Soft ground? No problem!

CE 152 Introduction to Civil Engineering

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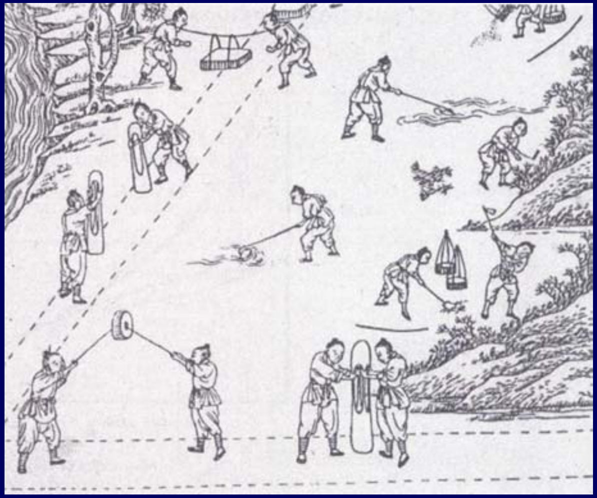


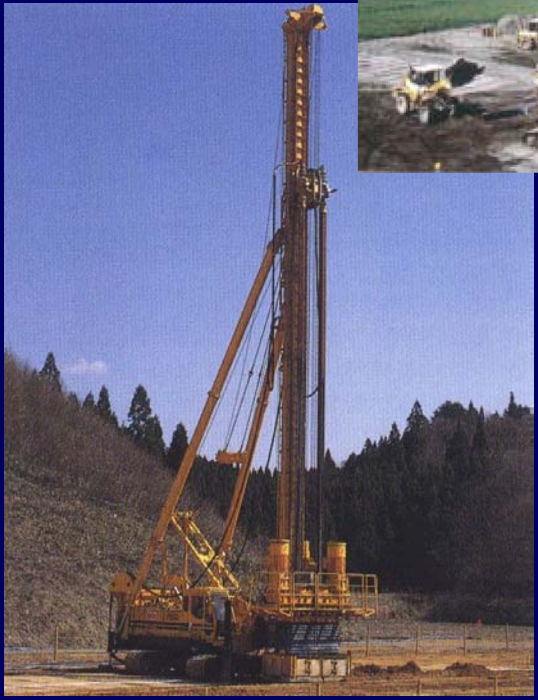
Surface densification to increase soil strength (11th Century Chinese Building Standards)

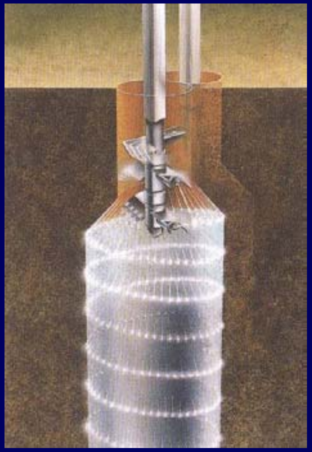
Surface compaction using a giant tamper to compact loose soil (2006 AD)

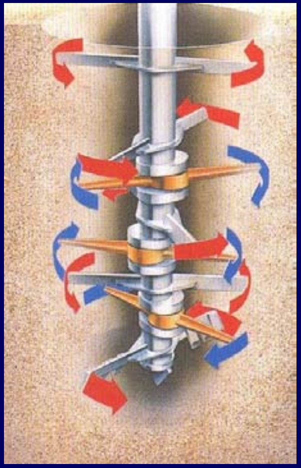
What is soft ground?

- 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)

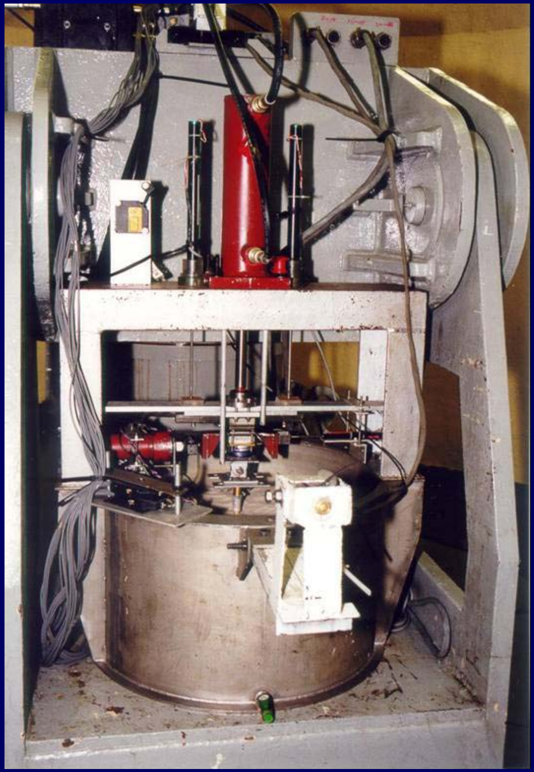
Significant development in the past 50 years with the introduction of composer piles, deep mixing and new injection materials

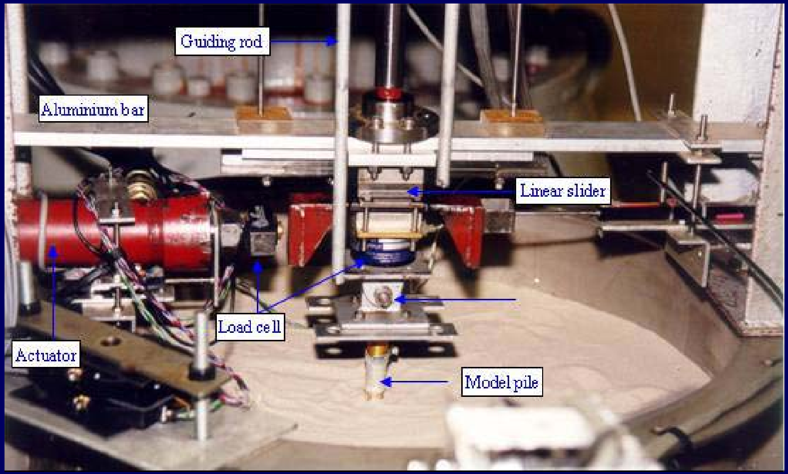


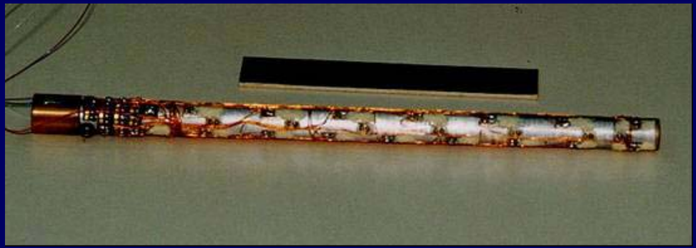


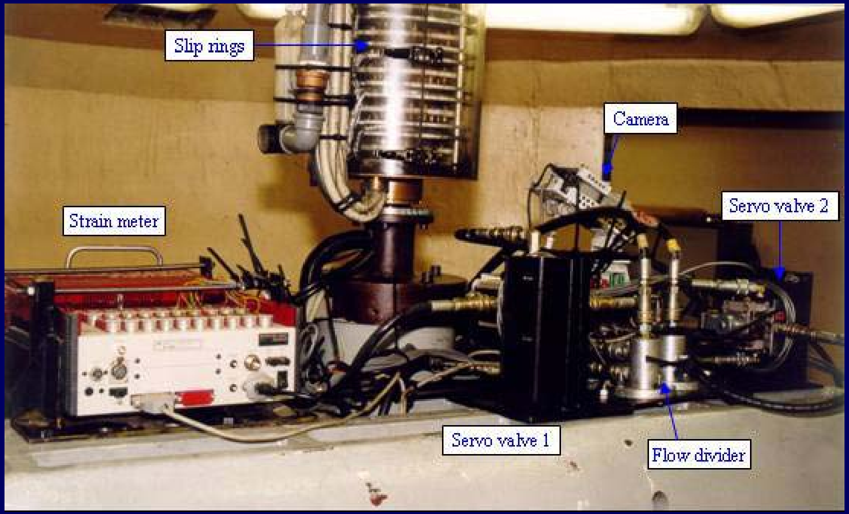


Physical modelling of ground modification…where are we now?



