Soil stabilization and Ground Reinforcment

Samer Rababa'h, Ph.D, P.E
The Hashemite University
Civil Eng. Dept.

Ground Improvement

Ground improvement technologies are geotechnical construction methods used to improve poor ground conditions when removal and replacement, avoidance of such conditions, or the use of deep foundations is infeasible or too costly. earth pressures.

Ground Improvement

Ground improvement may be used to

- Mitigate liquefiable soils.
- Improve loose or soft soil in order to reduce settlement, increase bearing capacity, shear, or frictional strength as well as overall improvement of stability for embankment and structure foundation.
- Improve slope stability for mitigation of landslides.
- Increase density.
- Decrease imposed load.
- Form seepage cutoff or fill voids.
- Accelerate consolidation.
- Control deformation.
- Provide/increase lateral stability.
- Reduce earth pressures.

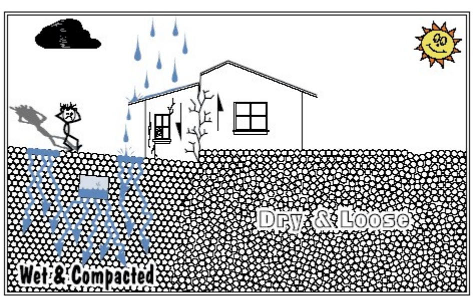
Leaning tower of Pisa

4

Effect of Swelling

5

Collapsible Soils

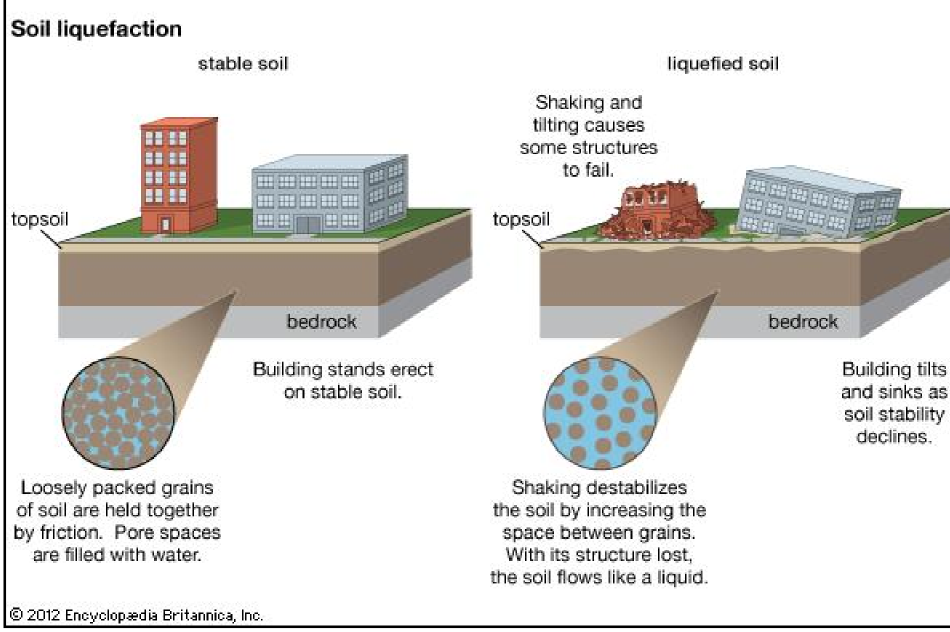


6

Failure of Slope

7

Effects of Liquefaction



Effects of Liquefaction

9

Effects of Liquefaction

10

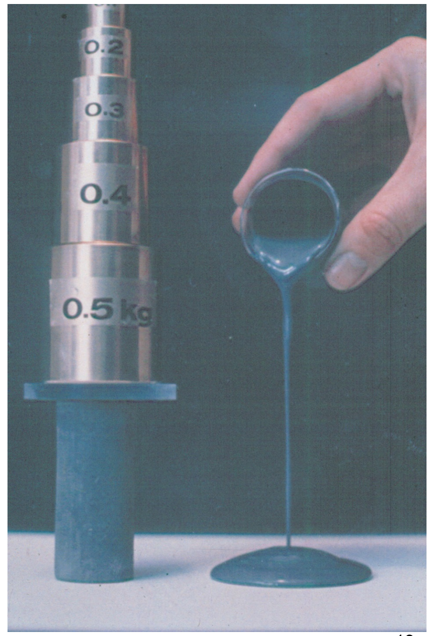
Sinkhole in Guatemala – February 2007

11

Effects of Liquefaction

12

Effect of Disturbance on a Quick Clay



13

Need for Ground Improvement:

Where a project encounters difficult foundation conditions, possible alternative solutions are:

1. Avoid the particular site. Relocate a planned highway or development site.

2. Design the planned structure accordingly. Some of the many possible approaches are to: - Use a raft foundation supported by piles,

- Design a very stiff structure which is not damaged by settlement,

- Or choose a very flexible construction which accommodates differential movement or allows for compensation.

3. Remove and replace unsuitable soils. This is a standard precaution in road or foundation construction.

4. Attempt to modify the existing ground

Factors affecting choice of improvement method

1-Soil type : this is one of the most important parameters that will control what approach or materials will be applicable to only certain types of soil types and grain sizes

2-Area , depth and location of treatment required- many ground improvement methods have depth limitations that render them unsuitable for applications for deeper soil horizons.

3- **Desired/required soil properties-** obviously, different methods are use to achieve different engineering properties, and certain methods will provide various levels of uniformity to improved sites.

15

Factors affecting choice of improvement method

4. **Availability of materials-** Depending on the location of the project and materials required for each feasible ground improvements approach.

5. **Availability of skills**, local experience, and local preferences- While the engineer may possess the knowledge and understanding of a preferred method.

6. **Environmental concerns-** With a better understanding and a greater awareness of effects on the natural environment, more attention have been placed on methods that assure less environmental impacts.

16

Soil Replacement

- Excavating the soil that needs to be improved and replacing it
- Excavated soil can be recompacted to a satisfactory state, or treated with admixtures and replaced in a controlled manner
- Can also be replaced with a different soil with more suitable properties for the proposed application

17

Benefits of Ground Modification Techniques

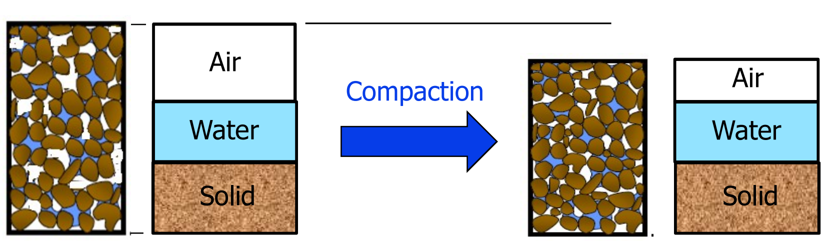
- Improves performance
- Reduces cost
- Saves time
- Reduces unknown risks
- Provides benefits on other aspects of the project, i.e.:
  - Reduced variance
  - Better constructability/workability
- May be the only option

18

Soil Compaction

What is Compaction?

- Compaction- Densification of soil by reducing air voids by application of mechanical energy.
- Compaction is used in construction of highway embankments, earth dams and many other engineering structures, loose soils must be compacted to improve their strength by increasing their unit weight
- The degree of compaction is measured in terms of its dry unit weight.



Purpose of Compaction

- Increases shear strength of soils
- Increases the bearing capacity of foundations
- Decreases the undesirable settlement of structures
- Reduction in hydraulic conductivity
- Increasing the stability of slopes on embankments.

Role of Water in Compaction

- ❑ Water is added to the soil during compaction which acts as a lubricating agent on the soil particles. The soil particles slip over each other and move into a densely packed position.

- ❑ For a given soil, the dry unit weight increases as water is added to the soil. This continues up to certain moisture content (optimum moisture content).

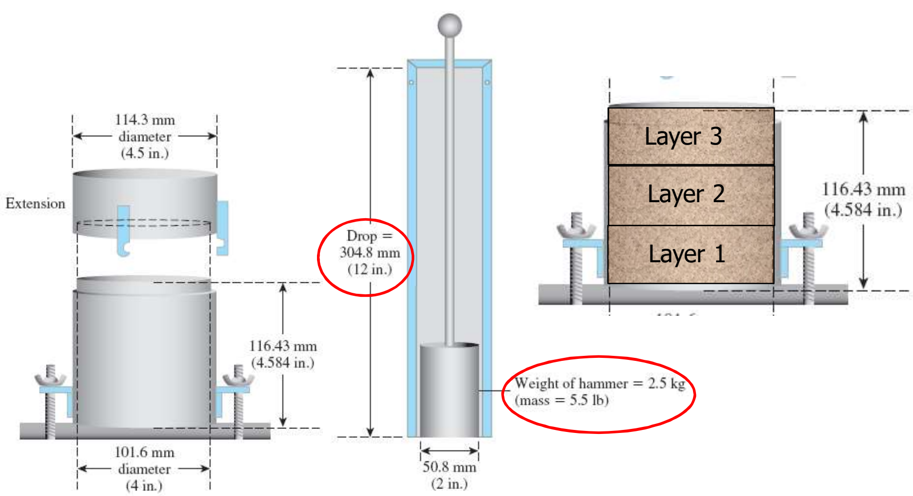
- ❑ Beyond this moisture content, more water added will fill the void space with water so further compaction is not possible.

Laboratory Compaction tests

- Purpose: Find the maximum dry unit weight and corresponding optimum moisture content.
- The standard was originally developed to simulate field compaction in the laboratory
- There are two types of standard tests (ASTM – 698) :
  1. Standard Proctor test
  2. Modified Proctor test

5

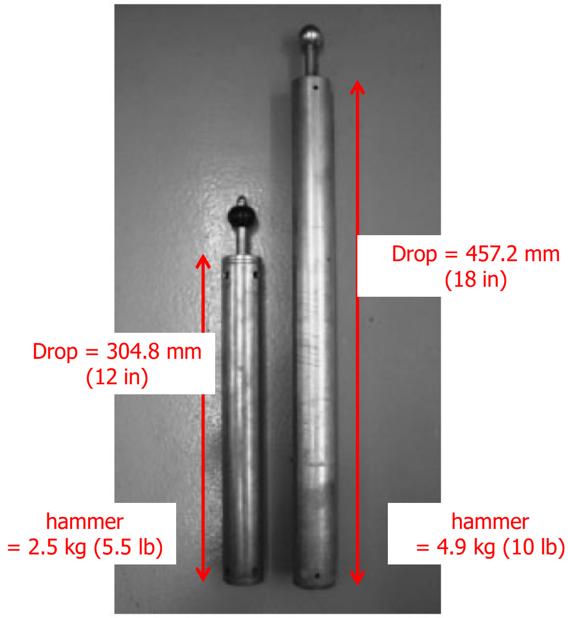
Standard Proctor Test

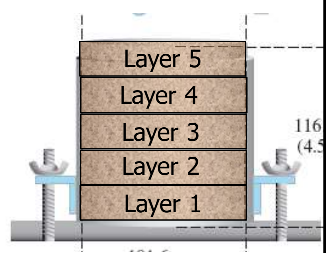


No. of blows = 25

6

Modified Proctor Test





No. of blows = 25

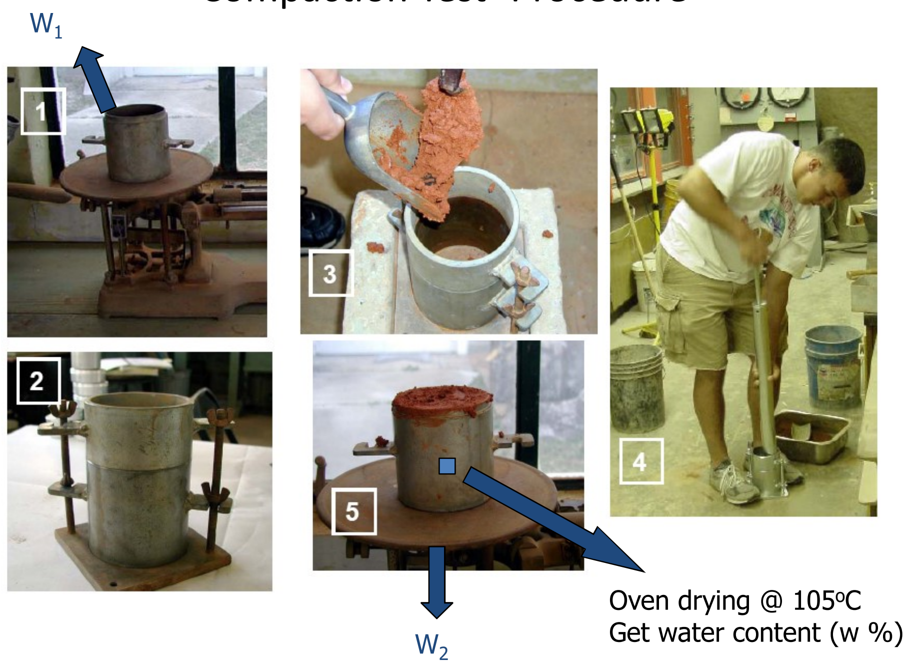
Summary of Laboratory Compaction Tests

Test	Hammer weight	Height of drop	#Blows per layer	# Layers	Volume of Mold
Standard proctor Test	2.5 kg (5.5 lb)	304.8 mm (12 in)	25	3	944 cm^3 (1/30 ft^3)
Modified Proctor test	4.9 kg (10 lb)	457.2 mm (18 in)	25	5	944 cm^3 (1/30 ft^3)

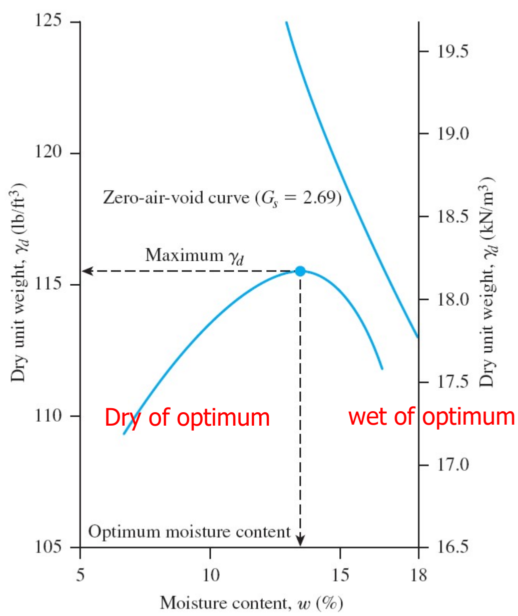
$$\text{Compaction effort per unit volume} = \frac{(\text{Hammer weight}) \times (\text{height of drop}) \times (\#\text{blows per layer}) \times (\#\ \text{layer})}{(\text{volume of mold})}$$

