Soft ground? No problem!

CE 152 Introduction to Civil Engineering

Prof Ashish Juneja

Department of Civil Engineering
Indian Institute of Technology Bombay
Email: ajuneja@iitb.ac.in
Tel # 2576 7327

Surface densification to increase soil strength (11th Century Chinese Building Standards)

Surface compaction using a giant tamper to compact loose soil (2006 AD)
What is soft ground?

- Any soil which is susceptible to failure or cause excessive settlement when superstructure is constructed over it

- Types of soils classified as soft:
  - Saturated clays and fine silts (alluvium), marine clays and fine silts
  - Loose sand (especially when under water table)
Significant development in the past 50 years with the introduction of composer piles, deep mixing and new injection materials
Physical modelling of ground modification...where are we now?

Vertical reinforcement subjected to combined loading
Excavation support systems
Ground improved using deep mixing

Deformations of grouted ground around tunnel
Vibro pile installation
The methods which are capable of improving certain characteristics of the soft ground for civil engineering construction are all considered as ground improvement techniques.

**Soft ground?.....available options**

You can:

- **Redesign the structure and its foundations for support by the poor soil**
- **Bypass the site - by moving to a new site e.g. highway route planning**
- **Remove the poor soil and replace it with a good one**
- **Treat the soil in-place and improve its properties**
Worker safety during geotechnical construction
Factors influencing the choice of improvement method:

1. Purpose of the improvement project
2. Time factor
3. Area and depth of soil to be treated
4. Type of soil and its initial properties
5. Material availability
6. Equipment and skills available
7. Environment factors
8. Local experience and preference
9. Feasibility of construction
10. Cost
Geotechnical engineering criteria used in evaluating a site:

1. Bearing capacity
2. Settlement
3. Seepage
4. Long term stability and durability
5. Liquefaction stability
6. Environmental problems
Methods of ground improvement

1. Over-excavation or replacement method
2. Densification and compaction (mechanical modification)
3. Hydraulic modification: “Free” excess water is extracted e.g. use of pumping, vertical drains and surcharge
4. Admixture stabilisation: Physically mixing of additives with surface soils or soils at depth

Additives include: natural soils, lime, cement or industrial by product and waste material
Methods of ground improvement

5. Reinforcement method:
   - Vertical reinforcement (e.g. piles, stone columns)
   - Horizontal reinforcement (e.g. soil nailing, geosynthetic products)

6. Electrical modification methods: Using electrical gradient to cause water movement

7. Thermal modification methods: Heating the ground can cause permanent change in the soil mineral structure; Freezing bonds individual particles together for temporary soil improvement
Instrumentations, monitoring and evaluating the level of improvement

How do you know that the ground improvement measures that you have done achieve what you want?

- install some instruments to verify it!!
Two categories of measuring instruments:
Tests conducted before and after ground improvement:-

(i) Density & water content measurement
(ii) Strength and stiffness e.g. SPT, CPT
(iii) Compressibility and Permeability

Tests to measure continuous performance:-

(i) Stress measurement; and
(ii) Deformation or strain measurement
Choice of instrument:

1. Property or parameter to be measured e.g. density, GWT, etc.

2. Operating principle e.g. standpipe, dipmeter, piezometer and PPT, amongst others

3. Reliability: range -vs- sensitivity; consistency and range of soils for it to be suitable for testing

4. Data logging: equipment, logging method and frequency

5. Data interpretation – what these data mean?
Overexcavation and replacement

If good bearing stratum exists close to the footing level, then excavation should be taken to the top of the bearing stratum.
Principle of overexcavation and replacement

Excavate poor or inadequate bearing material and either:

(a) Stabilise, dry or wet and recompress the excavated material
(b) Replace it with stiffer and stronger material

Replaced material is usually sand, gravel or sand-gravel mixes
Compaction is usually done in lifts (typically 150mm)
Settlement is reduced and bearing capacity is increased
Failure modes

Plane strain shear failure

\[ q_{ult} = q_b + \frac{pP_h \tan \phi + pHc_u - Wt}{A} \]

Plane strain cavity expansion

\[ q_{ult} = (\gamma D + 2c_u) \tan^2 \left( 45 + \frac{\phi}{2} \right) \]
Choice of $\phi$ values: plane strain or triaxial value?

