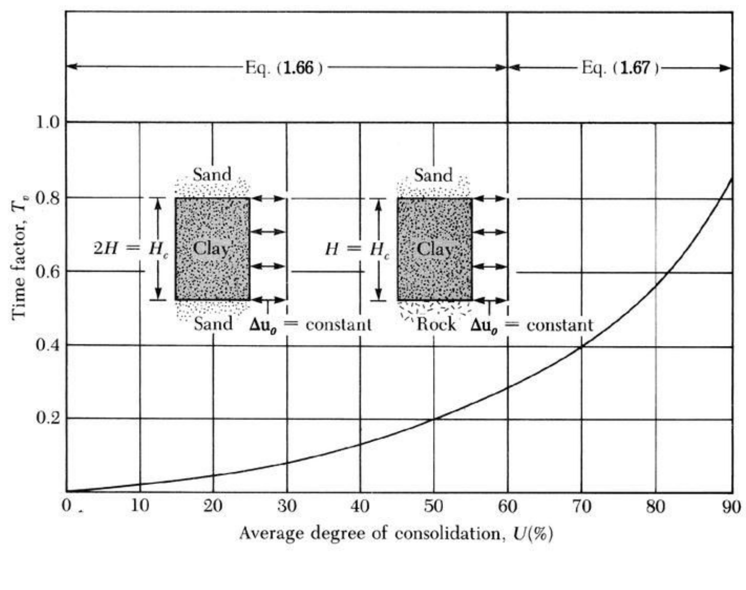
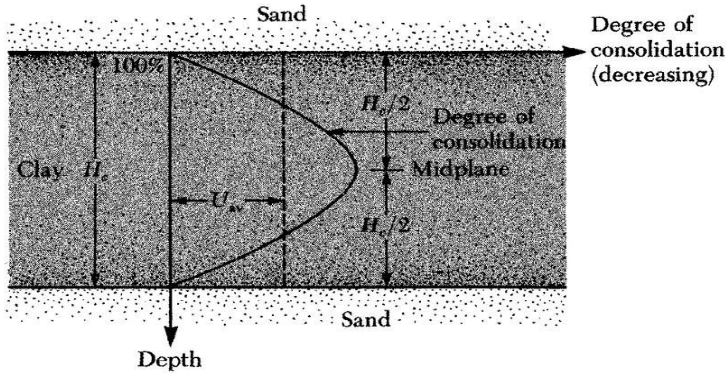



Fig 1.24 Plot of time factor against average degree of consolidation ($\Delta U_0$ =constant)

Notes :




- After removal of $\Delta\sigma'_{(p)} + \Delta\sigma'_{(f)}$ and placement of structural load, compression at the middle of clay layer can be occurred.

- In some cases, net continuous settlement might result.

- The conservative approach can be applied. (that is assume that $U$ in above equation is the midplane degree of consolidation. And you get $T_v$ with Fig 14.21)

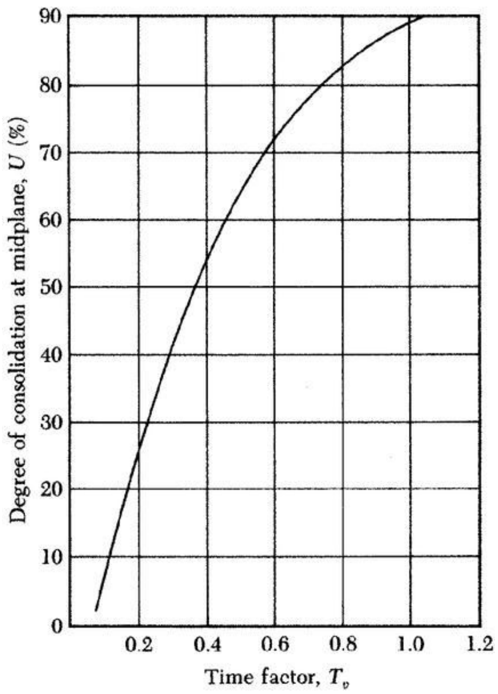



Fig 14.21 Plot of midplace degree of consolidation against $T_v$

- We can also compute the amount of surcharge needed for a given $t_{removal}$.

- Estimation of consolidation time for vertical drains.
  [Barron (1948)]

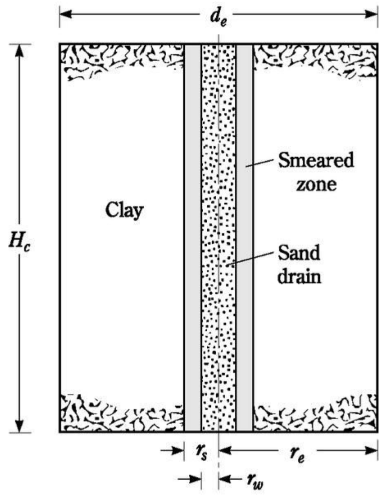
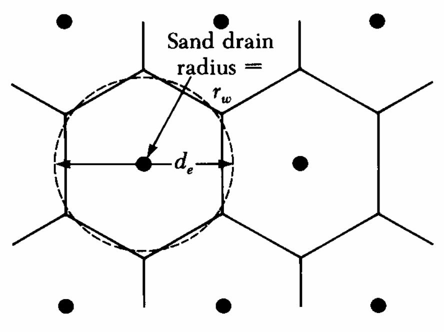



Fig 14.25 Schematic diagram of a sand drain




$d_e = 1.05d(triangular\ distribution)$

$d_e = 1.13d(square\ distribution)$

.