Standard test compaction effort = 600 kN-m/m^3 (12,400 lb-ft/ft^3)
Modified test compaction effort = 2700 kN-m/m^3 (56,000 lb-ft/ft^3)

Compaction Test- Procedure



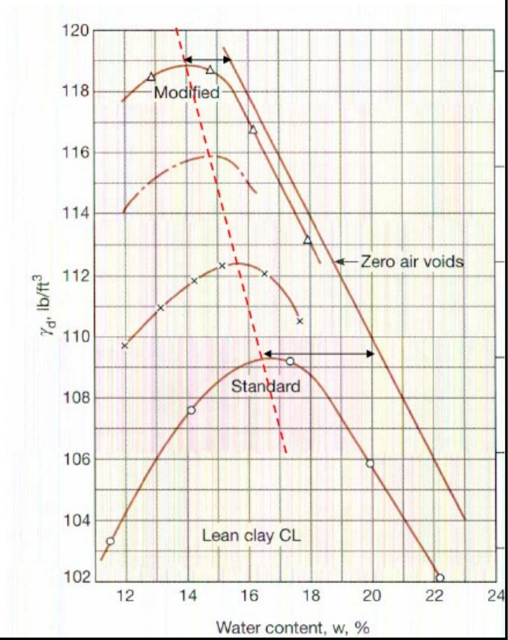
Presentation of Results



Factors Effecting Compaction

Compaction Effort

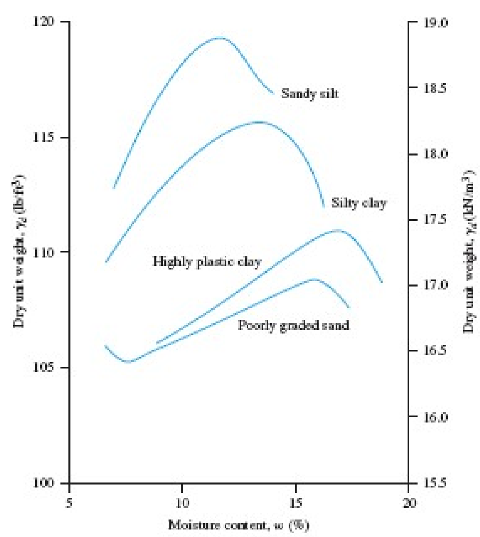
- Compaction effort is the energy per unit volume
- As the compaction effort increases:
  - The maximum dry unit weight of compaction increase.
  - The optimum moisture content decreases.



Factors Effecting Compaction

Soil Type

- Grain-size distribution, shape of the soil grains, specific gravity of soil solids, and amount and type of clay minerals present
- Fine grain soil needs more water to reach optimum; while coarse grain soil needs less water to reach optimum.



Field Compaction Equipment

Smooth wheel rollers

- Suitable for proof rolling subgrades and for finishing operation of fills with sandy and clayey soils.
- They are not suitable for producing high unit weights of compaction when used on thicker layers.

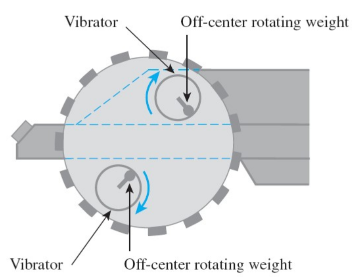
Pneumatic rubber-tired rollers

- Better than the smooth-wheel rollers.
- can be used for sandy and clayey soil compaction.
- Compaction is achieved by a combination of pressure and kneading action.

Field Compaction Equipment

Sheepsfoot roller

- most effective in compacting clayey soils.



Vibratory rollers

Field Compaction Equipment

Impact Roller

- Provides deeper ~1m compaction.

Specifications and Quality Control

- Specifications and control tests are intended to ensure adequate performance of foundation or embankment of compacted soil according to the chosen design criteria.
- In order to comply with these objectives, control tests have to be
  - **Relevant**. Density and water content have to be related to stability, volume change etc.
  - **Cost-effective**. Testing expenses must be reasonable in relation to construction costs and consequences of failure.
  - **Representative**. Sample size should be related to the known or estimated variation of the soil properties being evaluated.

Compaction Control Procedures

- Laboratory tests are conducted on samples of the proposed borrow materials to define the properties required for design.
- After the earth structure is designed, the compaction specifications written.
- Field compaction *control tests* are specified, and the results of these become the standard for controlling the project.
- These specifications are expected to ensure an expected level of performance (in terms of shear strength, compressibility, permeability which are related to bearing capacity, settlements and drainage and seepage etc)

Types of Specifications

(1) End-product specifications

- This specification is used for most highways and building foundation, as long as the contractor is able to obtain the specified *relative compaction*, how he obtains it doesn't matter, nor does the equipment he uses.

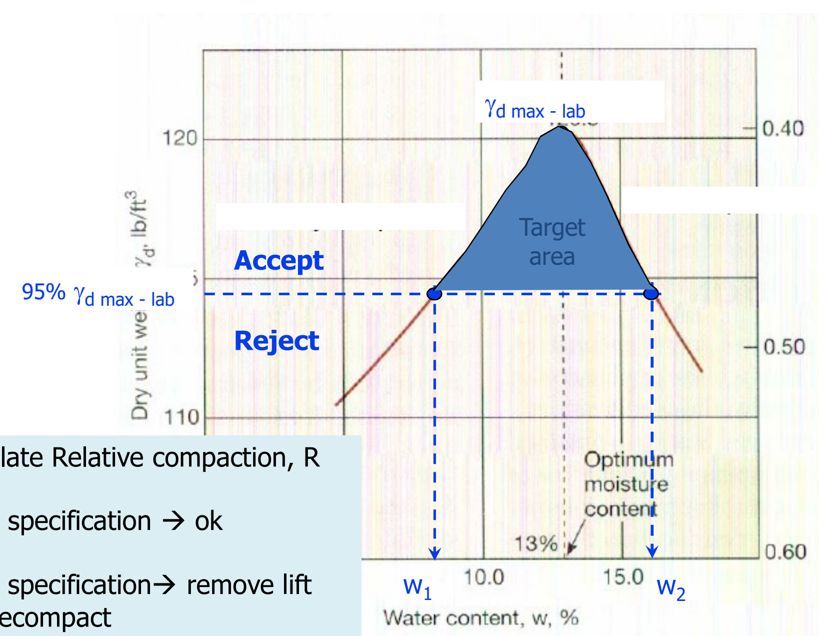
(2) Method specifications

- The type and weight of roller, the number of passes of that roller, as well as the lift thickness are specified. A maximum allowable size of material may also be specified. *It is typically used for large compaction project.*

Relative Compaction (R.C.)

$$R.C. = \frac{\rho_{d-field}}{\rho_{d\max-laboratory}} \times 100\%$$

Specification of Field Compaction



Calculate Relative compaction, R

If R≥ specification → ok

If R< specification→ remove lift and recompact

Compaction Field Control

The standard procedures for determining the field unit weight of compaction include:

1. Sand cone method
2. Rubber balloon method
3. Nuclear method

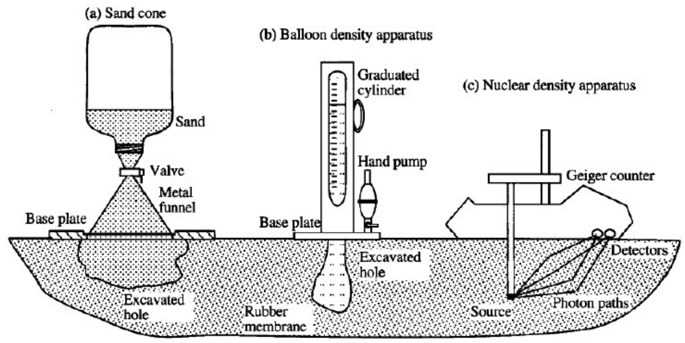
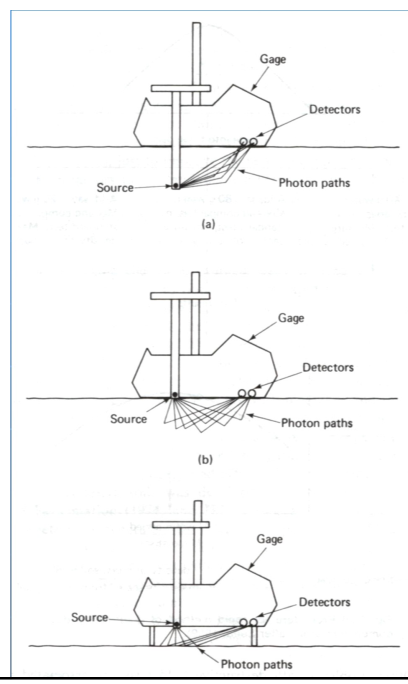


Figure 1. Methods of determining the unit weight of soils in the **field**

Non-Destructive methods-
Nuclear densometer



Results can be obtained a few minutes time compared to 16 to 24 hours

Principles

- Density

The Gamma radiation is scattered by the soil particles and the amount of scatter is proportional to the total density of the material. The Gamma radiation is typically provided by the radium or a radioactive isotope of cesium.

- Water content

The water content can be determined based on the neutron scatter by hydrogen atoms. Typical neutron sources are americium-beryllium isotopes.

Deep Dynamic Compaction

Deep Dynamic Compaction (DDC)

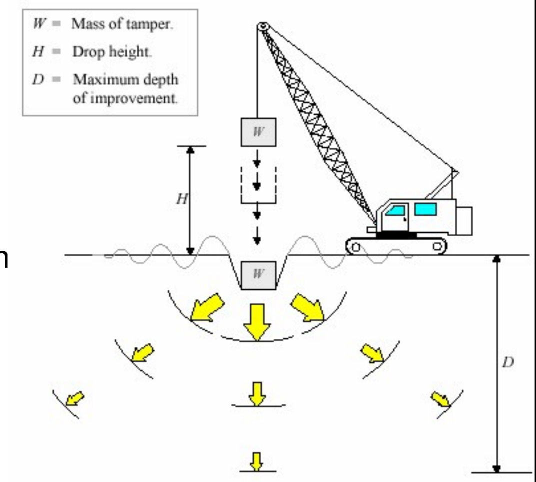
- Repeated dropping of a weight onto the soil over a given area to improve soil properties by impact compaction.
- - Weight referred to as a "pounder" or "tamper“
- Dropping preferably done by cranes modified to allow for freefall
- - AKA: "dynamic deep consolidation" or "heavy
- tamping".

- A movable crane is the most common method for lifting and dropping the DOC Pounder.

- Impact of dropped weight creates a large crater. The size of weight and fall distance depend on the treatment depth required and Equipment availability. The weight is dropped several times at each location in a grid pattern.

- Typical pattern of craters formed by repeated drops of a DOC pounder. In most projects the site will be leveled and a second or third phase carried out with drops at intermediate points in the grid.
- Craters may be filled with sand after each pass

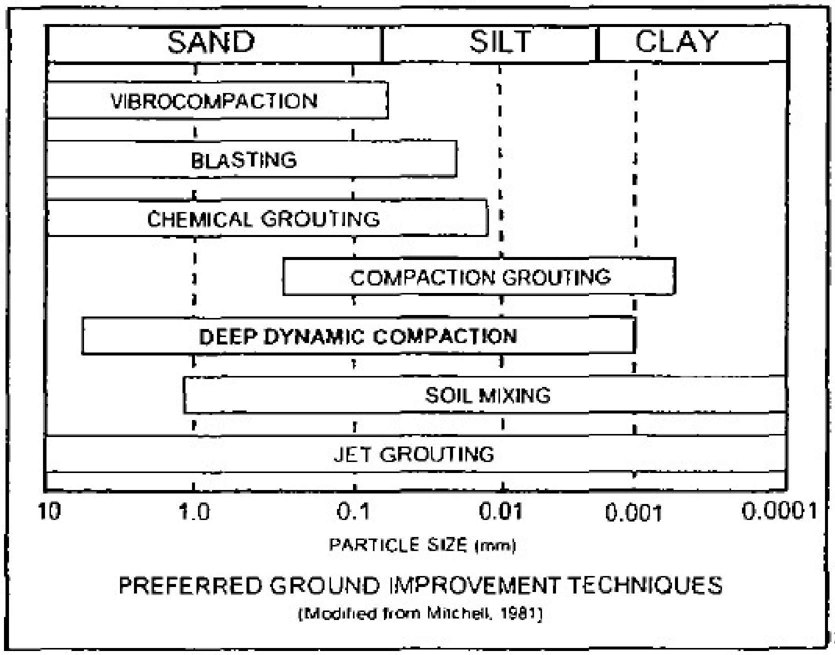
• Degree of densification achieved is a function of the energy input (weight and drop height) as well as the saturation level, fines conten and permeability of the material
• 6 – 30 ton weight can densify the loose sands to a depth of 3 m to 12 m



Application of DDC

• An effective and economical method for improvement of open areas of cohesionless and partly saturated soils to moderate depths (±1 0 m)

• Best if fines content < 15-20%, but may be effective also in partly-saturated finer-grained soils and for the densification of municipal solid waste.



Degree of Improvement

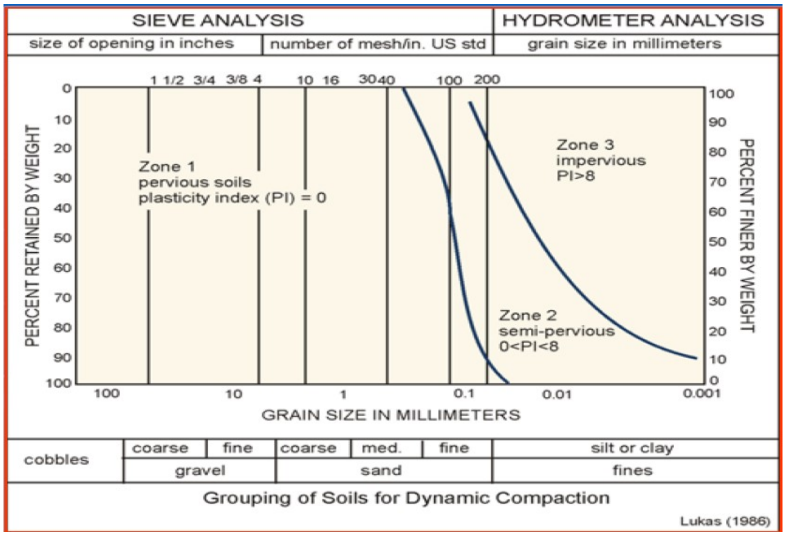
• Surface Settlement:
  -5 to 10% of thickness of material being treated
  -Occurs almost immediately

•Pore Pressure Increase:
  - Instantaneous increase followed by rapid dissipation
  - Common to see rising GWT and localized boiling

•Strength and Compressibility:

  -Improved by a factor of 2 to 4 (as measured by in-situ tests)

Applicable Soils



Zone 1 : Best

Zone 3 : Worst (consider alternate method s)

Zone 2 : Must apply multiple phases to allow for pore pressure dissipation

Degree of Improvement

- Depth of compaction is a function of the weight and the drop height.