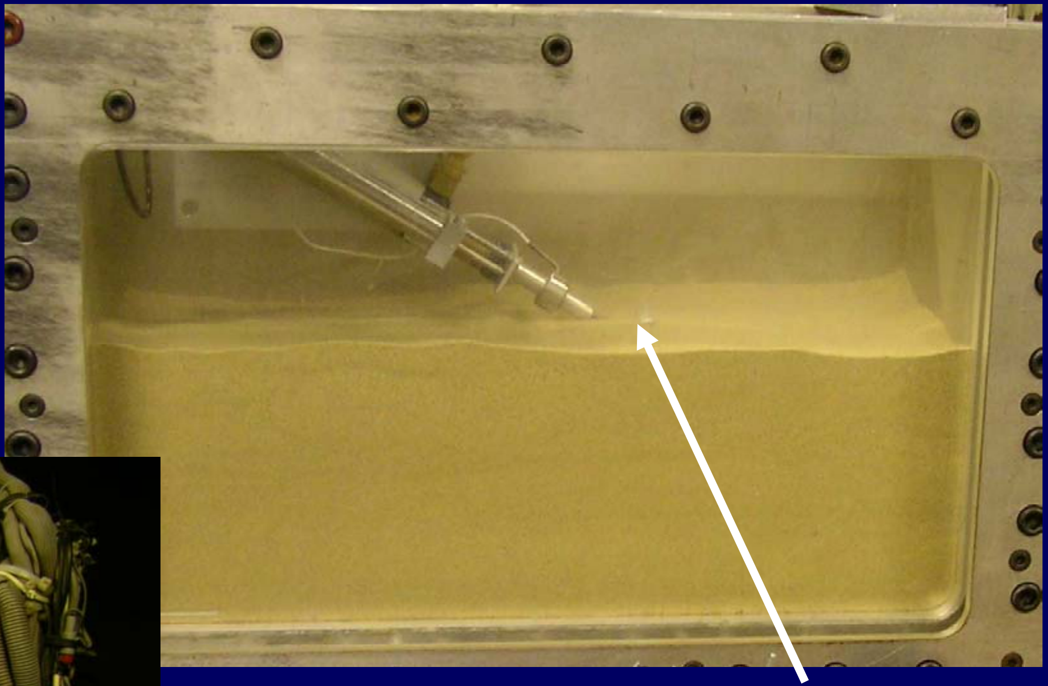


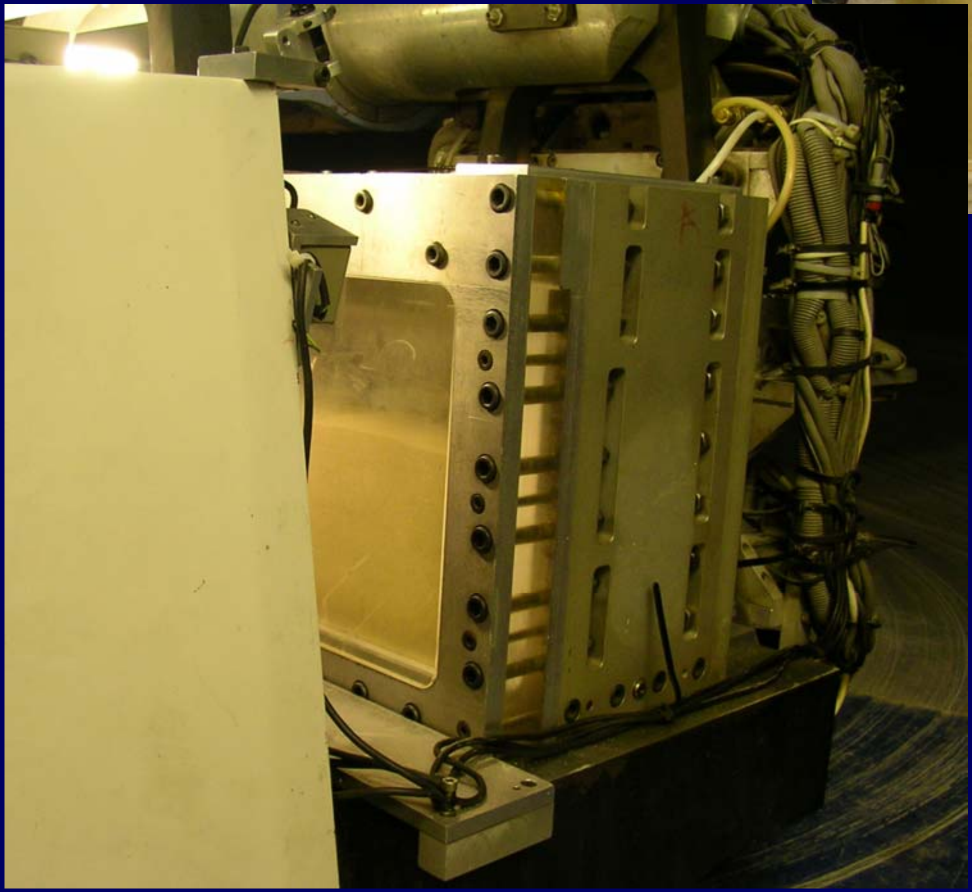


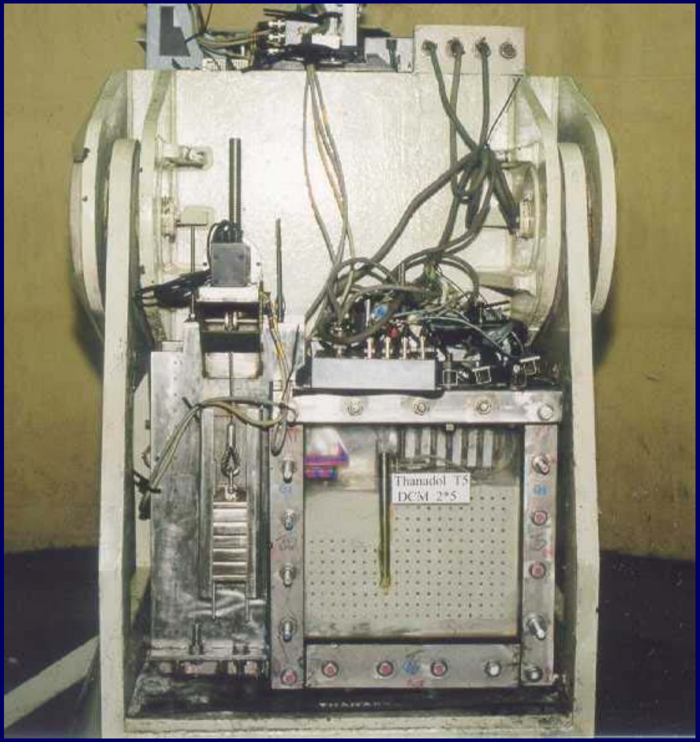


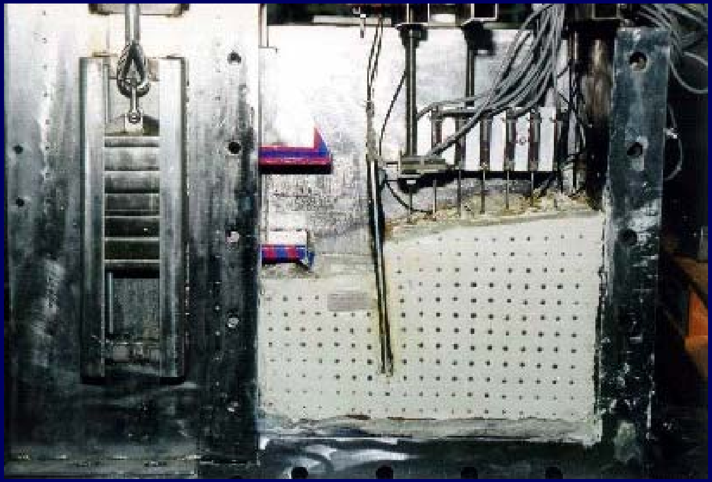
Vertical reinforcement subjected to combined loading