- Soil is smeared during installations of drains. => decrease permeability of soils.
- For radial drainage only with equal strain and instantaneously loading,

$$U_r = 1 - \exp(\frac{-8T_r}{m})$$

where

$$m = (\frac{n^2}{n^2 - S^2})\ln(\frac{n}{S}) - \frac{3}{4} + \frac{S^2}{4n^2} + \frac{k_h}{k_s}(\frac{n^2 - S^2}{n^2})\ln S\ ,\ n = \frac{d_e}{2r_w}\ ,\quad S = \frac{r_s}{r_w}$$

$k_h$ = coefficient of permeability of clay in the horizontal direction

$k_s$ = coefficient of permeability in the horizontal direction of the smeared zone

$$T_r = \frac{C_{vr}t}{{d_e}^2}$$

$C_{vr} \equiv$ coefficient of consolidation for radial drainage = $\dfrac{k_h}{\left[\dfrac{\Delta e}{\Delta p(1+e_0)}\gamma_w\right]}$

- Simplified way to consider the effects of smeared zone and well resistance

  Use the equation for non-smeared case with following considerations

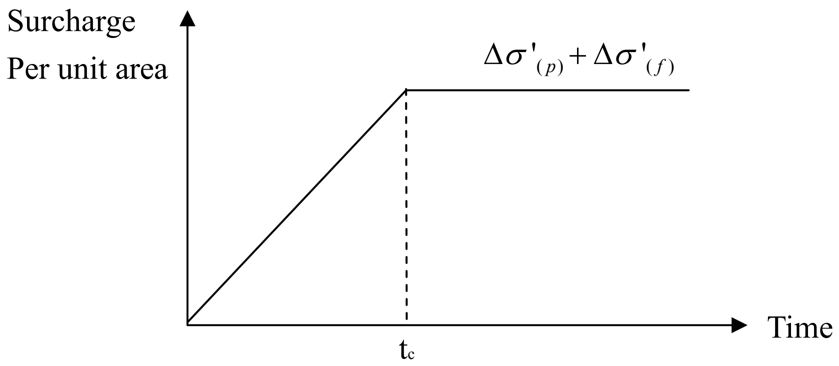
  i )

  ii)

- Average degree of consolidation due to vertical and radial drainage

$$U = 1 - (1 - U_r)(1 - U_v)$$

- Ramp load (no smear)




i) radial drainage (Olson)

$$U_r = \frac{T_r - \frac{1}{A}[1 - \exp(-AT_r)]}{T_{rc}} \quad (for\ T_r \le T_{rc})$$

and

$$U_r = 1 - \frac{1}{AT_{rc}}[\exp(AT_{rc}) - 1]\exp(-AT_r) \quad (for\ T_r \ge T_{rc})$$