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

D = *Depth* of influence (meters)
W =weight of tamper (metric tons)
H = Drop height (meters)
n = mulitplying factor

n ranges from 0.3 to 0.7 depending on soil type.

Equipment limitations

• Crane capacity
• Height of drop
•Mass of tamper
• Tamper size

Grid Spacing

•Significant effect on depth of improvement

• First pass compacts deepest layer, should be equal to the compressible layer

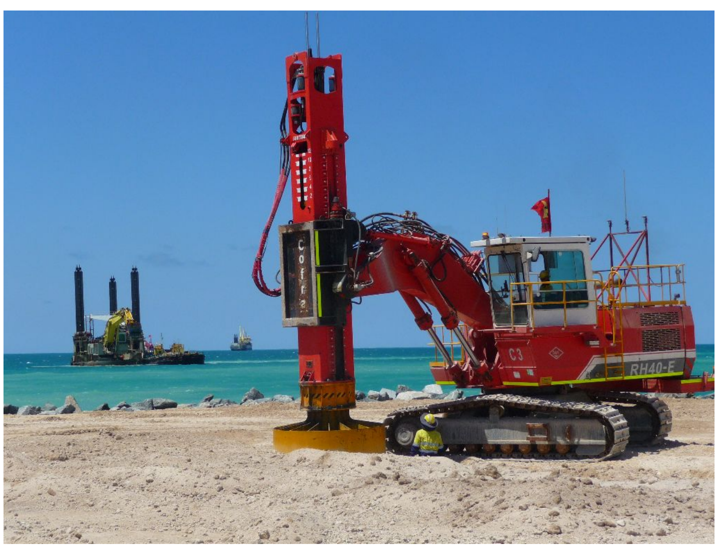
• Subsequent passes compact shallower layers, may require lesser energy

• Ironing pass compacts top layer

Ground Vibrations

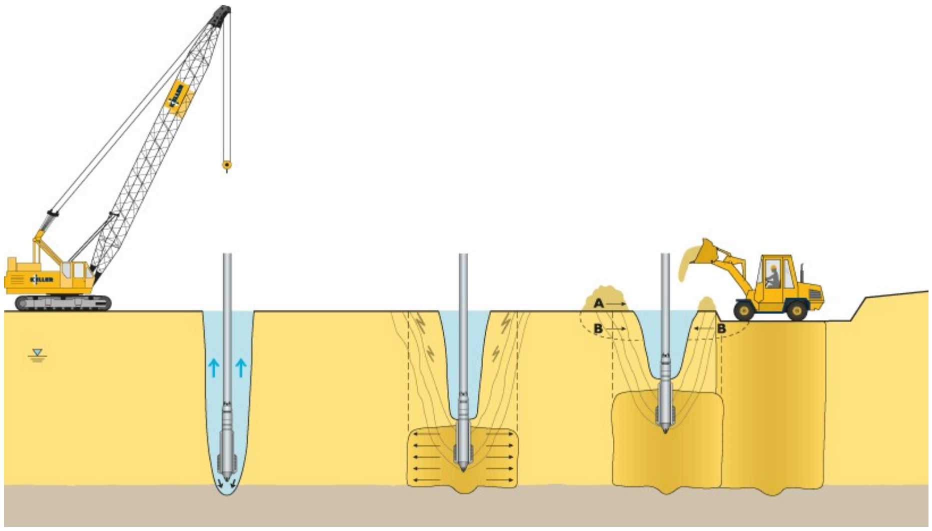
- Dynamic compaction generates surface waves with a dominant frequency of 3 to 12 Hz
- The ground vibrations are quantified in terms of peak particle velocity (PPV); the maximum velocity recorded in any of the three coordinate axes
- The measurement of vibrations is necessary to determine any risk to nearby structures
- The vibrations can be estimated through empirical correlations or measured with the help of instruments.

Rapid Impact Dynamic Compaction



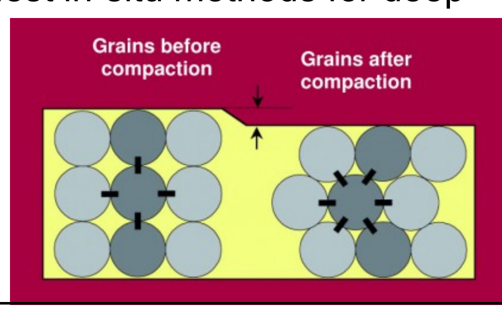
Approach for design

Vibro-Compaction Methods

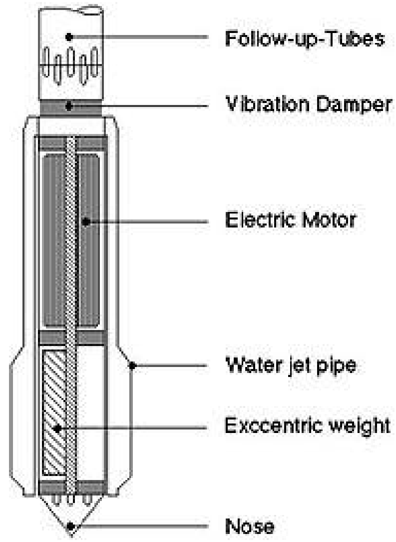


Vibro-Compaction Methods

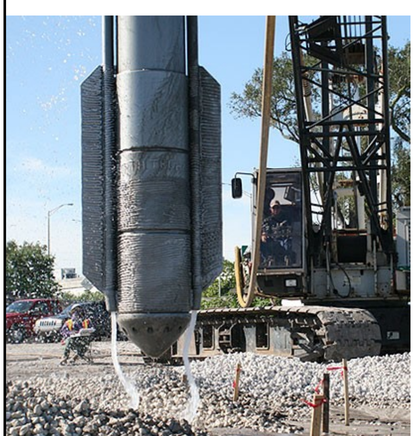
- In-situ deep densification method for granular soils
- Rearrangement of loose cohesionless sand grains into a denser array by insertion of a vibratory probe
- One of the earliest in-situ methods for deep densification.

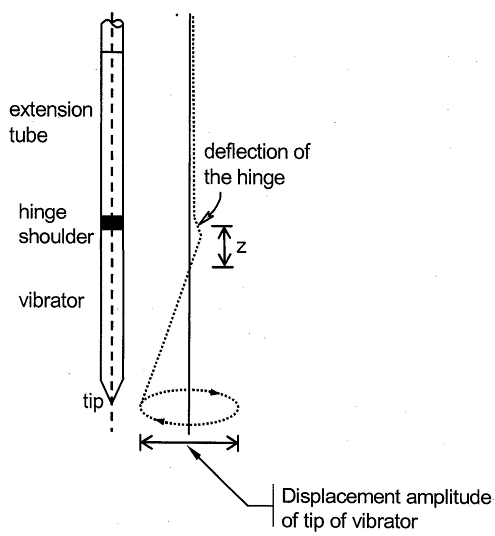


Vibro-Compaction



Vibro-Compaction





History & Development

- Vibratory methods in use for over 70 years: Probably the oldest dynamic deep compaction method in existence
- *1930's: Vibroflot developed in Germany*
- *1936: Introduced by the Johann Keller Company* and developed to maturity
- During the last 20 years, the main improvement in vibro-compaction has been the introduction of larger, more powerful vibrators:

  - Allows larger spacings

  - Performs densification to higher DR%

  -Allows densification to greater depths

Uses & Applications

- Increases bearing capacity
- Reduces foundation settlement
- Mitigates potential for liquefaction and lateral spreading
- Permits construction on granular fills
- Increases horizontal stress in ground

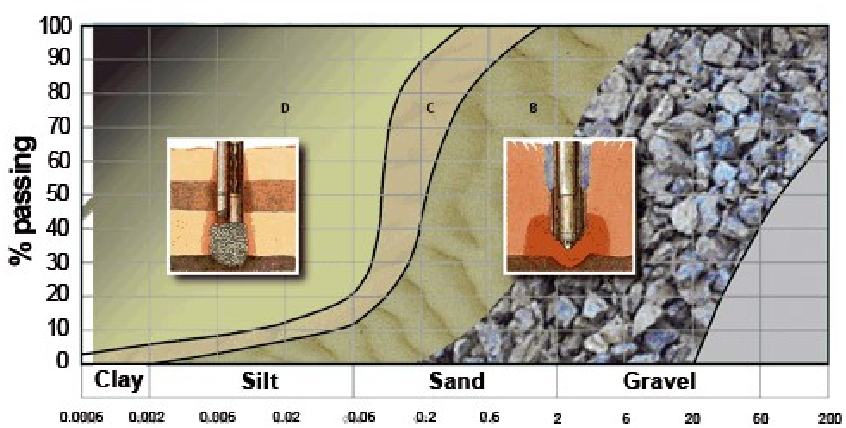
Uses & Applications

- Vibro-compaction limited by the fines and carbonate content
- Most suited to clean sands with <20% fines

  -Most successful in loose sandy soils with SPT N-value of 5 to 10 near the surface

  -Not applicable to clays, clay content < 3%

Vibro-Compaction Methods



Theoretical Considerations

- Used to densify clean, cohesionless soils
- Vibrator (often accompanied by water jetting) reduces inter-granular forces between soil particles
- Particles move to denser configuration typical DR = 75 to 80%
- Compaction possible above and below GWT, but best in saturated soil

Amount of Improvement

DR= *f*(probe energy, soil type, backfill type, & spacing)

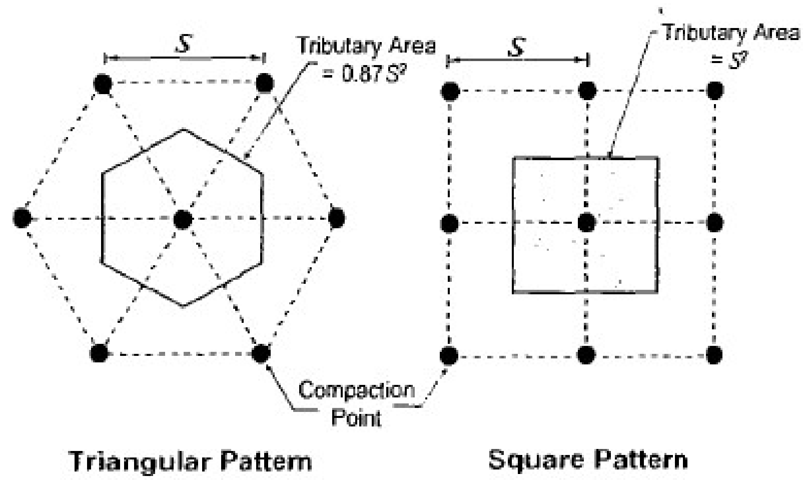
- Bearing capacities increased to as high as 10 tsf
- Angle of internal friction, Φ increased 5 to 8 degrees
- Modulus of deformation *E increased to around* 1,000 tsf (and sometimes higher)
- Possibility of continued stiffening and strength gain up to several months after densification

Vibro-Compaction Design Steps

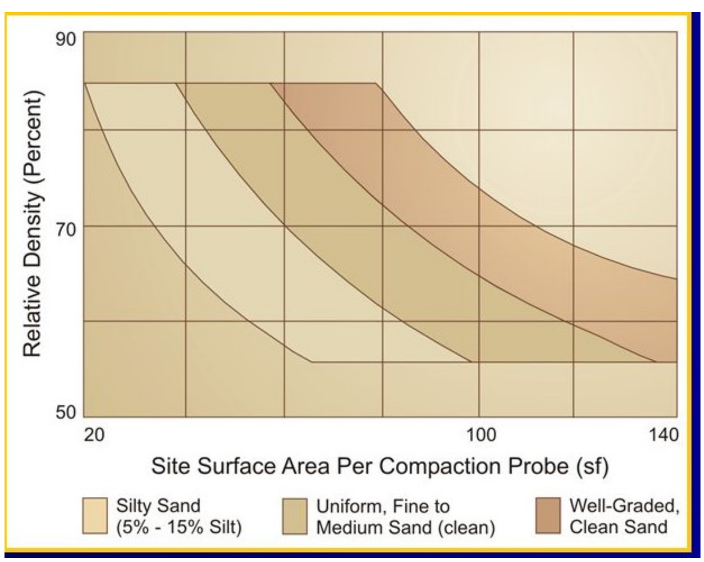
1. Perform site investigation
   -Soil gradation important
2. Calculate predicted settlements
   -Problem understood
3. Establish compaction requirements
   -Sufficient densification to reduce settlement and/or prevent liquefaction
4. Develop appropriate vibro-compaction approach
   -Treat entire site, or just one footing?
5. Establish testing criteria for evaluation of effectiveness
   -Relative density, SPT, CPT, PMT, etc.