Excavation support systems



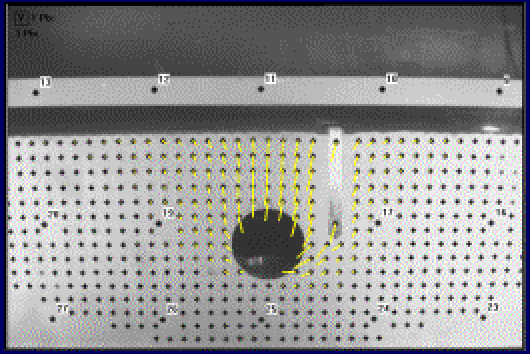


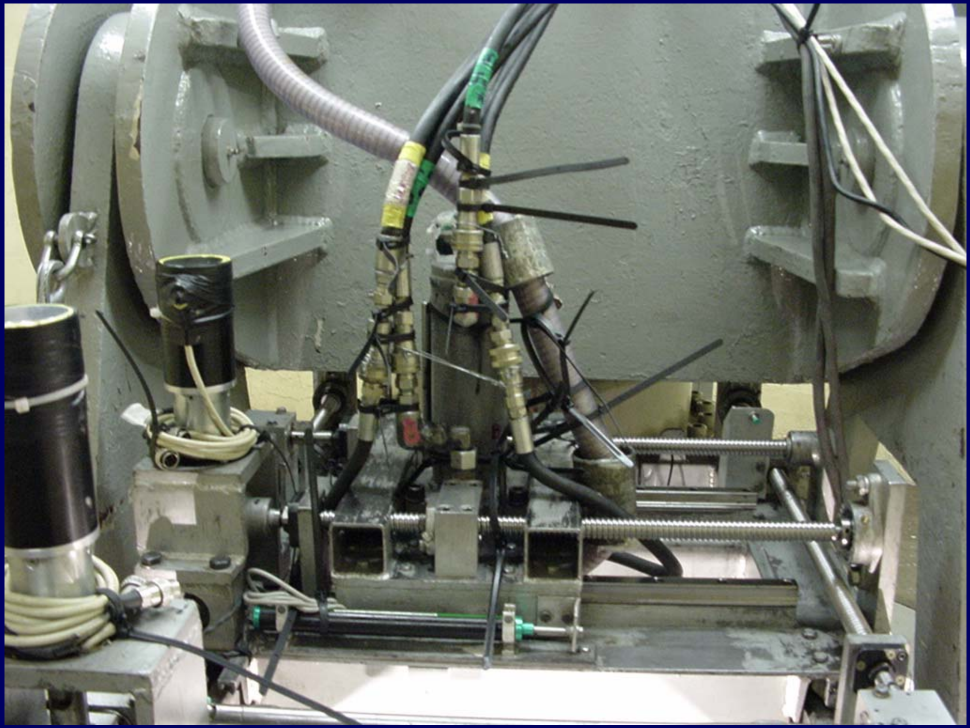


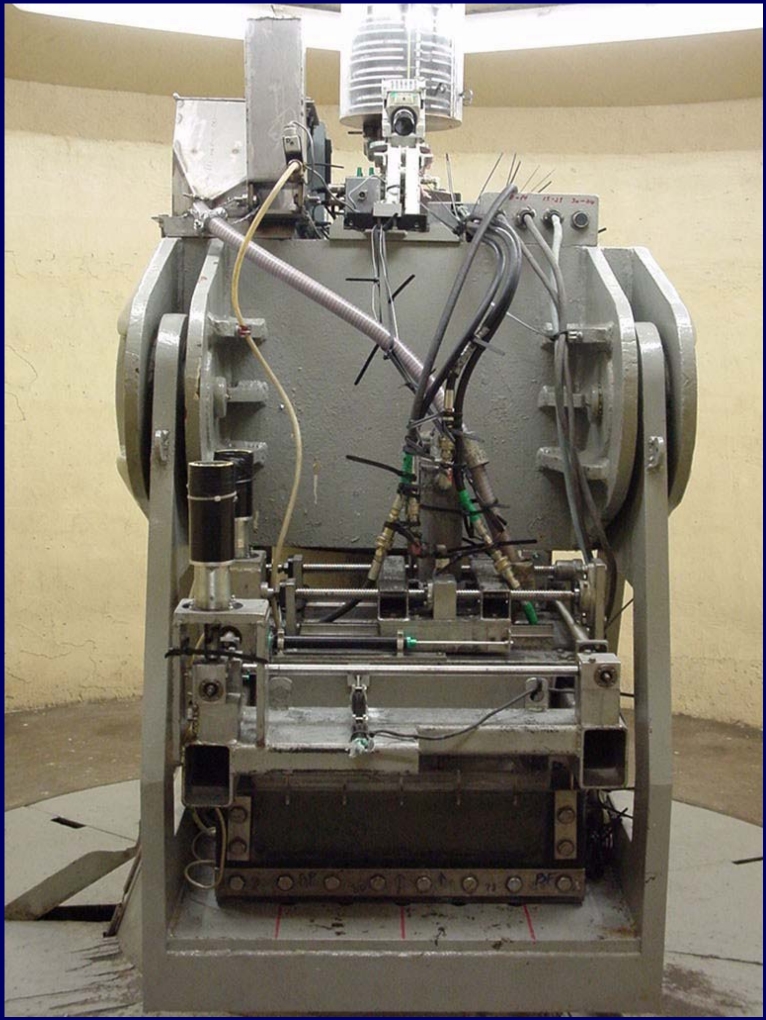


Ground improved using deep mixing

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

Kansai International Airport

Leaning Tower of Pisa

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

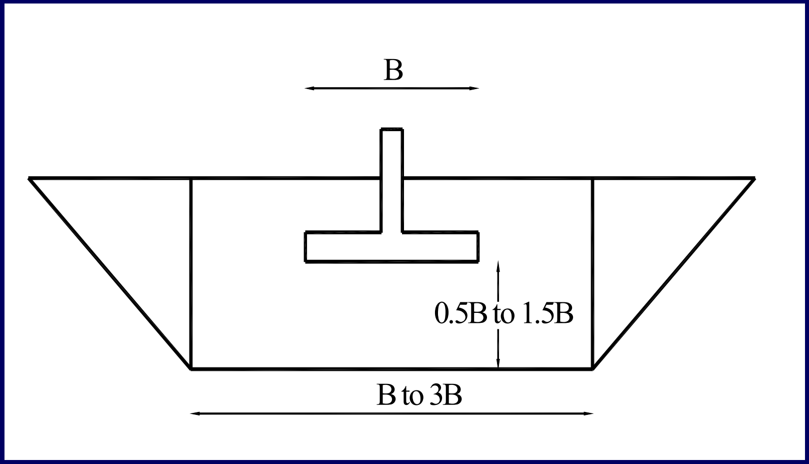
(ii) Deformation or strain measurement

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?

Earth pressure measurement

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 recompact the excavated material

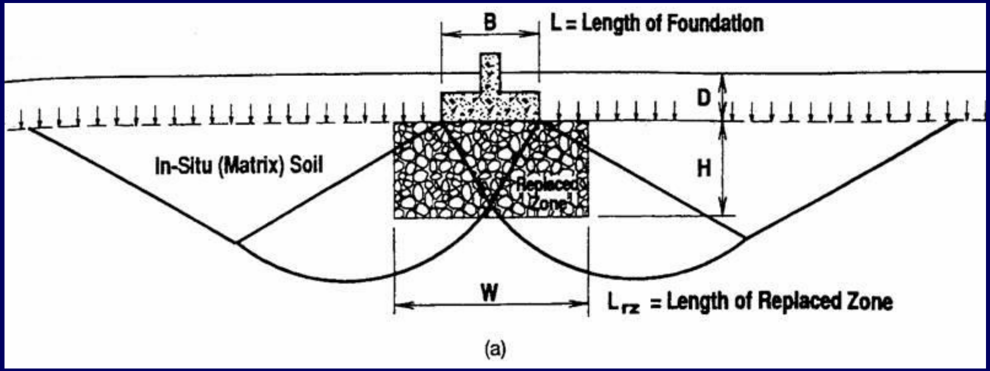
(b) Replace it with stiffer and stronger material

Replaced material is usually sand, gravel or sand-gravel mixes

Compaction is usually done in lifts (typically 150mm)

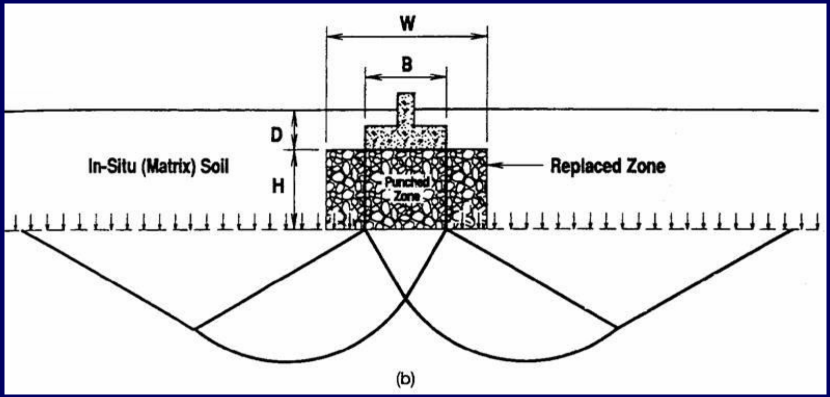
Settlement is reduced and bearing capacity is increased

Failure modes



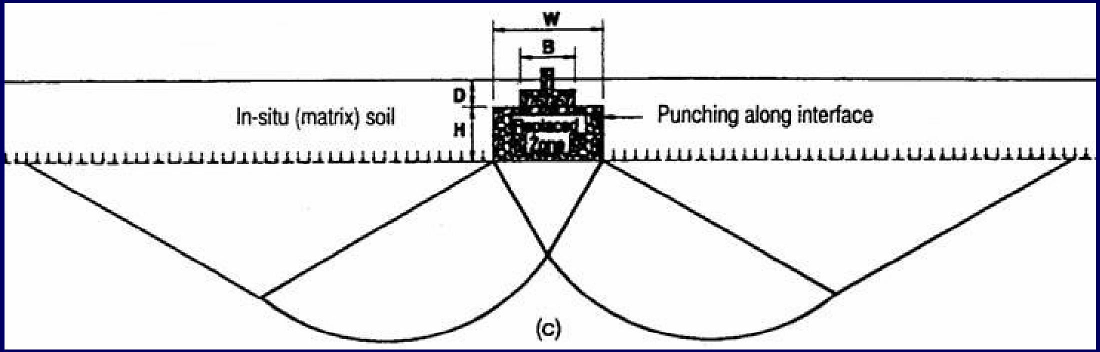
Plane strain shear failure

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



Plane strain cavity expansion

$$q_{ult} = (\gamma D + 2c_u)\tan^2\left(45 + \frac{\phi}{2}\right)$$



Choice of ϕ values: plane strain or triaxial value?