$\phi_{ps} = \phi_{tx}$ for $\phi_{tx} \leq 34^\circ$

$\phi_{ps} = 1.5\phi_{tx} - 17^\circ$ for $\phi_{tx} > 34^\circ$

Values of $\phi$ from direct shear tests are usually about 1 to 2° greater than $\phi_{tx}$ for the same range of confining stresses.
Settlement

As per IS 8009 (Part I)-1976 (Amendment 1 and 2, 1981, 1990), elastic or immediate settlement at the corner of flexible footing is derived from the following equation,

\[
\Delta H = qB \left[ \frac{1 - v^2}{E} \right] \left[ I_1 + \frac{1 - 2v}{1 - v} I_2 \right] I_F
\]
Limitation of overexcavation / replacement

- Slope protection during excavation
- Adjacent structures
- Pumping required for high ground water table conditions
- Replacement material not readily available
- Limited compaction achieved in confined areas (use vibratory plates compactor or high frequency rammer)
Precompression / preloading with vertical drains

It is a method of pre-empting potentially damaging settlements on soft soil increases the bearing capacity & reduces the compressibility of weak ground.

Precompression/preloading refers to the process of compressing foundation soils under applied vertical stress prior to placement of the final permanent construction load.

Vertical drains accelerate settlements but do not reduce final movement.

Preloading is only cost effective when large area is to be improved.
Methods of producing surcharge:

(1) Earth fill or embankment (most common)
(2) Water filled tanks
(3) Vacuum preloading: by pumping from beneath an impervious membrane placed over the ground surface
(4) Ground water lowering: there is an increase in effective stress which is equal to the unit weight of water times the drawdown height
(5) Consolidation by electro-osmosis
Main applications:

• Foundations for:
  Embankments
  Liquid storage tanks
  Buildings (less common)

Where soil properties and/or stress conditions vary with depth, it may be necessary to analyse the profile as a series of sub-layers.
Vertical drains and preloading

- Vertical drains are effective in inorganic clays and silts (exhibit primary consolidation); and if the deposits contain thin horizontal sand or silt lenses ($C_h \gg C_v$)

- Secondary consolidation settlement which is essentially a creep phenomenon is not speeded up by vertical drains
**Vertical Drains**

Broadly classified into two categories:

- Sand drains
- Geosynthetic drains or prefabricated vertical (PV) drains
Sand Drains

- Typically 200 to 500mm in dia
- Formed by infilling sand into a hole in the ground
- Hole formed by driving, jetting or augering
- Typical spacing: 1.5 to 6.0m
- Large diameter sand drains tend to behave as “weak piles” in soft soils. This may have the effect of stress concentration on the drains
Prefabricated Vertical (PV) drains

- Band shape drains consists of a central core wrapped around by a filter layer
- $k_{\text{filter}} > k_{\text{soil}}$
- The filter should retain fine soil particles
- PV should be strong enough to resist installation stresses
- Equivalent diameter
  $$d_e = \frac{2(B + t)}{\pi}$$
Advantages of PV drain

1. Creates less disturbance to host soil
2. Rapid installation
3. Installation equipment is lighter
4. Eliminates cost of sand backfill and water
5. Does not require disposal of soil waste
6. Continuity of drain is maintained

Limitation of PV drain

1. Ground settlement can cause the PV drain to buckle; hence reduce drain efficiency
2. Cannot bear vertical loads
Other design considerations for PV drains

Effect of smear
- Permeability in the narrow zone of remoulded soil is reduced; slows down the radial consolidation