- Spacing of probe compaction points depends on soil type, density requirements, and probe/vibrator characteristics.
- Usual spacing ranges from 5 to 12 feet (1.5-3.6 m)

Typical Patterns used to Treat Large Areas



Approximate Treatment Requirements for Densification

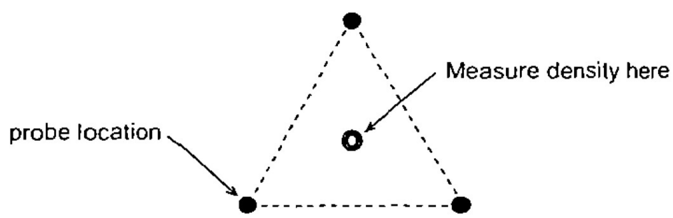


Common quality control checks:

- Monitor energy input by probe during treatment
- Surface settlement markers: simple, should always use
- Backfill volume added to hole
- SPT
- CPT
- PMT (Mostly in Europe)

Quality Control

- Measure density at locations that are expected to be least-improved by the treatment- "weak link“



- In earthquake-prone regions where liquefaction is possible, generally want SPT (N1)60 values greater than 25 to withstand *most earthquakes with acceptable performance*

Method Specifications

- Best to use standardized procedure established by a test section
  - Predetermined vibrator lifts and time intervals
  - Predetermined power consumption
- Regular procedure can reveal variations in test results due to non- homogeneity of in-situ soils
- End result (performance) specifications can be problematic if there is soil variability or unanticipated conditions encountered

Method Specification Parameters

- Location and grid spacing
- Start/stop times
- Treatment depth
- Vibration method
- Penetration and withdrawal rate
- Amount, type, and gradation of backfill used
- Resistance level as measured by amp meter
- Vibration monitoring
- Settlement monitoring

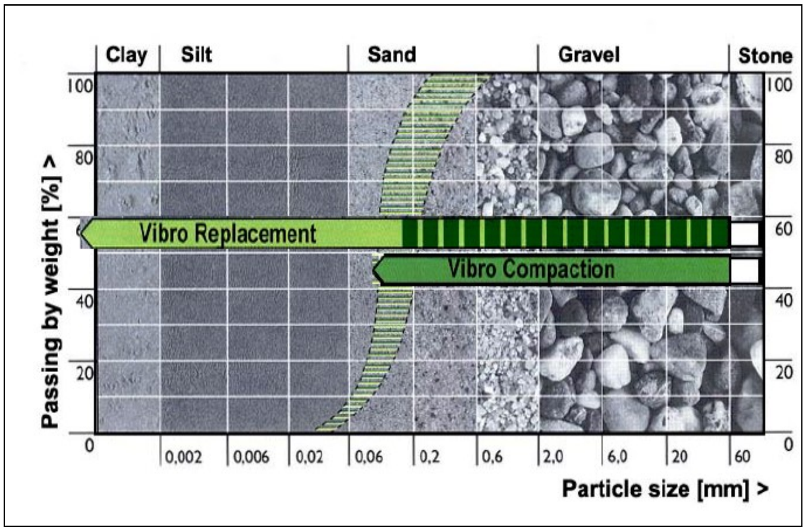
End-result Specifications

- The design of the vibro-compaction pattern usually depends on initial densities or penetration resistances indicated by the SPT and/or CPT.
- SPT and CPT tests are also used for verification testing. Relative densities between 70% and 80% are possible below 25 m, with even greater densities at shallower depths.
- Minimum relative densities or penetration resistance values may be specified as acceptance criteria for vibro-compaction.Measure density at locations that are expected to be least-improved by the treatment- "weak link“

Time Considerations

- Vibro-compaction elements and the treated soil tend to gain strength over weeks to months after treatment
- Use of verification test results immediately after treatment will give a conservative estimate of improvement
- A series of verification tests performed over time will give the best

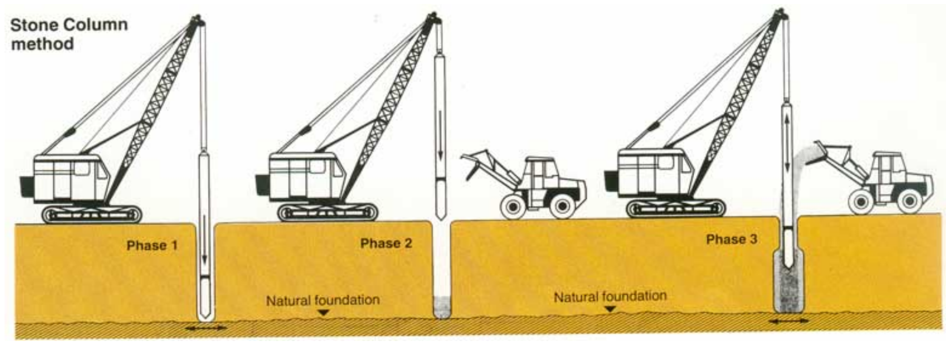
Range of Soil Types Treatable by VibroCompaction & Vibro-replacement



Vibro Replacement

- Vibro Replacement is a technique of constructing stone columns through fill material and weak soils to improve their load bearing and settlement characteristics.
- Unlike clean granular soils, fine grained soils (such as clays and silts) do not densify effectively under vibrations. Hence, it is necessary to form stone columns to reinforce and improve fill materials, weak cohesive and mixed soils.

Vibro Replacement



Vibro-Stone Columns

- Can be installed in sand or clay:

  -Used in sandy and silty soils to mitigate liquefaction problems

  In clays, a stone column can:

  -Act as a deep foundation, transferring load to a deeper, firmer stratum

  -Provide drainage

  -Increase resistance to inclined or horizontal shear

Vibro Replacement

- Typically about 3' diameter
- Can be bottom-feed or top-feed
- Top-feed is least cost

  -Essentially the same process as vibro-compaction

  - Considered "vibro-replacement" since significant quantities of stone are added to the native soil
- Use gravel or crushed stone backfill up to 3" dia

  - In sands, provides densification of surrounding soils and adds reinforcement.

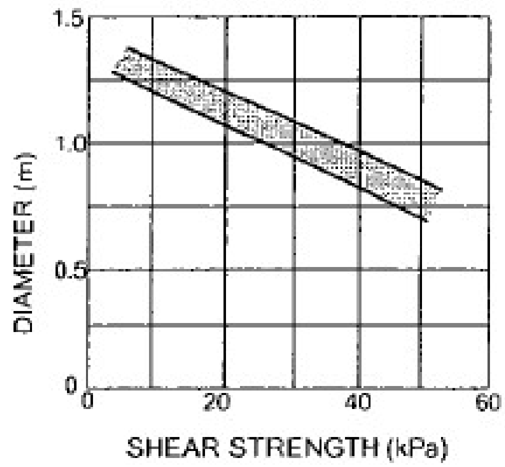
Vibro Replacement

- Installation technique:

  - Vibrate a probe into the ground to desired depth of treatment

  - Introduce stone backfill in controlled lifts

  - Repenetration of each backfill lift forces the stone radially into the ground, forming a vibro-stone column that is tightly interlocked with the surrounding soil
- Typically arranged in triangular, square, or rectangular grid spacing
- Center-to-center grid spacing of 4 to 11 feet (1.2-3.4 m)



- Stone column diameter is inversely related to the strength of the surrounding soil

Applications

- Improve the stability of embankments and natural slopes
- Increase bearing capacity
- Reduce total and differential settlements
- Increase the time rate of settlements, and
- Reduce liquefaction potential

Degree of Improvement

- Function of:
  -Soil type
  - Silt & Clay Content
  -Soil Plasticity
  - Backfill material
  - Pre-densification relative densities
  - Procedures

Degree of Improvement

- For granular soils with < 15 to 25% fines:
  -Stone backfill enhances displacement &
  drainage
  - Increased drainage contributes to stabilization in seismically active regions
- For cohesive soils:
  - Densified stone backfill performs as structural reinforcing element
  - Reinforcement increases bearing capacity, reduces total and differential settlements

Possible Problems in Cohesive Soils

•Clogging of column reduces drainage effectiveness
•Too much clay in the column weakens it-lose reinforcing effect.

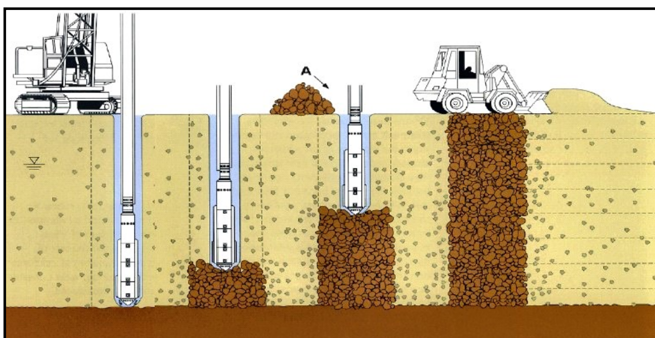
- Stone backfill is introduced in controlled lifts

- *Top feed: from the surface, down the* annulus created by penetration of the probe

-*Bottom feed: through feeder tubes directed* to the tip of the probe

Wet Top Feed process

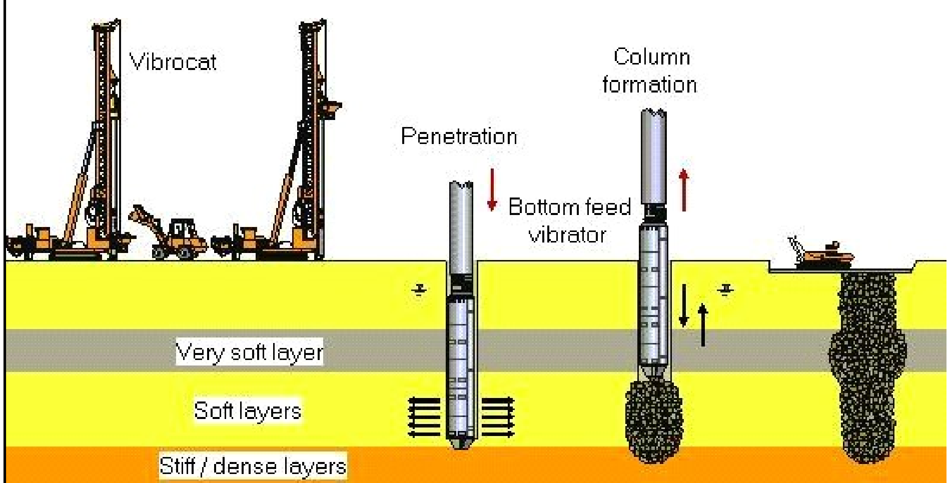
- The vibrator penetrates to the design depth by means of the vibrator's weight and vibrations, as well as water jets located in the vibrator's tip.
- The stone is then introduced at the ground surface to the annular space around the vibrator created by the jetting water.
- The stone falls through the annular space to the vibrator tip, and fills the void created as the vibrator is lifted several feet.
- The vibrator is lowered, densifying and displacing the underlying stone.



wet top Feed process

Bottom Feed Process

- The dry bottom feed process is similar except that no water jets are used and the stone is fed to the vibrator tip through a feed pipe attached to the vibrator.
- Predrilling of dense strata at the column location may be required for the vibrator to penetrate to the design depth.
- Both methods of construction create a high modulus stone column that reinforces the treatment zone and densifies surrounding granular soils.



QA/QC

- Load testing:

-becoming a more common method of QA for soil profiles where the native soil is not significantly improved between vibro-stone columns during column installation (>15- 20% fines)

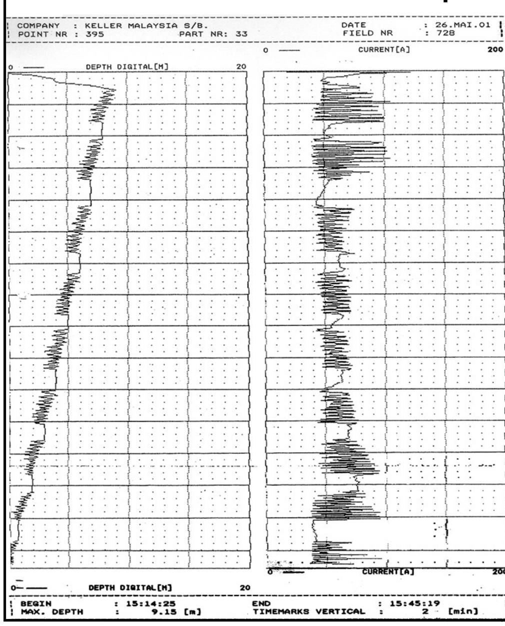
- Methods for stone column load testing:

-Load testing of a vibro-stone column alone

- Testing the area of one vibro-stone column and its tributary soil

-Testing of a full-scale footing, generally supported by several vibro- stone columns and the tributary soil

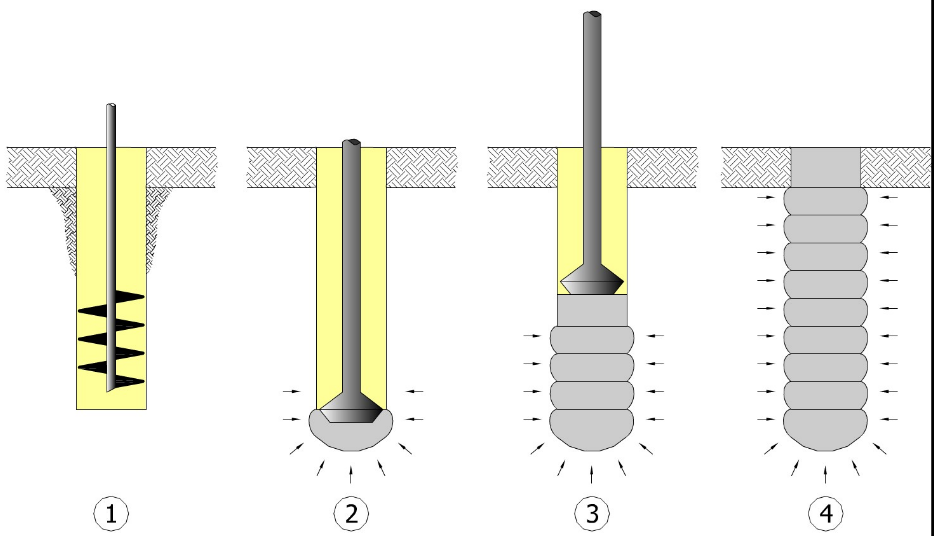
Real-Time Computerised Monitoring



Exposed Vibro Stone columns

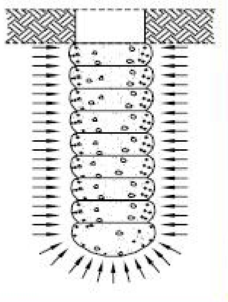
Load Test

Rammed Aggreagte



Rammed Aggreagte

Rammed Aggreagte



Rammed Aggreagte

Bridging Layers

- Granular mat typically placed above the area of stone column installation.
- Serves several purposes:
  - -Working platform for stone column installation.
  - - Forces the column to bulge at greater depth, increasing the capacity of the column.
  - - Drainage layer for dissipation of pore ressures during loading.
  - May be reinforced with one or more layers of geosynthetics.

Column Diameter

- Varies based on installation procedures and subsurface conditions.
- Varies for layers of differing soil stiffness.
- For vibro-replacement methods:
  -Range from 2.5 to 4.0 feet
- For rammed method:
  -Typically 2.5 feet or less.

Column Diameter

- Triangular, square, or hexagonal patterns.
- Triangular is the most efficient and common.
- Column spacing varies from 5 feet to 11.5 feet
  - Spacings larger than 4 diameters are inefficient
  - Spacings less than 5 ft pose construction problems.
- Staggered construction sequence can be used if necessary for close spacings.