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

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

Values of ϕ from direct shear tests are usually about 1 to 2^{o} greater than ϕ_{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,

$$\Delta H = qB\left[\frac{1-\nu^2}{E}\right]\left[I_1 + \frac{1-2\nu}{1-\nu} I_2\right] I_F$$

Calculation of elastic settlement (IS 8009 (Part 1)-1976)

(Common for square, rectangular and circular footing)

Type of footing: 1 (Note: If square or rectangular footing type 1 or else type 2 for circular footing)

Required data

Foundation parameters

1. Net safe bearing capacity (kg/cm²): 1.8
2. Width B of footing (m): 1.2
3. Length L of footing (m): 2
4. Depth of footing (m): 1.2

Soil parameters

1. Best description of soil (choose from assigned numbe: 2

Soil type	Assigned number
sand	1
sand (saturated)	2
sand (dense or desiccated)	3
gravelly sand and gravel	4
clayey sand	5
silty sand	6
pure clays	7

You have chosen sand (saturated) deposits

2. Thickness H of soil layer (m): 10
   (usually taken 5 time the width of footing or up to hard stratum)
3. Poisson's ratio ν: 0.3
   (usually between 0.25 to 0.35 for all soils; and between 0.4 to 0.5 for saturated clays)
4. Average observed N value: 19
5. UCS (kg/cm²): only for pure clays in lieu of N-value
   leave blank if no pure clays
6. Plasticity limit (%): only for pure clays in lieu of N value
   leave blank if no pure clays
7. Estimated Es in kg/cm2 for sand (saturated) deposits is 85
   Do you want to use the above Es value? OR ELSE input a user defined Es value in kg/cm2
   Leave blank if estimated value is to be used

Results

1. Steinbrenner's influence factors

I_1: 0.585 (corner) 0.647 (centre)

I_2: 0.031 (corner) 0.016 (centre)

2. Fox(1948) depth correction factor

I_F: 0.69

3. Settlement of footing (mm)

3.1 Flexible footing

Corner: 9.66

Centre: 21.03

3.2 Rigid footing (the entire footing settles uniformly)

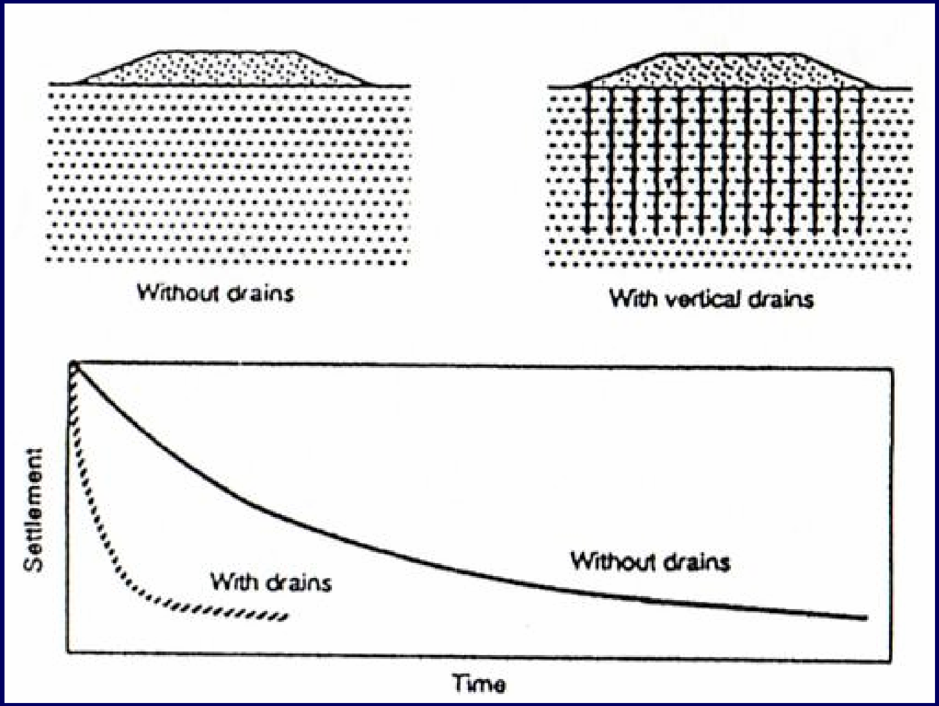
corner = centre = 16.82

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)

It is a method of pre-empting potentially damaging settlements on soft soil

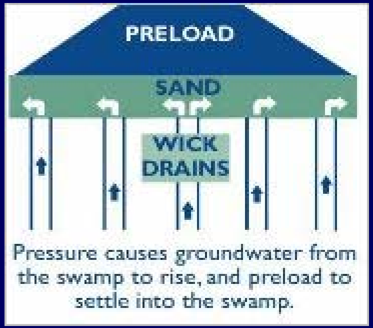
increases the bearing capacity & reduces the compressibility of weak ground



Vertical drains accelerate settlements but do not reduce final movement

Precompression / preloading with vertical drains

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



Preloading is only cost effective when large area is to be improved

Methods of producing surcharge:

(1) Earth fill or embankment (most common)

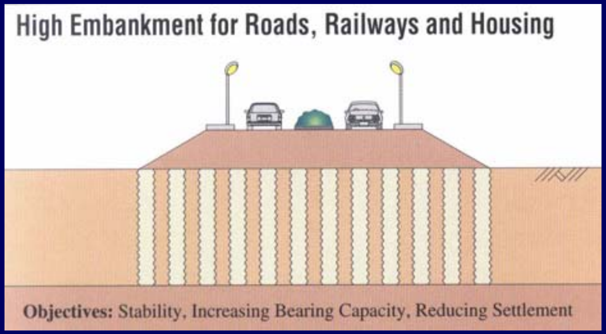
(2) Water filled tanks

(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

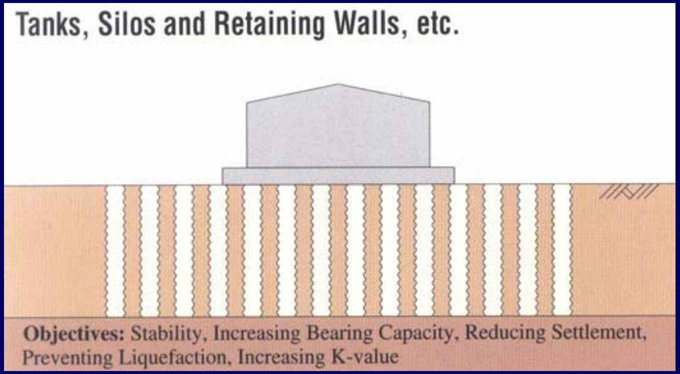
(5) Consolidation by electro-osmosis

Main applications:



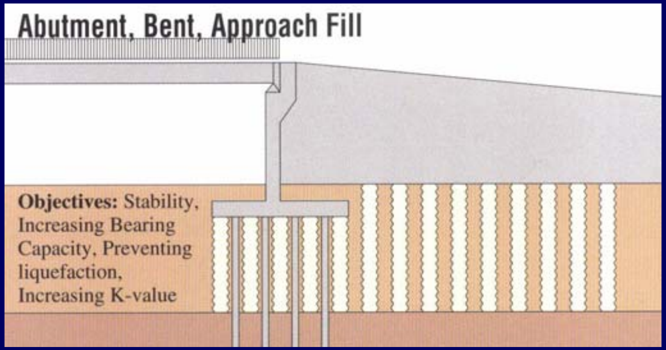
•Foundations for:

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 ($C_h >> C_v$)
- Secondary consolidation settlement which is essentially a creep phenomenon is not speeded up by vertical drains

Vertical Drains

Broadly classified into two categories:

- o Sand drains
- o 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
- $k_{filter} > k_{soil}$
- The filer 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