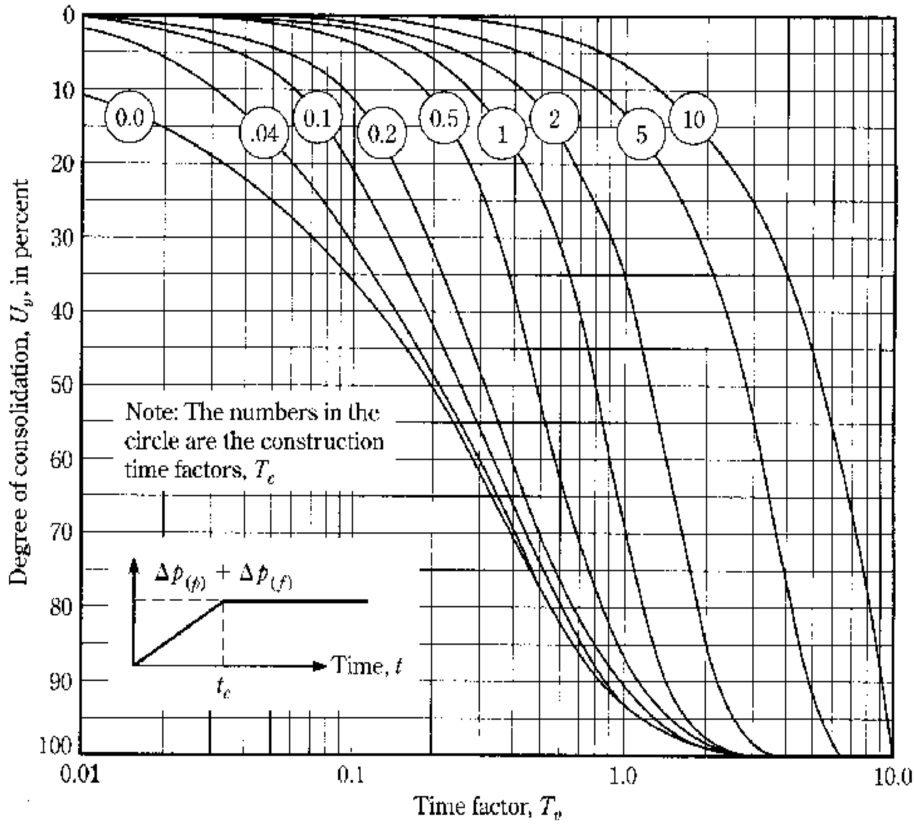
where

$$T_{rc} = \frac{C_{vr} t_c}{d_e^2}$$

$$A = \frac{2}{m}$$

$$m = \left( \frac{n^2}{n^2 - 1} \right) l_n(n) - \frac{3n^2 - 1}{4n^2} \Leftarrow \text{in Barron (without smear)}$$

ii) Vertical drainage (Olson)




▼ **FIGURE 12.31** Variation of $U_v$ with $T_v$ and $T_c$ (after Olson, 1977)

$$T_c = \frac{C_v t_c}{H^2}$$

where H = length of maximum vertical drainage path.

<u>Notes</u>

1)
2)

3)
4)

5)
6)

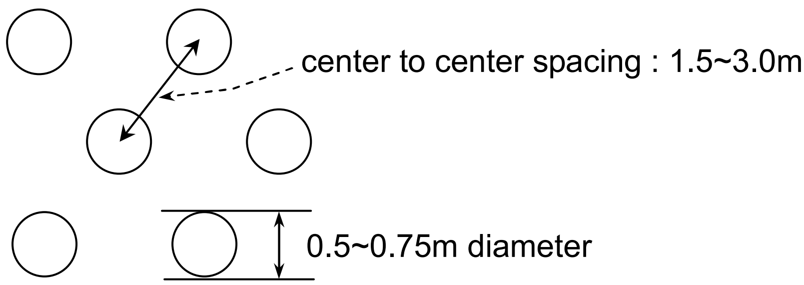
## 5) Stone Columns (and Sand Compaction Piles)

- Increase bearing capacity and stiffness of the soil mass by introducing vertical reinforcing materials on soft clay layers (can act as vertical drains in case of sand compaction piles(?))

- Procedure (stone columns)
  1) Water-jet a viboflot to make a hole.
  2) The hole is filled with imported gravel.
  3) The gravel is compacted as the vibrator is withdrawn.

- Procedure (sand compaction piles)
  ① Drive a hollow mandrel with its bottom closed.
  ② On partial withdrawal, sand is poured and compacted with opening bottom
  ③ Repeat until reaching sand compaction piles to the ground surface

- For stone columns



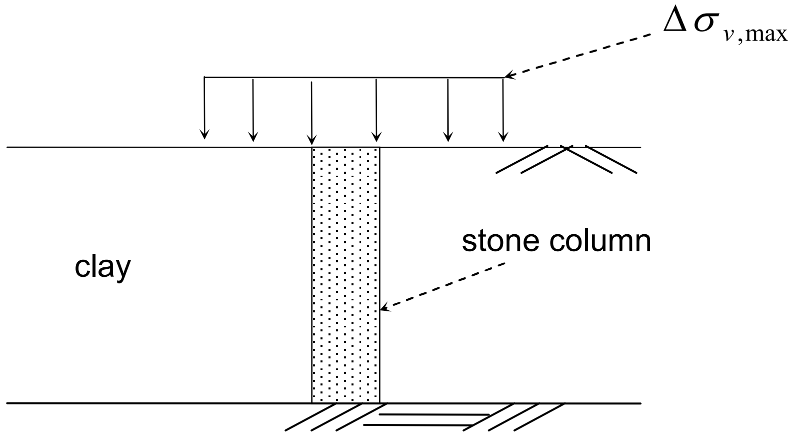

  - Gravel size for stone column: 6~40mm
  - Effective depth = 6~10 m (31m in maximum)
  - More effective to stable a large area with very soft clay soils ($s_u = 10 \sim 15\ kPa$).
  - Decrease in settlement

- Increase in bearing capacity

i) $\Delta\sigma_{v(\max)} = 26S_u$

Use F.S=3

$$\Delta\sigma_{\underset{allow}{v(\max)}} = \frac{26}{3}S_u$$




ii) Hughes et al. (1975)

$$q_{all} = \frac{\tan^2(45+\frac{\phi'}{2})}{FS}(4c_u + \sigma_r')$$

Where

FS = factor of safety (≈1.5 to 2.0)
$c_u$ = Undrained shear strength of the clay
$\sigma_r'$ = Effective radial stress as measured by a pressuremeter $(\approx 2c_u)$
$\phi'$ = friction angle of materials in stone column.

Advantages

1.

Limitations

1.
2.