Area Replacement Ratio, a_s

- Important geometric factor in stone column design:

$$a_s = \frac{A_{col}}{A_{col} + A_{soil}}$$

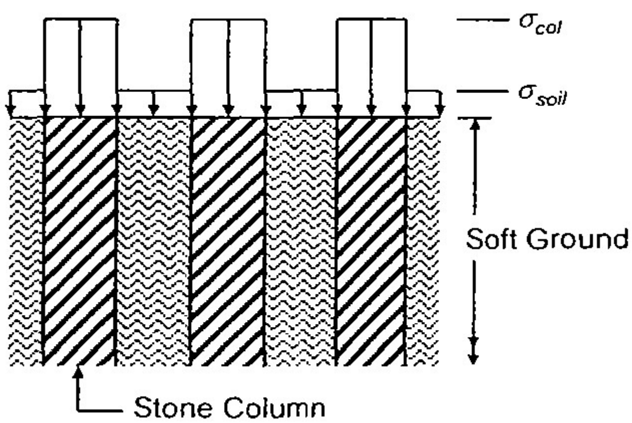
- *Acol = area of the column*
- *Asoil = area of soil surrounding the column*
- *Acol +A soil= effective area = tributary area*

Area Replacement Ratio, a_s

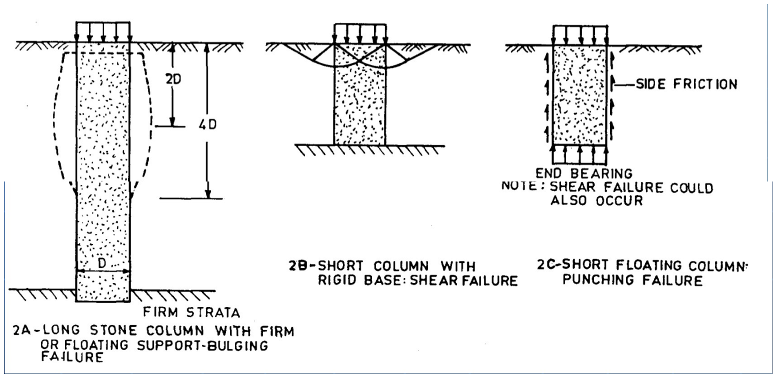
- Typical values vary from 0.15 to 0.35
- A large ratio is required to have a significant reduction in settlement.
- An area ratio of 0.3 (ratio of spacing to column diameter of about 1. 7) results in approx. 30% or more reduction in settlement.

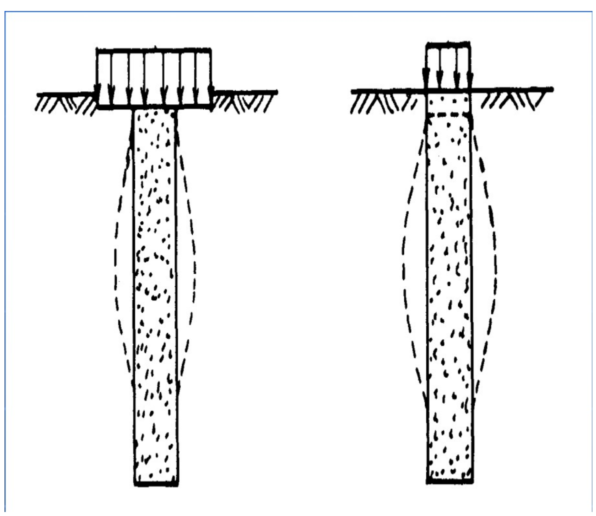
Load Distribution

Vertical equilibrium: $q = a_s\sigma_{col} + (1 - a_s)\sigma_{soil}$



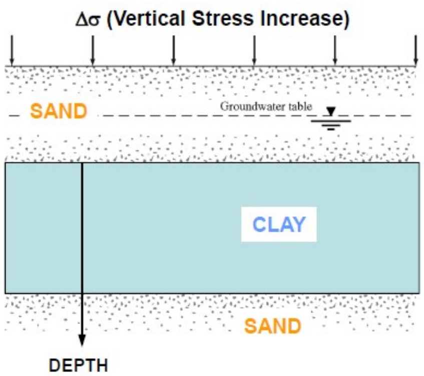
Failure Mechanisms of Stone Columns





where the loaded area is more than that of Stone columns experiences less bulging leading to ultimate load bearing capacity and reduced settlements since the load is carried by both soil and the stone columns.

FUNDAMENTALS OF CONSOLIDATION



CONSOLIDATION:
Volume change in saturated soils caused by the expulsion of pore water from loading.

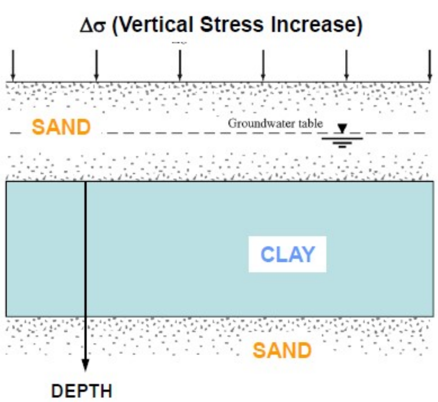
Saturated Soils:

Δσ causes *u* to increase immediately

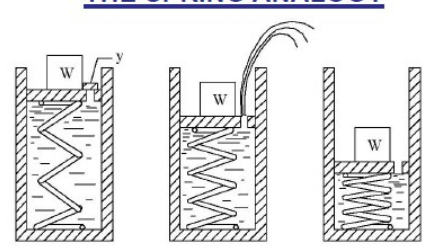
Sands: Pore pressure increase dissipates rapidly due to high permeability.

Clays: Pore Pressure dissipates slowly due to low permeability.

FUNDAMENTALS OF CONSOLIDATION



THE SPRING ANALOGY



(a) Initial Loading

Water takes load

Soil (i.e. spring) has no load

(b) Dissipation of Excess Water Pressure

Water dissipating

Soil start to take the load

(c) Final Loading

Water dissipated

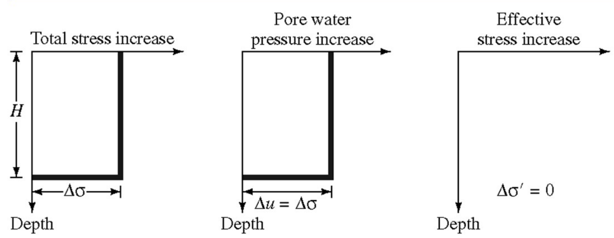
Soil has load

Fundamentals of Consolidation (Cont.)

-Clay has a very low hydraulic conductivity and water is incompressible.

- At time (t=0), the entire incremental stress, $\Delta\sigma$, will be carried by the water ($\Delta\sigma = \Delta U$) at all depths. None will be carried by the soil ($\Delta\sigma'$)=0.

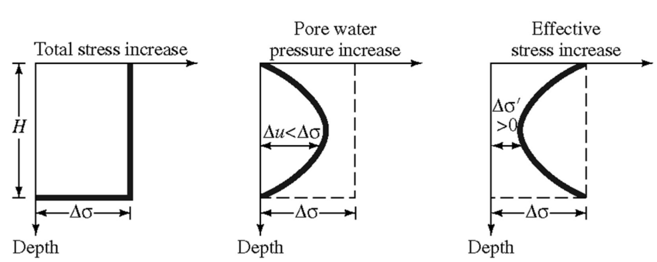
At Time of Initial Loading (t = 0)



Variation in Total, Pore water, and Effective Stresses in Clay Layer

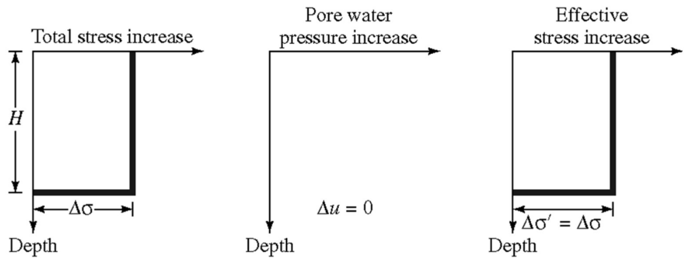
- After application of the $\Delta\sigma$ to the clay layer, water in the voids will start to be squeezed out and will drain in both directions in the sand. The excess pore water pressure at any depth in the clay layer gradually will decrease, and the stress carried by the soil (effective stress) will increase.

Between time t = 0 to t = ∞



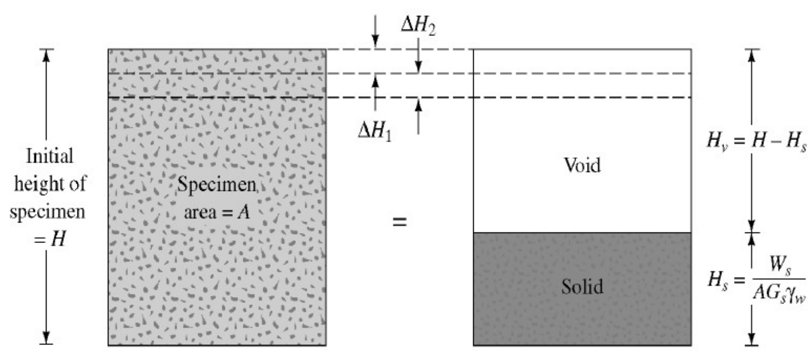
Variation in Total, Pore water, and Effective Stresses in Clay Layer

At time t = ∞



Variation in Total, Pore water, and Effective Stresses in Clay Layer

Void Ratio-Pressure Plots



Initial Void Ratio (e_o): $e_o = \frac{V_v}{V_s} = \frac{H_v A}{H_s A} = \frac{H_v}{H_s}$

VOID RATIO-PRESSURE PLOTS

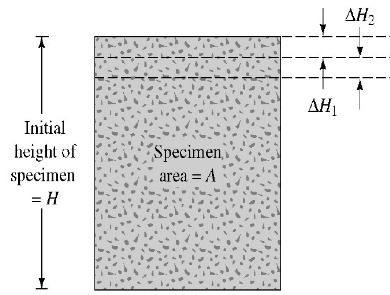
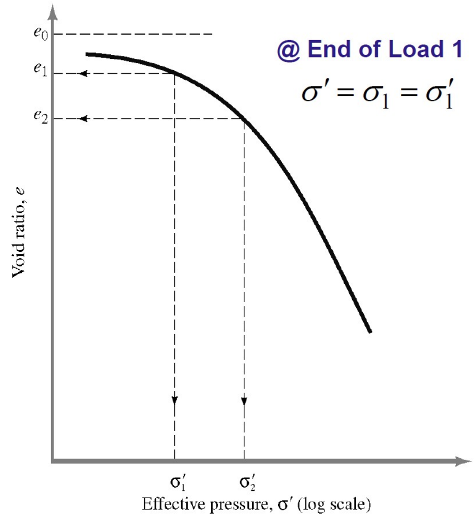


Figure 7.5. Das FGE (2005)



@ End of Load 1

$$\sigma' = \sigma_1 = \sigma'_1$$

Change in Void Ratio due to 1st Loading (Δe_1):

$$\Delta e_1 = \frac{\Delta H_1}{H_s}$$

New Void Ratio after 1st Loading:

$$e_1 = e_o - \Delta e_1$$

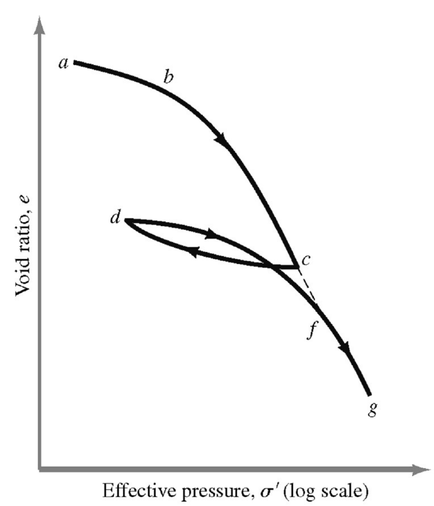
VOID RATIO-PRESSURE PLOTS

Final e – log σ´ plots consist of results of numerous load & unload increments

Two Definitions of Clays based on Stress History:

Normally Consolidated (NC):
The present overburden pressure (a.k.a. effective in-situ stress) is the most the soil has ever seen.

Overconsolidated Clay (OC):
The present overburden pressure is less than the soil has experienced in the past. The maximum effective past pressure is called the preconsolidation pressure (σ'_c) or ***Maximum Past Pressure (σ'_{vm})***



OVERCONSOLIDAITON RATIO (OCR)

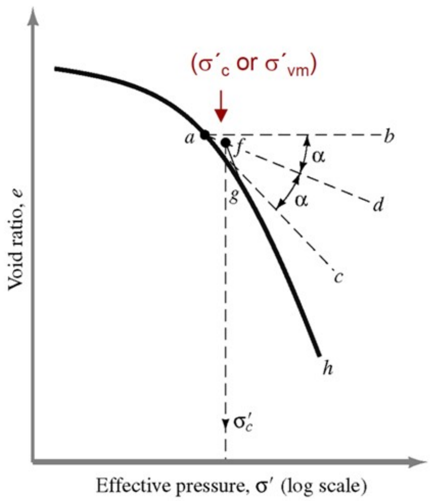


Figure 7.8. Das FGE (2005).

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

Where:

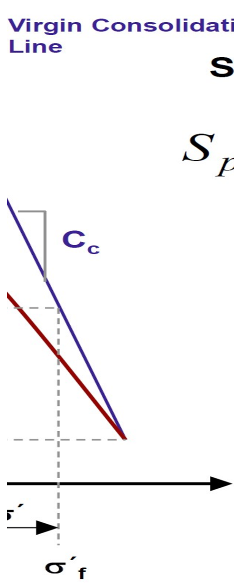
σ'_c (a.k.a. σ'_{vm}) = Preconsolidation Pressure (a.k.a Maximum Past Pressure).

σ' = Present Effective Vertical Stress

General Guidelines:
NC Soils: 1 = OCR
OC Soils : OCR > 1

Possible Causes of OC Soils:
Preloading (thick sediments, glacial ice); fluctuations of GWT, underdraining, light ice/snow loads, desiccation above GWT, secondary compression.