Effect of wall resistance
- Deterioration of filter can significantly reduce $d_e$
- Clogging/siltation of filter drain by fine particles can decrease the area available for flow
- Folding of drain due to soil settlement can decrease the discharge capacity
Relation between surcharge and degree of consolidation

\[ \Delta P_p = \text{Structural load} \]
\[ \Delta P_f = \text{Surcharge load} \]

\[ S_p = \frac{C_c}{1 + e_o} H \log \left[ \frac{P_o + \Delta P_p}{P_o} \right] \]

\[ U_{avg} = \frac{S_p}{S_{p+f}} \]

\[ S_p = \frac{C_c}{1 + e_o} H \log \left[ \frac{P_o + \Delta P_p + \Delta P_f}{P_o} \right] \]
\( U_{\text{avg}} \) and time

Carillo’s average degree of consolidation

\[
U_{\text{avg}} = 1 - (1 - U_v)(1 - U_h)
\]

Average degree of consolidation for vertical drainage

\[
T_v = \frac{\pi}{4} U_v^2 \quad \text{for } U_v \leq 60\%
\]
\[
T_v = 1.781 - 0.933 \log(100 - U_v) \quad \text{for } U_v > 60\%
\]

where

\[
T_v = \frac{C_v t}{H^2}
\]

Average degree of consolidation for radial drainage

\[
U_h = 1 - \exp\left(-\frac{8T_h}{m}\right)
\]

where

\[
m = \left(\frac{n^2}{n^2 - 1}\right) \ln(n) - \frac{3n^2 - 1}{4n^2}
\]

\[
T_h = \frac{C_h t}{D^2}
\]

where

n (drain spacing ratio) = D/d_e
Observational methods of monitoring consolidation

Hyperbolic method

Asaoka’s method
**Hyperbolic method** - Settlement-time plot in terms of $U_{\text{avg}}$ (avg degree of consolidation) and $T_v$ (time factor)

3 regions:

Region 1: Concave downwards from origin.

Region 2: Linear portion between $T_v = 0.25$ and $T_v = 0.848$. These points correspond to $U_{60}$ and $U_{90}$.

Region 3: Second linear portion for $T_v > 1.0$ which approaches the 45 degree line.
Using the inverse slope approach, the total primary consolidation $\delta_{ult}$ is estimated as $\alpha / S_i$. 

\[
S_{60} = \frac{1}{0.6} \left[ \frac{S_i}{\alpha} \right]
\]

\[
S_{90} = \frac{1}{0.9} \left[ \frac{S_i}{\alpha} \right]
\]
Procedure for using the hyperbolic plot method

**Step 1** Plot field settlement data as $t/\delta$ vs $t$; where $t =$ time and $\delta =$ settlement from the start of constant load application

**Step 2** Identify first linear segment and measure its slope $S_i$ (corresponding to data between $\delta_{60}$ and $\delta_{90}$)

**Step 3** From $n$, $C_h/C_v$ and $H/D$, determine the theoretical slope $\alpha$ from Fig. 3

**Step 4** Calculate the total primary consolidation settlement from theoretical slope $\alpha$ and $S_i$, that is $\delta_{ult} = \alpha/S_i$

**Step 5** Calculate the slope of lines
Step 6  Construct these lines and locate \( \delta_{60} \) and \( \delta_{90} \) points.

The total primary settlement is estimated from

\[
\delta_{\text{ult}} = \alpha \frac{S_i}{S_i} \quad \text{or} \quad \delta_{60} = \frac{\delta_{60}}{0.6} \quad \text{or} \quad \delta_{90} = \frac{\delta_{90}}{0.9}
\]

All 3 values should be close to one another
**Asaoka’s method** - Readings taken at constant time interval $\Delta t$ or equivalent values interpolated from the time-settlement curve

**Step 1** Plot Settlement $\delta_n$ versus preceding settlement $\delta_{n-1}$

**Step 2** Draw a line through the points plotted and extrapolate to intersect with the $45^0$ line (note: irregular early points are ignored in the standard analysis)
High energy impact is a type of deep compaction technique in which a heavy tamper is repeatedly raised and dropped onto the ground surface to compact the underlying soil deposits to typical depths of improvement of about 3 to 10m.

**High Energy Impact**

The heavy weight/tamper is usually between 10 to 20 tonnes.