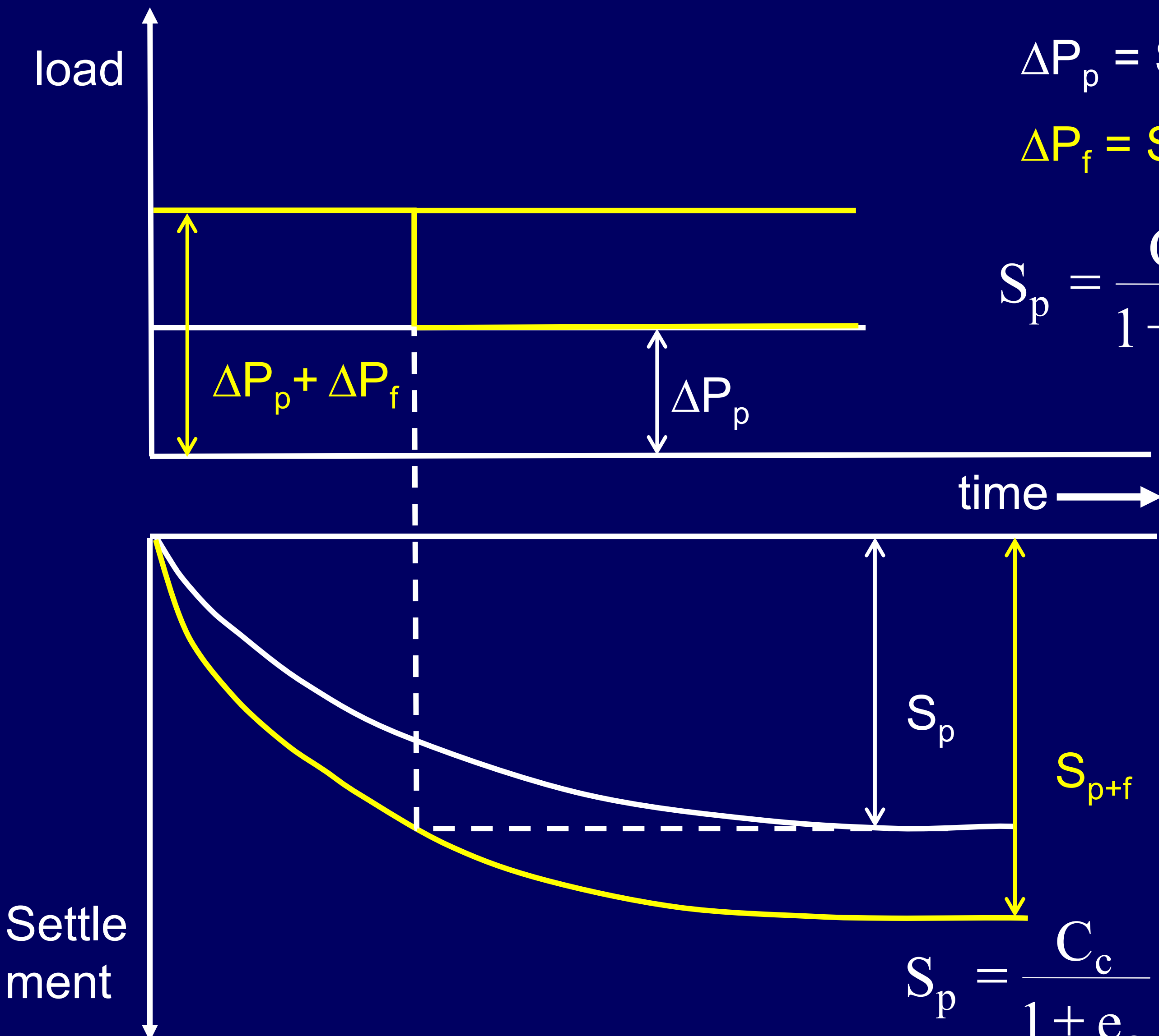
Effect of wall resistance

- 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

ΔP_p = Structural load

ΔP_f = 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_{avg} and time

Carillo's average degree of consolidation

$$U_{avg} = 1 - (1 - U_v)(1 - U_h)$$

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

where

$$T_h = \frac{C_h t}{D^2}$$

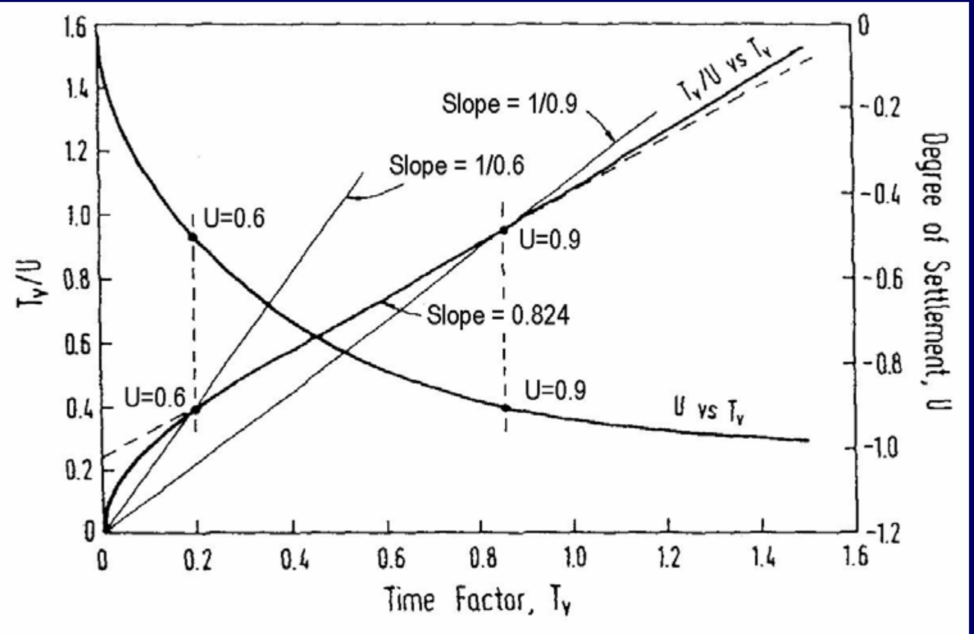
n (drain spacing ratio) = D/d_e

Observational methods of monitoring consolidation

Hyperbolic method

Asaoka's method

Hyperbolic method - Settlement-time plot in terms of U_{avg} (avg degree of consolidation) and T_v (time factor)



Hyperbolic plot of Tv/Uavg -vs- Tv for Terzaghi Theory

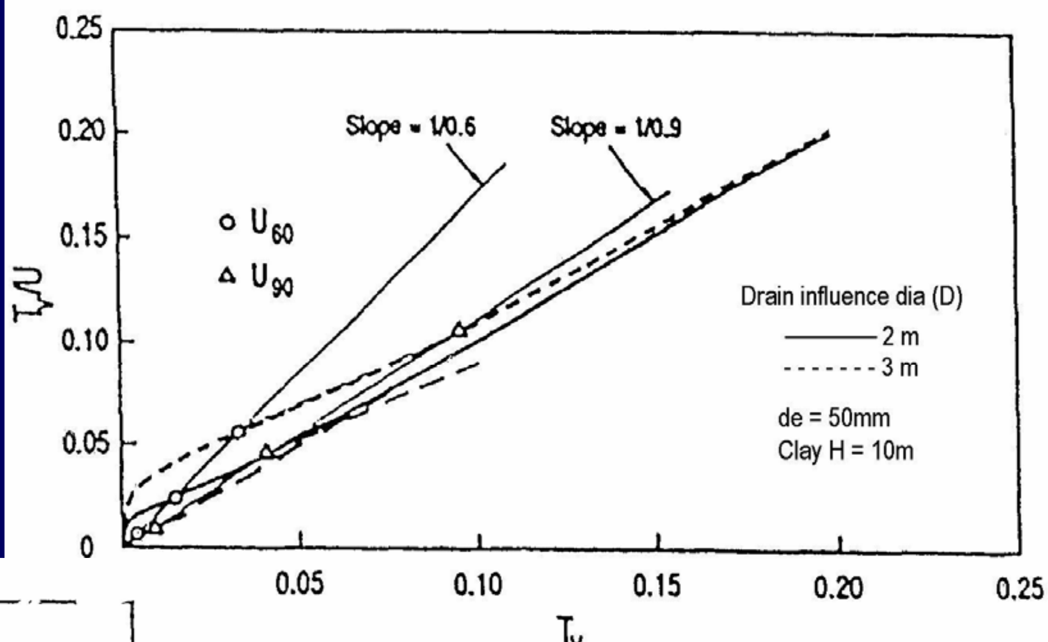
3 regions:

Region 1: Concave downwards from origin.