NC Clay



Settlement (S_p) using Void Ratio

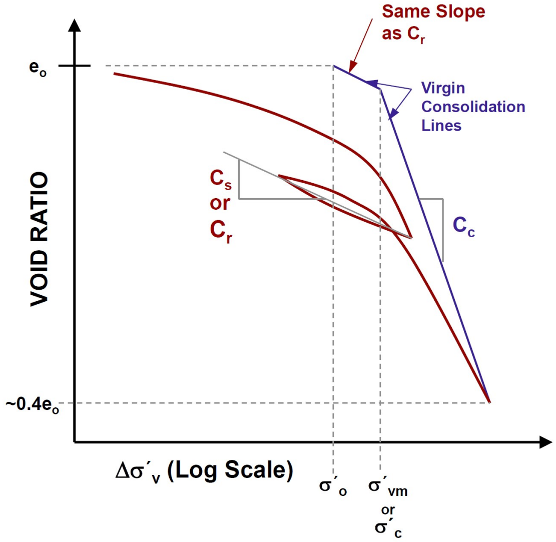
$$S_p = \frac{C_c H}{1 + e_0} \log\left(\frac{\sigma'_o + \Delta\sigma'}{\sigma'_o}\right)$$

Where:

S_p = Settlement
H = Height of Soil Layer
σ'_{vm} = Maximum Past Pressure
= σ_o' - Current Vertical Effective Stress
$\Delta\sigma'$ = Change in Vertical Effective Stress
σ_f' = Final Vertical Effective Stress
e_f = Final Void Ratio

Slide 23 of 74

Settlement from 1D Primary Consolidation



OC Clay

Where:

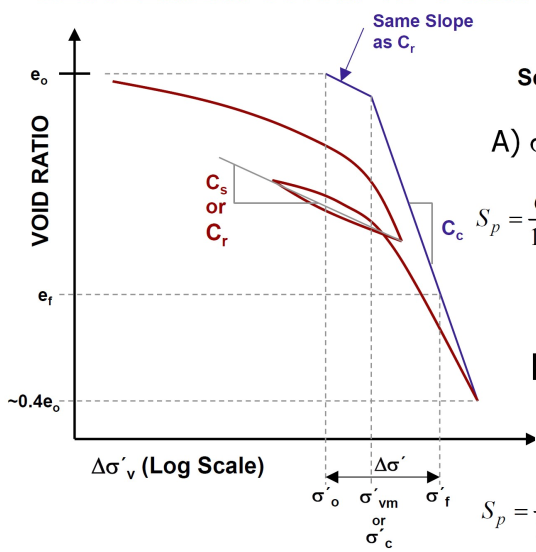
C_c = Slope of Field Virgin Consolidation Curve = **Compression Index**

C_s (or C_r) = Slope of Rebound Curve = **Swell Index**

σ´$_{vm}$ = Maximum Past Pressure

σ´$_o$ = Initial Vertical Effective Stress

Settlement from 1D Primary Consolidation



OC Clay

Settlement (S_p) using Void Ratio

A) σ'$_o$ + Δσ' ≤ σ'_{vm}

$$S_p = \frac{C_r H}{1+e_0}\log\left(\frac{\sigma'_o + \Delta\sigma'}{\sigma'_o}\right)$$

B) σ'$_o$ + Δσ' > σ'_{vm}

$$S_p = \frac{C_r H}{1+e_0}\log\left(\frac{\sigma'_{vm}}{\sigma'_o}\right) + \frac{C_c H}{1+e_0}\log\left(\frac{\sigma'_o + \Delta\sigma'}{\sigma'_{vm}}\right)$$

Time Rate of Consolidation

$$T_v = \frac{c_v t}{H_{dr}^2} = \text{time factor}$$

C_v= Coefficient of consolidation.
U= Degree of consolidation.
H_{dr}= is the max. drainage path (half the thickness of the clay layer).

$$T_{90} = \frac{c_v t_{90}}{H_{dr}^2}$$

Time factor to reach 90% consolidation, T_{90}= 0.848

$$T_{50} = \frac{c_v t_{50}}{H_{dr}^2}$$

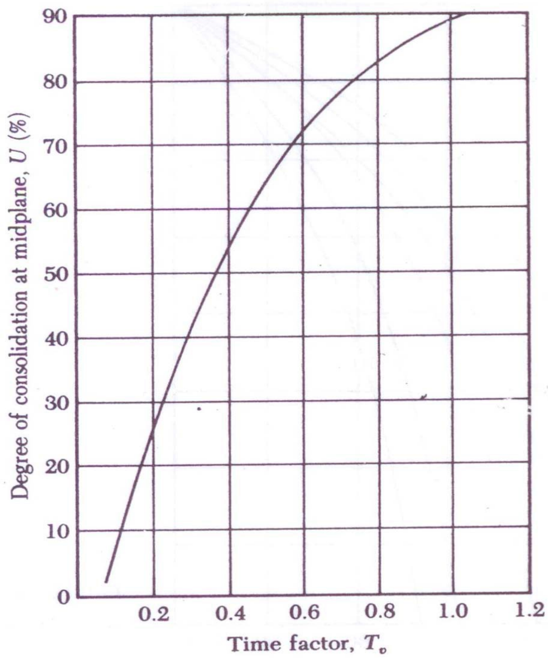
Time factor to reach 50% consolidation T_{50}= 0.197 as shown in Table 11.7

Time Rate of Consolidation (Cont.)

$$\text{For } U = 0 \text{ to } 60\%, \quad T_v = \frac{\pi}{4}\left(\frac{U\%}{100}\right)^2$$

→ $$\frac{c_v t_{\text{field}}}{H_{\text{dr(field)}}^2} = T_v \propto U^2$$ → $$t \propto U^2 \qquad \frac{t_1}{t_2} = \frac{U_1^2}{U_2^2}$$

$$\text{For } U > 60\%, \quad T_v = 1.781 - 0.933 \log(100 - U\%)$$



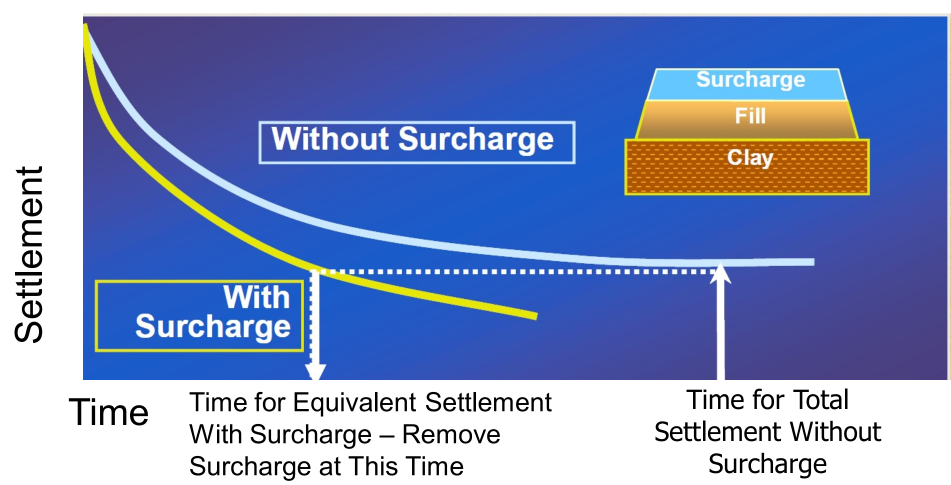
Preloading and Vertical Drains

- When highly compressible, normally consolidated clayey soil layers lie at limited/large depths, large consolidation settlements are expected as the result of the loads from large buildings, highway embankments, or earth dams etc. Pre-compression (preloading) and provision of vertical drains in soft soil may be used to minimize postconstruction settlement.

Preloading

- Simply places a surcharge fill (temporary, permanent or combination of both on top of the soil that requires consolidation (silty and clayey soils).
- The temporary surcharge can be removed when the settlements exceeds the predicted final settlement.
- Once sufficient construction, the fills can be removed and construction takes place.

Embankment on Clay Foundation
Effect of Surcharge Treatment



Preloading – General Considerations

Loading an area prior to placement of the planned structural loading to limit post-construction settlement. Also known as Surcharging.

Settlement caused by structural loading (S_p):

$$S_p = \frac{C_c H}{1+e_0}\log\left(\frac{\sigma'_o + \Delta\sigma'}{\sigma'_o}\right)$$

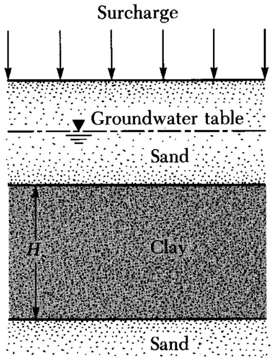
Settlement caused by structural loading and surcharging (S'_p or S_{p+f}):

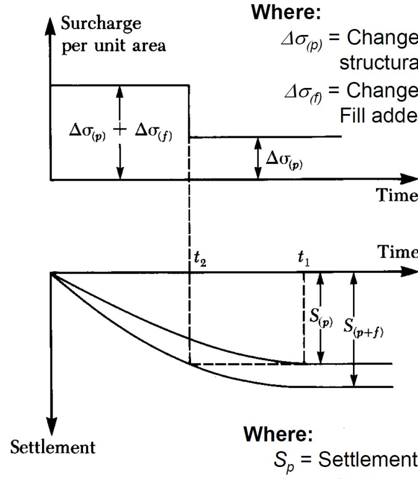
$$S'_p = S_{p+f} = \frac{C_c H}{1+e_0}\log\left(\frac{\sigma'_o + \left[\Delta\sigma' + \Delta\sigma_f\right]}{\sigma'_o}\right)$$

Where:

$\Delta\sigma_f$ = Change in vertical stress due to Fill added.

Preloading – General Considerations





Where:

$\Delta\sigma_{(p)}$ = Change in vertical stress due to structural load.

$\Delta\sigma_{(f)}$ = Change in vertical stress due to Fill added.

Where:

S_p = Settlement due to structural load.

S_{p+f} = Settlement due to structural load and Fill.

Mathematical Equations

$$U = \frac{S_p}{S'_p}$$ **Definition of average Degree of Consolidation U**

$$U = \frac{\log\left[\dfrac{\sigma'_o + \Delta\sigma'_{(p)}}{\sigma'_o}\right]}{\log\left[\dfrac{\sigma'_o + \Delta\sigma'_{(p)} + \Delta\sigma'_{(f)}}{\sigma'_o}\right]}$$ **Substitution**

$$U = \frac{\log\left[1 + \dfrac{\Delta\sigma'_{(p)}}{\sigma'_o}\right]}{\log\left\{1 + \dfrac{\Delta\sigma'_{(p)}}{\sigma'_o}\left[1 + \dfrac{\Delta\sigma'_{(f)}}{\Delta\sigma'_{(p)}}\right]\right\}}$$ **Re-arranging**

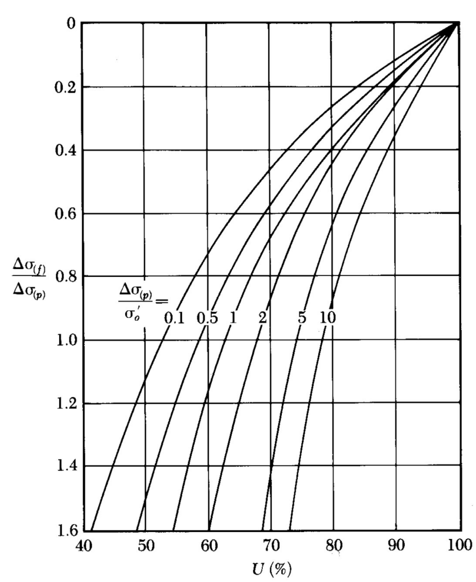
Place in graphical form for design use

Where:

$\Delta\sigma_{(f)}$ = Change in vertical stress due to Fill added.

$\Delta\sigma_{(p)}$ = Change in vertical stress due to Structural Loading.

σ'_o = Initial vertical effective stress.



STEPS:

1. Calculate primary consolidation settlement from planned loading (S_p).
2. Calculate primary consolidation settlement from planned loading plus surcharge (S_{p+f}).
3. Calculate average degree of consolidation U. Note $U = S_p/S_{p+f}$.

4 Find T_v from calculated U. To find time to when surcharge loading should be removed (i.e. t_2):

$$t_2 = \frac{T_v H_{dr}^2}{c_v}$$

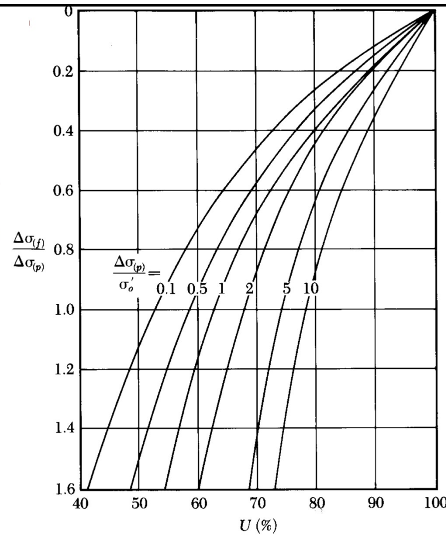


Figure 7.27. Das FGE (2006).

Example:

During construction of a highway bridge, the average permanent load on the clay layer is expected to increase by about 115 kN/m^3. The average effective overburden pressure at the middle of the clay layer is 210 kN/m^3. Here, Hc = 10m,C_c = 0.81, e_o = 2.7 and Cv = 1.08m^2/month. The clay is normally consolidated.

Determine

a.The total primary consolidation settlement of the bridge without preloading.

b.The surcharge, Δσ′(f), needed to eliminate the entire primary consolidation settlement in nine months by preloading.

Solution

Part a

The total primary consolidation settlement may be calculated from Eq:

$$S_p = \frac{C_c H}{1+e_0}\log\left(\frac{\sigma'_o + \Delta\sigma'}{\sigma'_o}\right)$$

$$= \frac{(0.81)(10)}{1+.24} log\left[\frac{210+115}{115}\right]$$

= 0.4152m = 415.2mm

We have,

Cv = 1.08 m^2/month.