Drop height is between 10 to 25m.

With special lifting equipment and a heavy tamper, the ground can be affected to depths as great as 30m.
Variant of this technique are:

1. Dynamic compaction (DC): The stress waves generated by the impact travel to considerable depths to *rearrange* the particles into a dense configuration.

Dynamic compaction carried out in the trial area of Changi East Reclamation Project

(mass 25 tons, drop height 25 m)
2. Dynamic replacement (DR): Highly compressible soil is *replaced* with granular columns formed by systematic punching-in charges of imported granular material. These granular columns serve as foundation and for drainage.
3. Dynamic replacement and mixing (DRM): The granular column formed by DR is further subjected to very high impact resulting in rupture of the surrounding soft peaty soil and direct mixing of the granular material into the peaty soil.

Mechanism of DR and DRM
Applications of high energy impact:

- Roads, highways, railroads, airport runways, taxiways, aprons
- Storage areas, Oil tanks
- Housing development
- Industrial plants
- Ports
- Reclaimed land
Equipment

- Tampers raised and dropped with a conventional heavy crawler crane using a single cable with a free spool
- Tampers constructed of steel or steel shells filled with sand or concrete (area of tamper ~ contact pressure 40 to 75kPa)
- Tampers are square, circular or octagonal
- Impact points are spaced to prevent the creation of dense zone of material at intermediate depth
- Spacing between primary impact points ~ maximum depth to be improved
Ground vibrations produced by high energy impact may be undesirable in built-up areas (this can be reduced by having trenches around the area being compacted; as the trenches would stop the vibrations from transmitted further).
 Deposits suitable for improvement

Coarse grained pervious deposits (less than 35% silt)

- Immediate response is observed; energy causes the particles to reorient themselves into a denser packing

- Permeability of these deposits is high that, the pore pressure generated during tamping dissipate within a short time
Semi-pervious deposits (less than 25% clay and PI< 8)

- The energy applied is effective in partially saturated soils (MC less than the plastic limit)
- In saturated or near saturated semi-pervious deposits, the induced excess pore pressures may require days or weeks to dissipate. Therefore, rest period is required between two phases/passes
Saturated impervious deposits

- These soils are nearly impervious to water and are generally NOT suitable for dynamic compaction

- The applied energy produces distortion of the soil mass. Hence, no significant densification occurs and the ground surface around the crater heaves
Summary of particle size suitable for DC

Lukas (1986)
Depth of improvement

where

\[ D = \alpha \sqrt{WH} \]

\[ D = \text{depth of improvement (m)} \]
\[ W = \text{weight of the pounder (tonnes)} \]
\[ H = \text{drop height (m)} \]
\[ \alpha = \text{empirical coefficient} \]

For granular soils, \( \alpha \) is typically taken to be 0.5
Typical range of design parameters

Pounder: Steel or concrete blocks

Weight \( W = 10 \) to 20 tonnes

Dimension: 1.5 to 2m square

(Circular up to 5m dia)

Drop height: \( H = 10 \) to 20m

Total energy \( I = 100 \) to 400 tm/m\(^2\)

Grid/print spacing \( S = 3 \) to 8m (square grid)

No of blows per pass \( 5 \) to 15 (Rest period is to be given in clayey and silty soils)

No of passes \( 2 \) to 8
Applied energy and crater depth
Planning the field procedures

• Test Program
• Area to densify
• Position of water table
• Print spacing
• Drops per print
• Number of passes
• Ground levelling and surface compaction
• Pore water pressure monitoring
Monitoring the improvement

(a) **Crater depth measurement**
Crater volume calculated from diameter and depth of crater; the measurement used in identifying local weak spots

(b) **Average ground settlement**
Following a complete pass, the ground surface is levelled. The average ground settlement or enforced settlement is indicative of the improvement

(c) **Field / in-situ tests**
Commonly used field tests: SPT, CPT, PMT
The quick landslide in Rissa, Norway 1978
Relation between liquidity index and shear strength of moulded clays