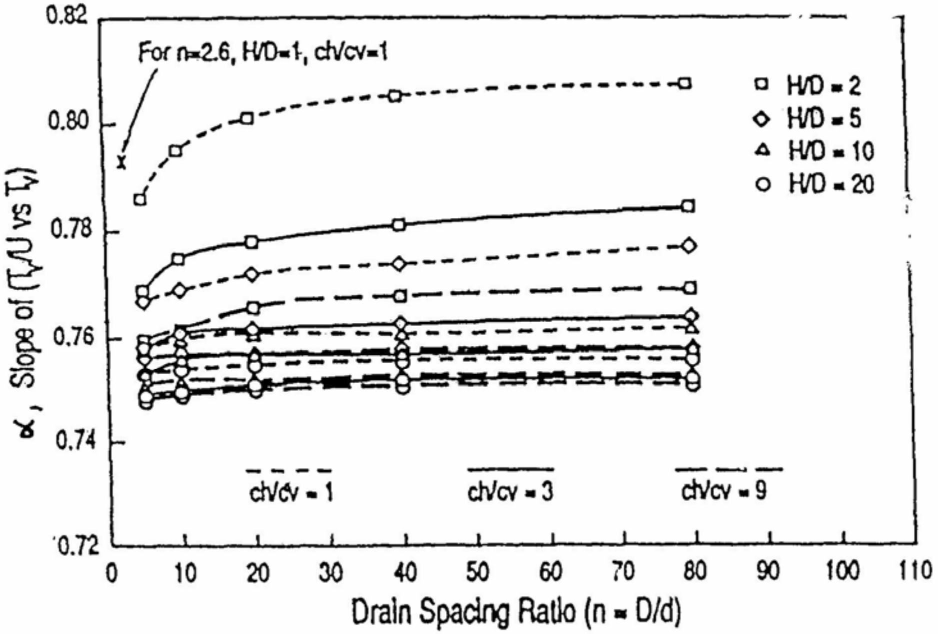
Region 2: Linear portion between T_v = 0.25 and T_v = 0.848. These points correspond to U_{60} and U_{90}.

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 δ_{ult}, is estimated as α/S_i.



Hyperbolic plot for combined horizontal and radial consolidation using Terzaghi's and Barron's theory



Relationship of slope α of initial linear portion (between U60 and U90) segments of theoretical hyperbolic plots with parameters n, H/D and Ch/Cv

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

$$S_{90} = \frac{1}{0.9}\left[S_i / \alpha\right]$$

Procedure for using the hyperbolic plot method

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

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

Step 3 From n, C_h/C_v and H/D, determine the theoretical slope α from Fig. 3

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

Step 5 Calculate the slope of lines

$$S_{60} = \frac{1}{0.6}\left[{S_i}/{\alpha}\right] \qquad S_{90} = \frac{1}{0.9}\left[{S_i}/{\alpha}\right]$$

<u>Step 6</u> Construct these lines and locate δ_{60} and δ_{90} points.

The total primary settlement is estimated from

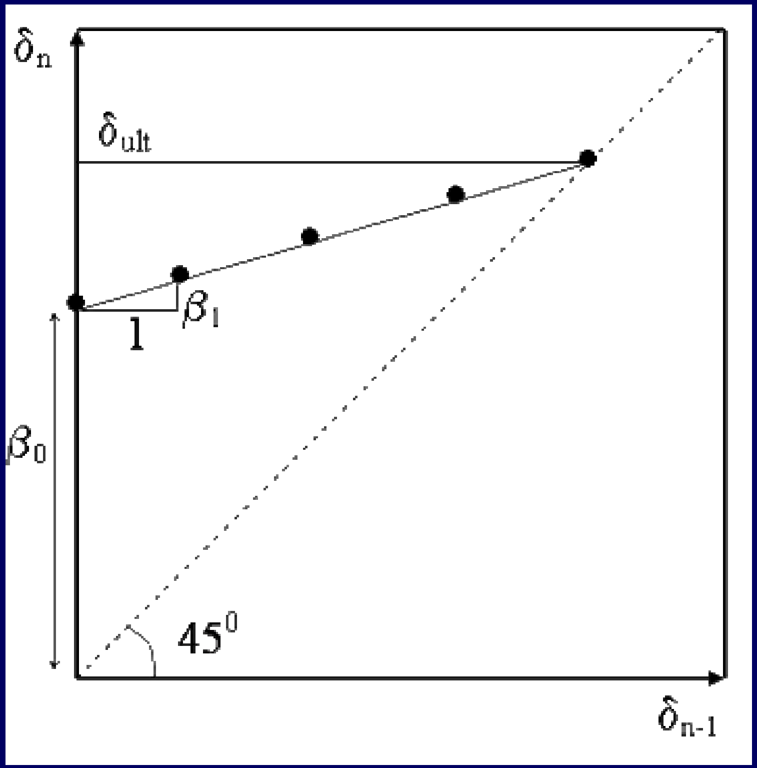
$$\delta_{ult} = \frac{\alpha}{S_i} \quad \text{or} = \frac{\delta_{60}}{0.6} \quad \text{or} = \frac{\delta_{90}}{0.9}$$

All 3 values should be close to one another

Asaoka's method - Readings taken at constant time interval Δt or equivalent values interpolated from the time-settlement curve

Step1 Plot Settlement δ_n versus preceding settlement δ_{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

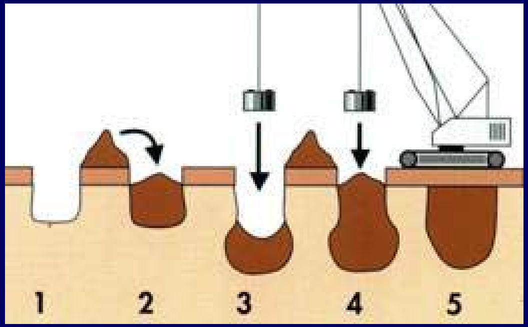
Variant of this technique are:

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)

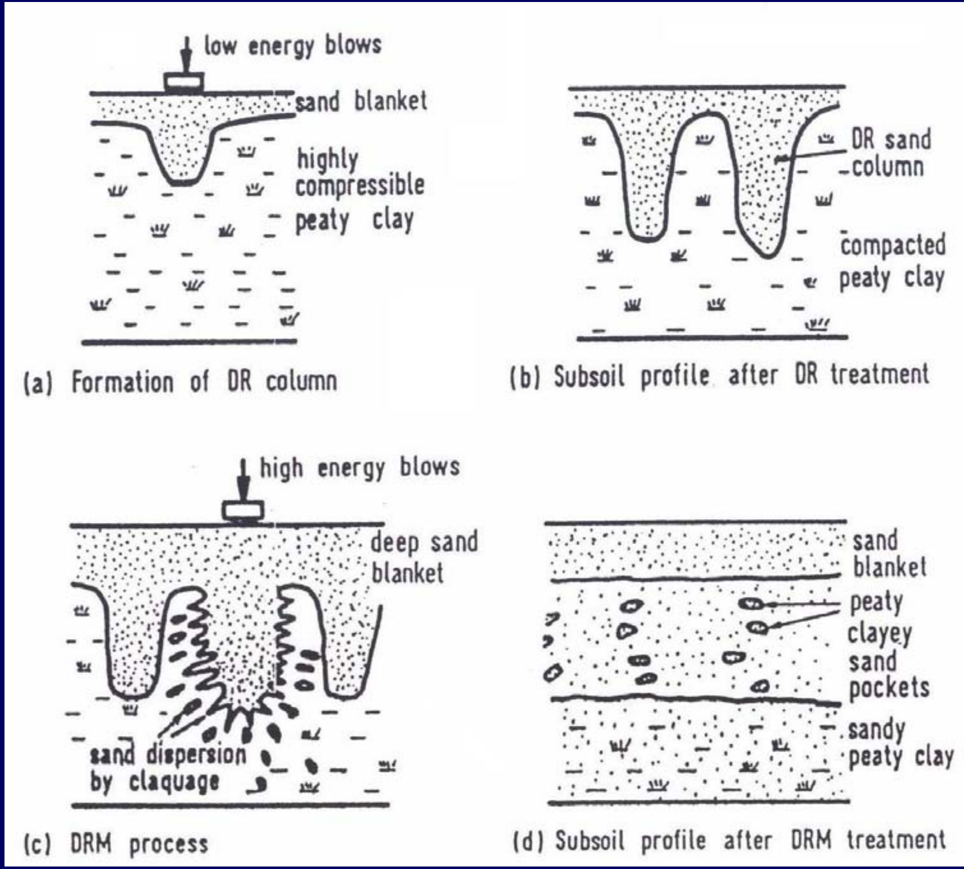
2. Dynamic replacement (DR): Highly compressible soil is *replaced* with granular columns formed by systematic punching-in charges of imported granular material. These granular columns serve as foundation and for drainage.