H = 5m (two way drainage)

t_2 = 9 months.

$$T_v = \frac{1.08 * 9}{5^2} = 0.39$$

According to Figure , for Tv = 0.39, the value of U is 50%

$\Delta\sigma'(p)$ = 115 kN/m^2

and $\Delta\sigma'_o$ = 210kN/$m^{2,}$ so

$\Delta\sigma'(p)/ \Delta\sigma'_o$=0.55

According to Figure, $\Delta\sigma(f)/\sigma(p)$ =1.5; $\Delta\sigma(f)$ = (1.5)(115) =172.5kN/m^2

we have,

$\Delta\sigma'(p) = 115\ kN/m^2$

and $\Delta\sigma'o = 210 kN/m^2$

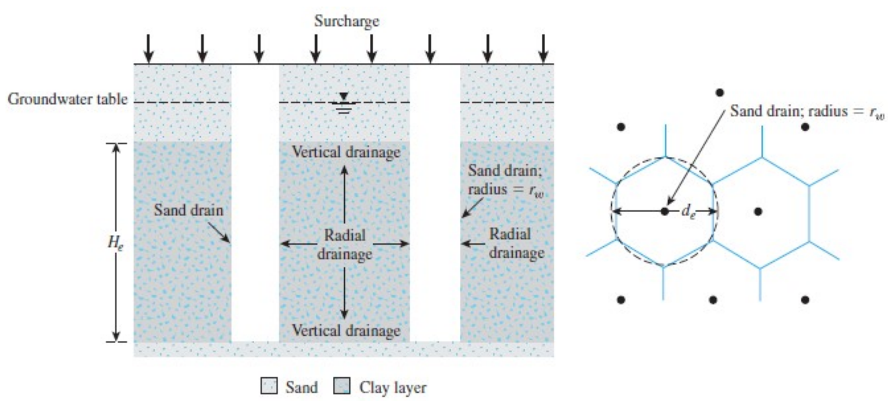
so

$\Delta\sigma'_{(p)}/\ \Delta\sigma'_{o}=.55$

According to Figure, $\Delta\sigma(f)/\sigma(p) = 1.5$; $\Delta\sigma(f) = (1.5)(115) = 172.5 kN/m^2$

Methods for Accelerating Consolidation Settlement

1- Sand drains are constructed by drilling holes and backfilling them with sand

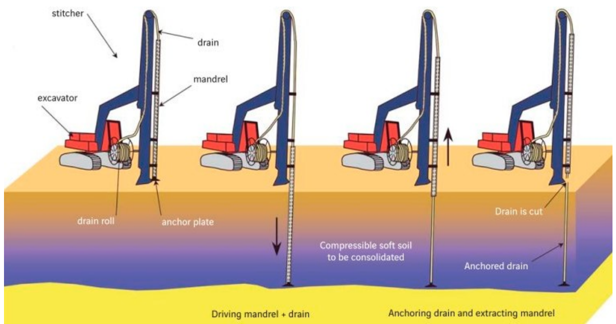


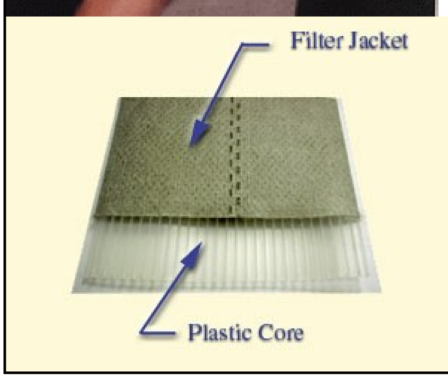
(a) Section

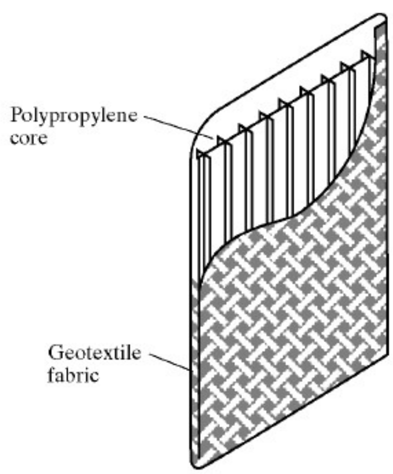
(b) Plan

Methods for Accelerating Consolidation Settlement (Cont.)

2. **Prefabricated vertical drains (PVDs)** are also called ***wick* or *strip drains*.** They may be installed much faster than sand drains because they do not require drilling.








KOMATSU

GROUND MODIFICATION FOR CONSOLIDATION

RADIAL CONSOLIDATION

U_r = Average Degree of Radial Consolidation

$$U_r = 1 - \exp\left(\frac{-8T_r}{m}\right)$$ **Barron (1948)**

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

$$n = \frac{d_e}{2r_w}$$

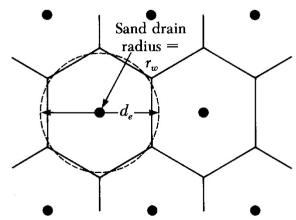
d_e = Effective Diameter
r_w = Sand Drain Radius

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

c_{vr} = Coefficient of Radial Consolidation
T_r = Time Factor for Radial Consolidation

$$c_{vr} = \frac{k_h}{\left[\dfrac{\Delta e}{\Delta\sigma'(1 + e_o)}\right]\gamma_w}$$

k_h = Coefficient of Horizontal Permeability
T_r = Time Factor for Radial Consolidation
e_o = Initial Void Ratio

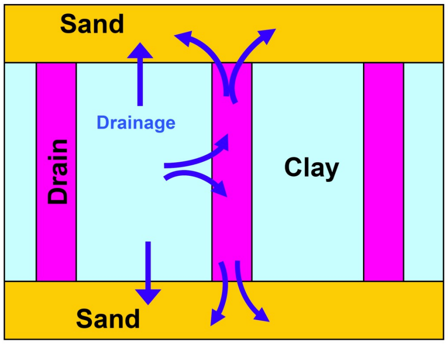


Plan View – Sand Drain Triangular Spacing
Figure 7.30. Das FGE (2006).

Variation of T_r with U - T

Degree of consolidation, U_r (%)	Time factor, T_r, for values of n				
	5	10	15	20	25
0	0	0	0	0	0
1	0.0012	0.0020	0.0025	0.0028	0.0031
2	0.0024	0.0040	0.0050	0.0057	0.0063
3	0.0036	0.0060	0.0075	0.0086	0.0094
4	0.0048	0.0081	0.0101	0.0115	0.0126
5	0.0060	0.0101	0.0126	0.0145	0.0159
6	0.0072	0.0122	0.0153	0.0174	0.0191
7	0.0085	0.0143	0.0179	0.0205	0.0225
8	0.0098	0.0165	0.0206	0.0235	0.0258
9	0.0110	0.0186	0.0232	0.0266	0.0292
10	0.0123	0.0208	0.0260	0.0297	0.0326
11	0.0136	0.0230	0.0287	0.0328	0.0360
12	0.0150	0.0252	0.0315	0.0360	0.0395
13	0.0163	0.0275	0.0343	0.0392	0.0431
14	0.0177	0.0298	0.0372	0.0425	0.0467
15	0.0190	0.0321	0.0401	0.0458	0.0503
16	0.0204	0.0344	0.0430	0.0491	0.0539
17	0.0218	0.0368	0.0459	0.0525	0.0576
18	0.0232	0.0392	0.0489	0.0559	0.0614
19	0.0247	0.0416	0.0519	0.0594	0.0652
20	0.0261	0.0440	0.0550	0.0629	0.0690
21	0.0276	0.0465	0.0581	0.0664	0.0729
22	0.0291	0.0490	0.0612	0.0700	0.0769
23	0.0306	0.0516	0.0644	0.0736	0.0808
24	0.0321	0.0541	0.0676	0.0773	0.0849
25	0.0337	0.0568	0.0709	0.0811	0.0890
26	0.0353	0.0594	0.0742	0.0848	0.0931
27	0.0368	0.0621	0.0776	0.0887	0.0973
28	0.0385	0.0648	0.0810	0.0926	0.1016
29	0.0401	0.0676	0.0844	0.0965	0.1059
30	0.0418	0.0704	0.0879	0.1005	0.1103
31	0.0434	0.0732	0.0914	0.1045	0.1148
32	0.0452	0.0761	0.0950	0.1087	0.1193
33	0.0469	0.0790	0.0987	0.1128	0.1239
34	0.0486	0.0820	0.1024	0.1171	0.1285
35	0.0504	0.0850	0.1062	0.1214	0.1332
36	0.0522	0.0881	0.1100	0.1257	0.1380
37	0.0541	0.0912	0.1139	0.1302	0.1429

GROUND MODIFICATION FOR CONSOLIDATION
Average degree of consolidation due to vertical & radial drainage



Vertical and Radial Drainage
Courtesy of www.nhi.fhwa.dot.gov

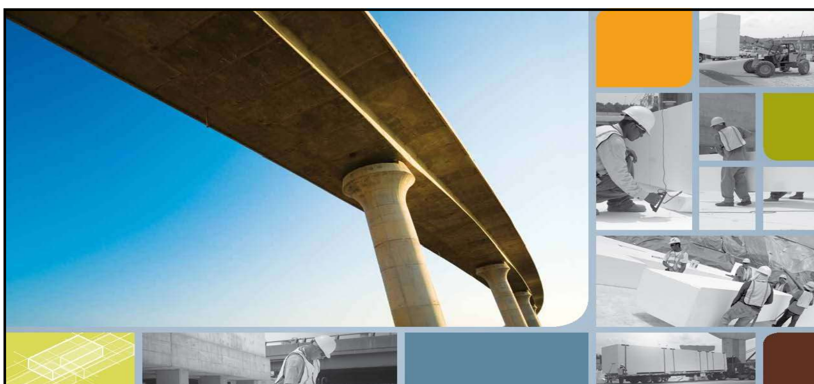
$$U_{v,r} = 1 - (1 - U_r)(1 - U_v)$$

Where:

$U_{v,r}$ = Average Degree of Consolidation due to Vertical & Radial Drainage

U_v = Average Degree of Consolidation due to Vertical Drainage

U_r = Average Degree of Consolidation due to Radial Drainage



Expanded Polystyrene (EPS) Geofoam Applications & Technical Data

EPS Industry Alliance
Geofoam Civil Engineering

EPS Geofoam

- Expanded polystyrene (EPS) geofoam used as geotechnical material since the 1960s.
- Solves engineering challenges.
- Lightweight.
  - Approximately 1% the weight of soil.
  - Less than 10% weight of other lightweight fill alternatives.
- Reduces loads imposed on adjacent and underlying soil & structures.

EPS Geofoam Benefits

- Accelerates project schedules.
- Easy to handle.
- Unaffected by weather conditions.
- Can be cut & shaped onsite.
- Retains physical properties under engineered condition of use.
- Arrives onsite having undergone rigorous QA/QC testing.

EPS Geofoam Applications & Use

- Road construction over poor soils
- Road widening
- Bridge abutment
- Bridge underfill
- Culverts, pipes & buried structures
- Compensating foundation
- Rail embankment
- Landscaping & vegetative green roofs
- Retaining & buried wall backfill
- Slope stabilization
- Stadium & theatre seating
- Levees
- Airport runway/taxiway
- Foundations for lightweight structures
- Noise & vibration damping
- Compressible application
- Seismic application
- Permafrost embankments
- Rockfall/impact protection

EPS geofoam specification

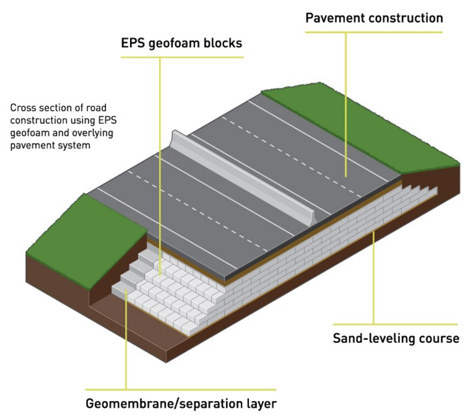
ASTM D6817 Physical Property Requirements of EPS Geofoam

Type	EPS12	EPS15	EPS19	EPS22	EPS29	EPS39	EPS46
Density, min., kg/m^3 (lb/ft^3)	11.2 (0.70)	14.4 (0.90)	18.4 (1.15)	21.6 (1.35)	28.8 (1.80)	38.4 (2.40)	45.7 (2.85)
Compressive Resistance, min., kPa (psi) at 1 %	15 (2.2)	25 (3.6)	40 (5.8)	50 (7.3)	75 (10.9)	103 (15.0)	128 (18.6)
Compressive Resistance, min., kPa (psi) at 5 %	35 (5.1)	55 (8.0)	90 (13.1)	115 (16.7)	170 (24.7)	241 (35.0)	300 (43.5)
Compressive Resistance, min., kPa (psi) at 10 % [A]	40 (5.8)	70 (10.2)	110 (16.0)	135 (19.6)	200 (29.0)	276 (40.0)	345 (50.0)
Flexural Strength, min., kPa (psi)	69 (10.0)	172 (25.0)	207 (30.0)	240 (35.0)	345 (50.0)	414 (60.0)	517 (75.0)
Oxygen index, min., volume %	24.0	24.0	24.0	24.0	24.0	24.0	24.0

The typical design load limit for EPS Geofoam is the compressive resistance at 1%. Please refer to section 4.2 for additional information.

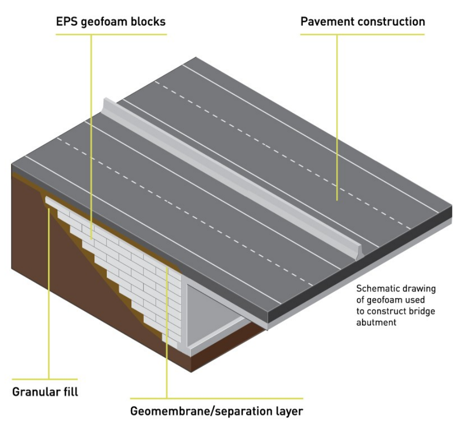
Road construction over poor soils

- Replaces compressible, soft soils or heavy fill materials.
- Prevents unacceptable loading on underlying soils and adjacent structures.
- High compressive strength supports interstate traffic loadings.



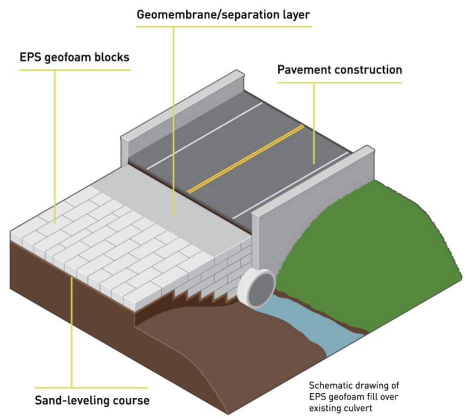
Bridge abutment

- Safely supports highway loading without over-stressing underlying soils.
- Less differential movement at bridge/approach.
- Reduces lateral forces on abutment walls, foundations & other retaining structures.



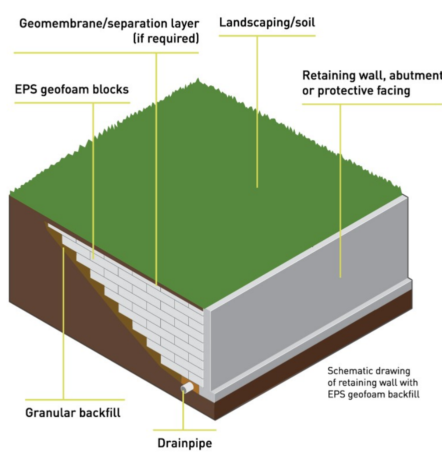
Culverts, pipelines & buried structures

- Used in lieu of heavier traditional fills over structures that were not designed to support increased loads.
- Eliminates the need for removal or strengthening of existing underground structures.



Retaining & buried wall backfill

- Reduces lateral pressures on structure.
- Limits horizontal forces that can develop during earthquakes.



Special applications

- Noise & vibration dampening
  - Free-standing walls or embankments to reduce highway noise.
  - Reduce transmission of ground borne vibrations under railways or pavements.
- Compressible application
  - Designed for strains beyond 1%.
- Seismic application
  - Reduces seismic forces imposed on buried structures, retaining walls, pipelines, etc.
- Permafrost embankments
  - Insulates underlying permafrost & reduces thawing & thaw-consolidation of ice-rich permafrost soils.
- Rockfall/impact protection
  - Improves performance of protection galleries due to high energy absorption.