Dynamic replacement

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)

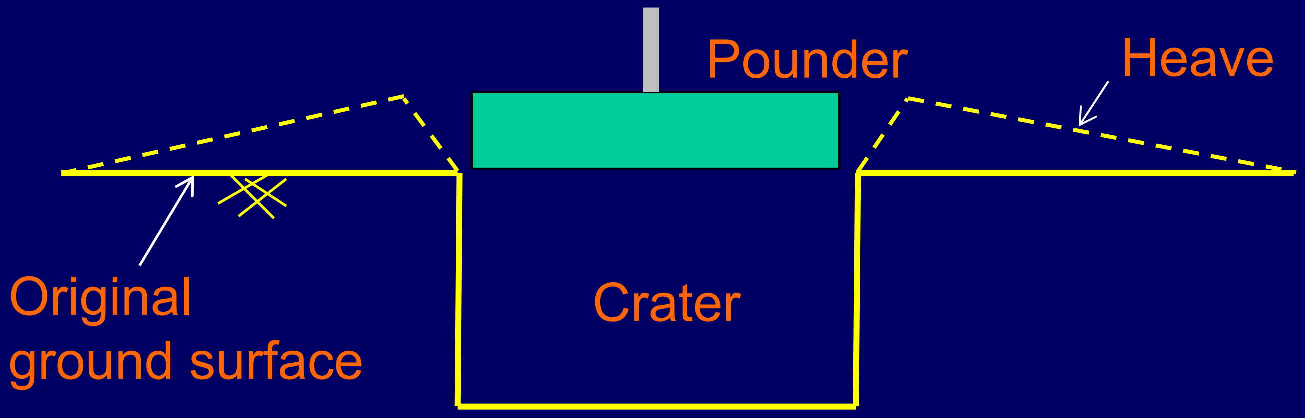
➔ The energy applied is effective in partially saturated soils (MC less than the plastic limit)

➔ 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

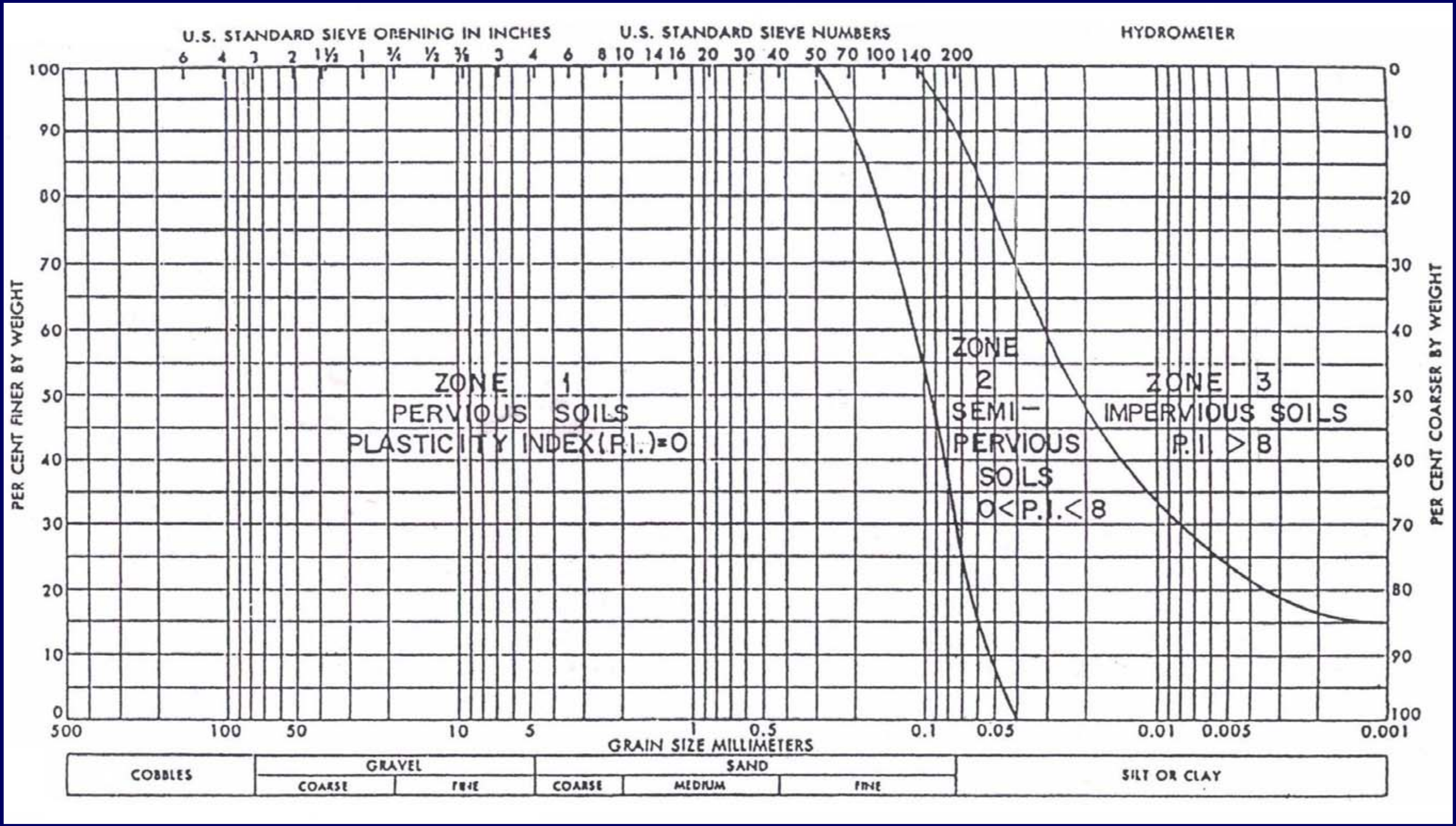
➔ These soils are nearly impervious to water and are generally NOT suitable for dynamic compaction

➔ 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)

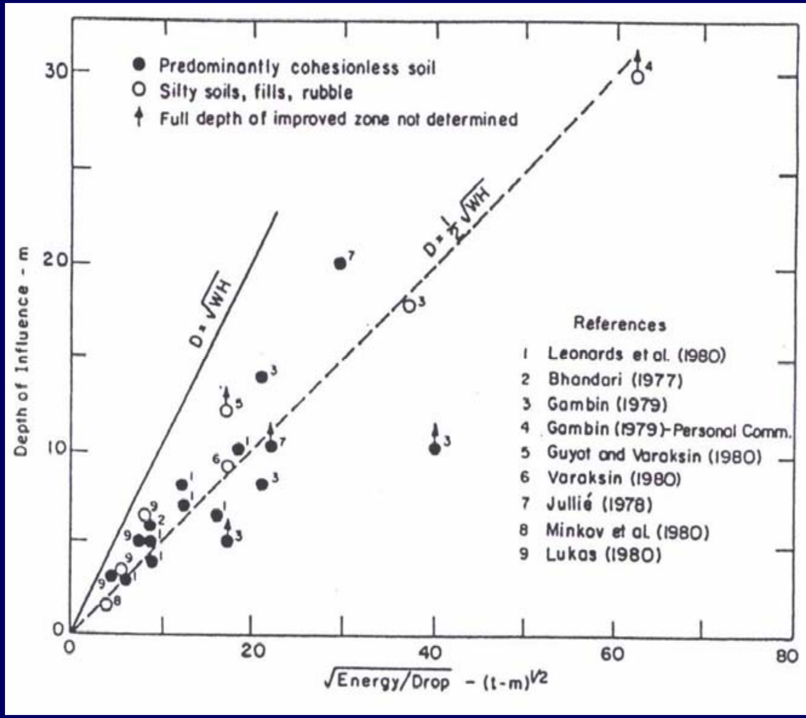


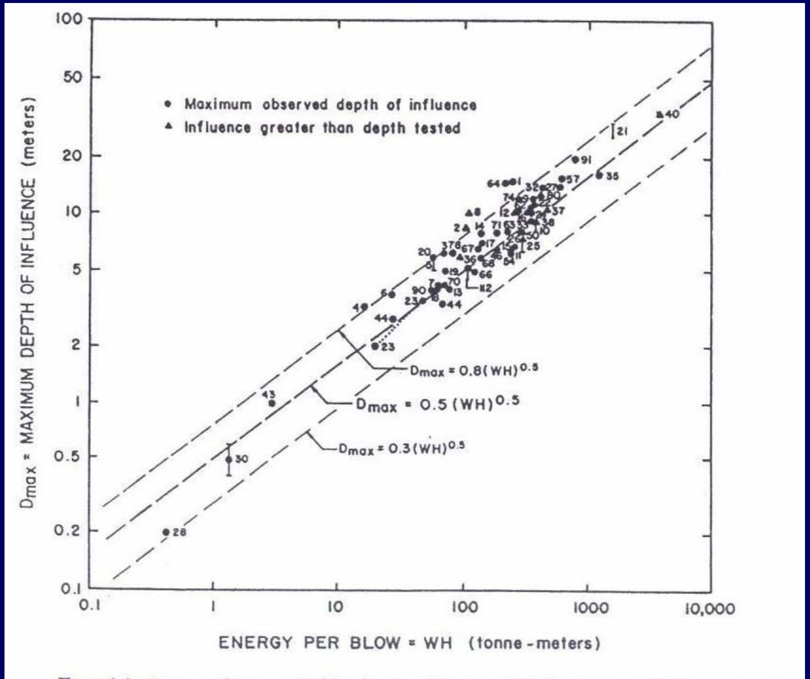
Depth of improvement

$$D = \alpha\sqrt{WH}$$

where D = depth of improvement (m)
W = weight of the pounder (tonnes)
H = drop height (m)
α = empirical coefficient

For granular soils, α is typically taken to be 0.5





Trend between Apparent Maximum Depth of Influence and Energy per Blow (Note: Numerals Refer to Sites Listed)

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

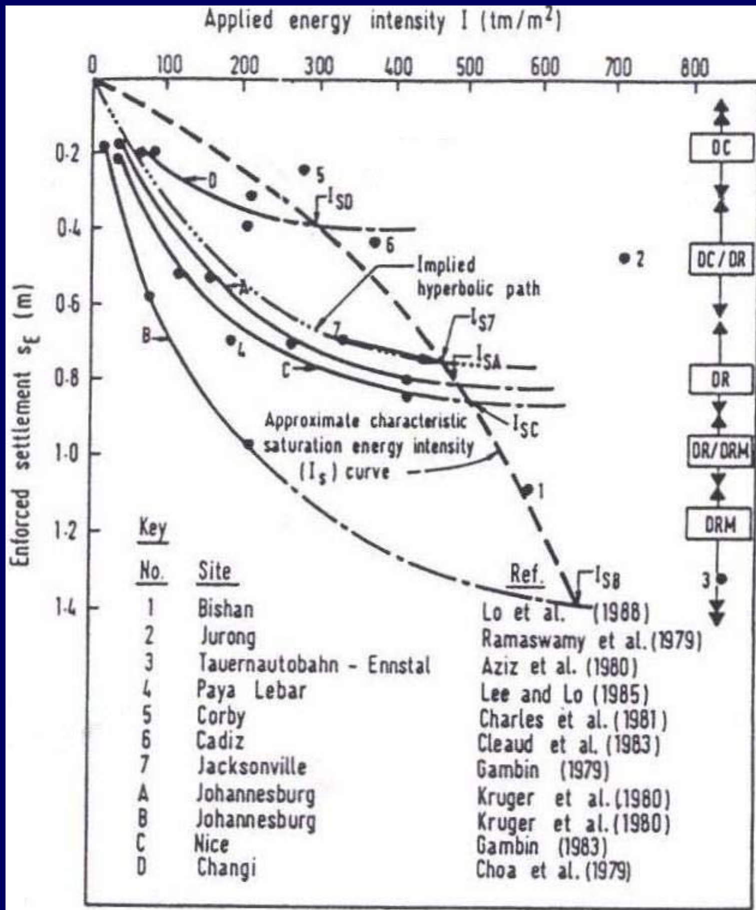
Total energy I = 100 to 400 tm/m^2

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

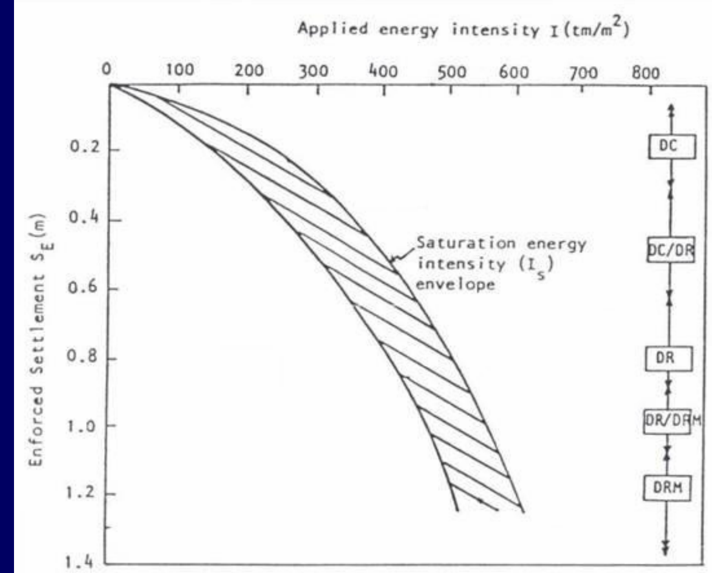
No of blows per pass 5 to 15 (Rest period is to be given in clayey and silty soils)

No of passes 2 to 8

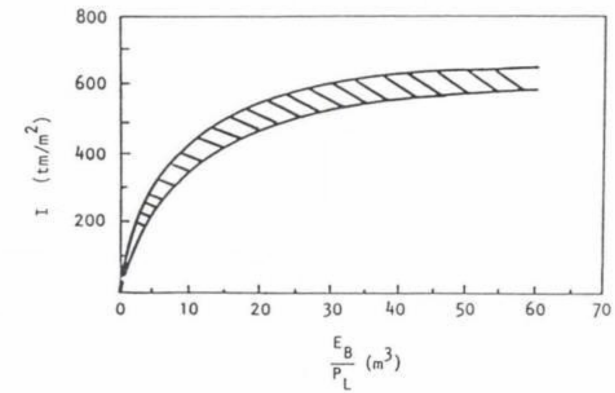
Applied energy and crater depth



Enforced Settlements due to Heavy Tamping



Enforced settlement due to heavy tamping



Saturation energy intensity characteristic curve

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

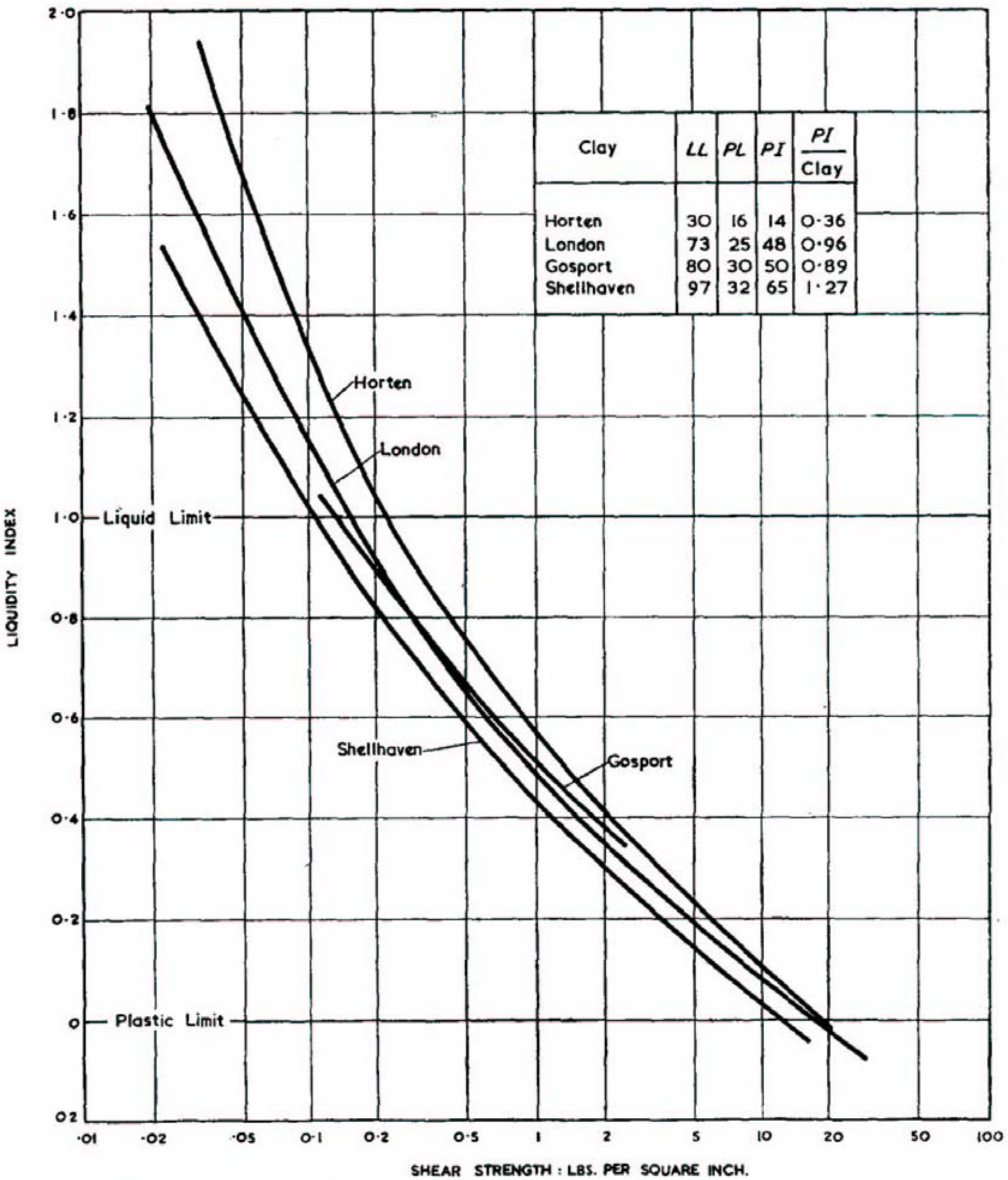
(b) Average ground settlement

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