Design considerations

- Lightweight
  - Manufactured in unit weights ranging from 0.7 – 2.85 lbs/cu^3/ft.
  - Imparts small dead load or stress to underlying soils, structures & utilities.
  - Eliminates need for specialized foundations or site preloading to reduce settlement & improve bearing capacity.
  - Reduces lateral stresses behind earth retaining structures.

Design considerations

- Strength
  - Available in a wide range of compressive resistances.
  - Different types of EPS geofoam can be specified on a single project to maximize savings.
- Ease of handling
  - Handled onsite by laborers or mechanized equipment.
  - Field cut using hot-wire cutter, hand saw or chain saw.

Design considerations

- Construction time
  - Faster placement rates, reduced utility relocation & less traffic disruption.
  - Not affected by adverse weather conditions.
- Construction cost
  - Adjacent structures can be designed to be less expensive.
  - Lower installation & maintenance costs.
- Stability
  - Permanent material when correctly specified & installed.

Design considerations

- Insulation
  - Superior, long-term thermal insulation.
- Protection
  - Can be damaged when exposed to certain hydrocarbons.
  - Hydrocarbon resistant geomembranes.
  - Manufactured with flame retardant.
  - Long-term UV exposure is generally surficial & does not cause detrimental property changes.
  - High wind speeds should be monitored; sandbags can be placed on top of EPS geofoam to prevent blocks from shifting.

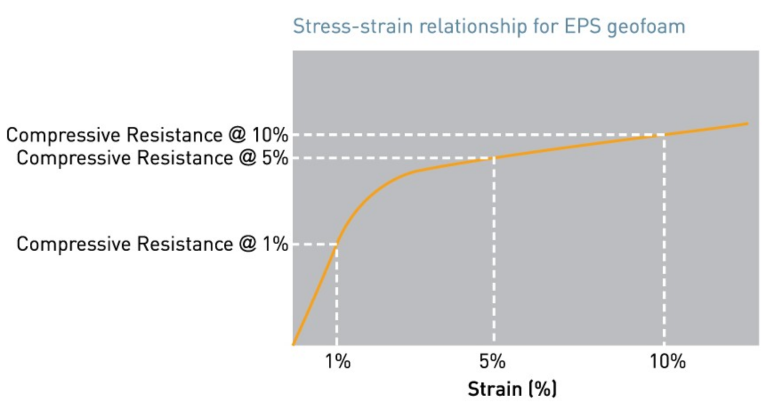
Design considerations

- Buoyancy
  - Adequate surcharge or passive restraint must be provided against uplift.
- Water absorption
  - Closed cell structure of EPS limits water absorption.
- Sustainability
  - Can be reground, recycled and reused in composite applications (lightweight concrete, plastic lumber, etc.)
  - Reduced transportation & fuel costs.
  - State-of-the-art manufacturing.

Technical data

- Compressive resistance
  - Design recommendation: limit loading to the compressive resistance at 1% strain.
  - Stress at compressive strain of 1% = elastic limit stress.

Technical data



Technical data

- Water absorption
  - Closed cell structure of EPS limits water absorption.
  - If installed in a submerged application, an increase in density will occur over time.
- Stability
  - Resistant to fungi & mold.
  - No nutritional value to insects.

General Grouting

•Grouting is… the injection of pumpable fluid materials into a soil or rock formation to change the physical characteristics of the formation.

The intent being to;
- -fill the voids in the ground,
- -strengthen the soil,
- -stabilize loose deposits, and
- -create a less permeable medium.

Grouting categories are classified according to the method of injecting the grout into the ground

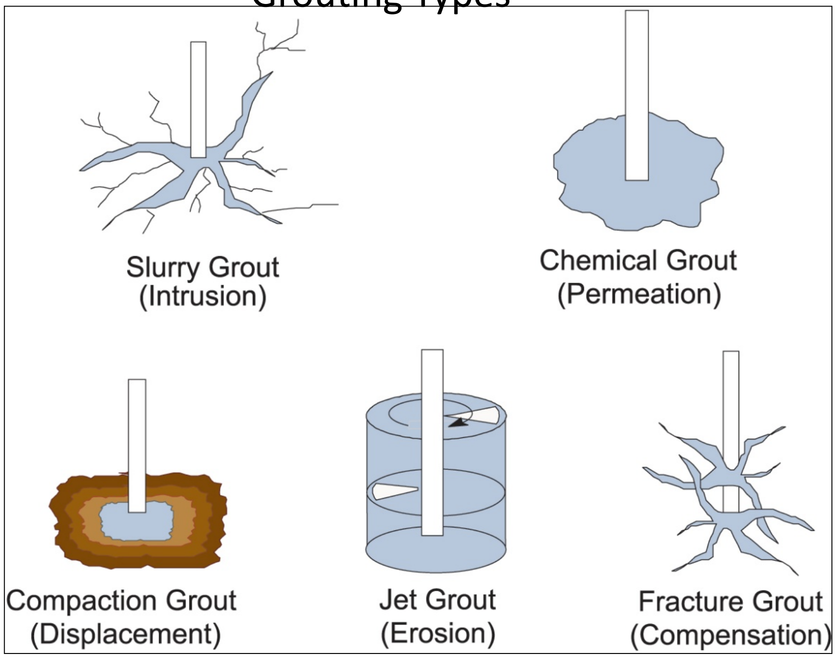
Learning Objectives: Grouting

•Subject is more qualitative than quantitative. Experts are specialty contractors

•We mainly need to understand:
- -The possibilities-what problems can we solve?
- -What grouted soil properties can we achieve?
- -Engineering behavior of grouted soil
- -How to estimate costs - major issue, as this is main disadvantage of grouting is cost of treated soil

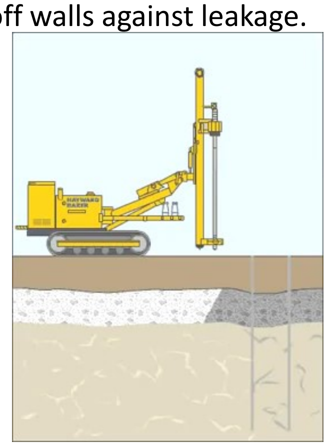
=> We need all of this information to make best Judgment.

Grouting Types



Basic Types of Grouting

Slurry Grouting – Slurry grouting consists of pressure injecting flowable suspensions of cement/clay grouts into open crack, fissures, and voids. Early uses were primarily to seal dam foundations via cut-off walls against leakage.



Basic Types of Grouting

Permeation Grouting – Permeation grouting is a process by which the pore spaces in soil or the joints in rock are filled with grout.

Either particulate or chemical grouts are used and the soils must be fairly permeable; i.e., coarse grained to allow passage of the grout.

Typically, grouting materials are cement, cement-bentonite mixtures, or clays are used in medium to coarse sands. Whereas chemical grouts are used for fine sand.

Displacement (Compaction) Grouting – Compaction grouting is the opposite of penetration grouting, where rather than the grout penetrating into the soil voids, the thick grout displaces the soil.

Compaction grout consists of a low slump concrete mortar injected into soft or loose soils. The grout forms a bulb and thus displaces and compacts the surrounding soil. “Slab-Jacking” refers to injecting the thick mortar beneath a concrete slab so as to “level” it.

Fracture Grouting – Is the most recent grouting technology introduced into the USA in the 1990's. Essentially it is precision "slab-jacking" whereby settled structures are restored to their original elevation and the bearing capacity increased.

It is used primarily in consolidating clayey soils not penetrable by grouts. Soil fracture grouting requires that the soil be fractured, not permeated. Cement or chemical grouts may be used.

Grouting Selection Consideration

- Site specific requirement
  - Strength
  - Permeability
- Soil type
- Soil groutability
  - Porosity
  - Gradation
  - Fines content
- Overburden stress

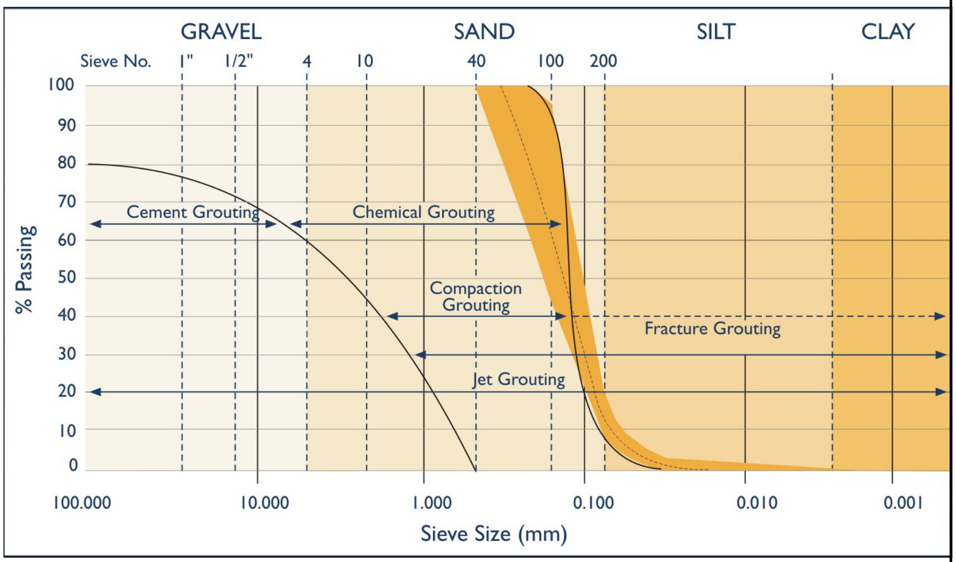
Grouting Can Prevent…

- Collapse of granular soils
- Settlement under adjacent foundations
- Groundwater movement
- Utilities damage
- Tunnel run-ins

Grouting Can Provide…

- Increased soil strength and rigidity
- Reduced ground movement
- Groundwater control
- Predictable degree of improvement

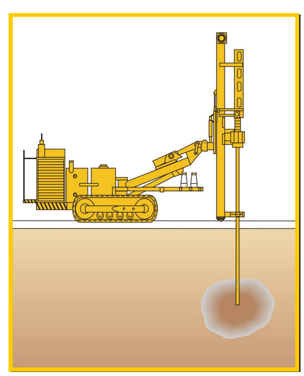
Ranges of Soils by Grouting Method



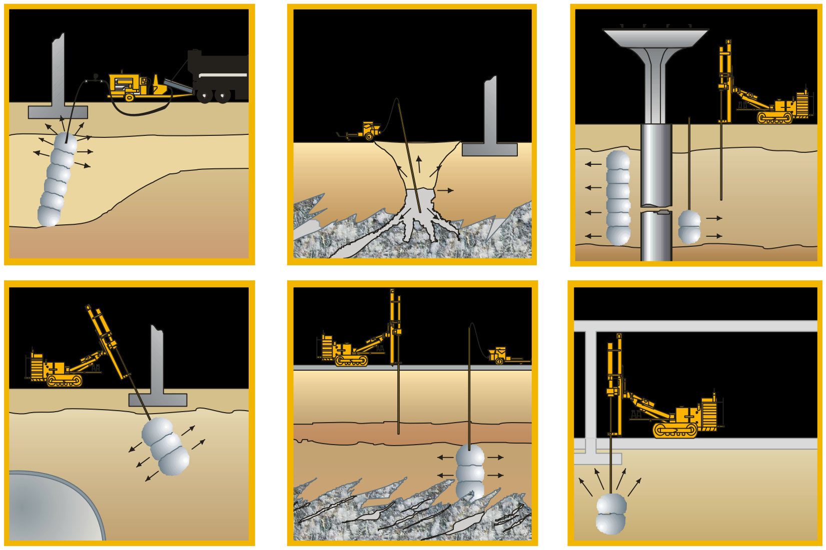
Compaction Grouting

Compaction Grouting uses displacement to improve ground conditions. A very viscous (low-mobility), aggregate grout is pumped in stages, forming grout bulbs, which displace and densify the surrounding soils.

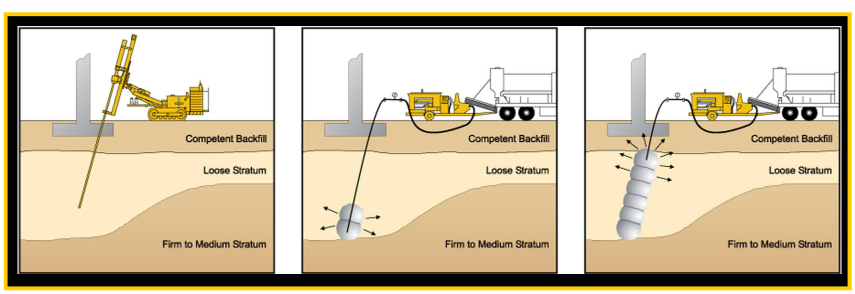
Significant improvement can be achieved by sequencing the grouting work from primary to secondary to tertiary locations.



Compaction Grouting
Applications



Compaction Grouting
Process



Compaction Grouting
Delivery Methods

Installation of grout pipe:

- Drill or drive casing
- Location very important
- Record ground information from casing installation

Initiation of grouting:

- Typically bottom up but can also be top down
- Usually pressure and/or volume of grout limited
- Slow, uniform stage injection

Compaction Grouting
Delivery Methods, cont'd

Continuation of grouting:

- On-site batching can aid control
- Pressure, grout quantity, injection rate, and indication of heave are controlling factors
- Sequencing of plan injection points very important

Compaction Grouting
Geotechnical Considerations

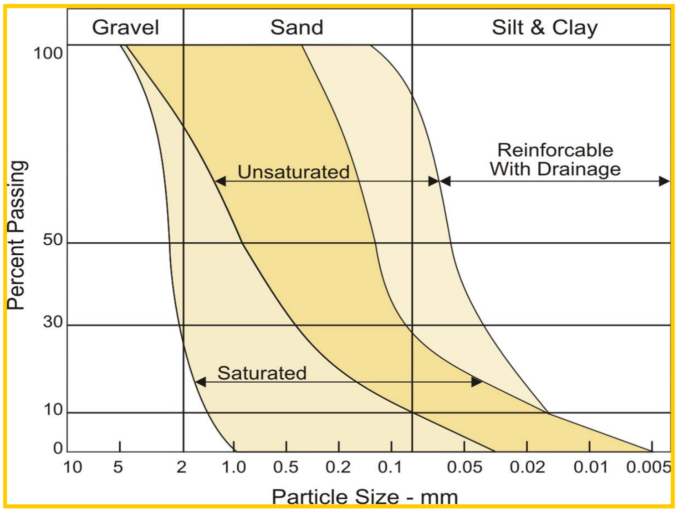
Several conditions must exist in order for compaction grouting to yield its best results:

- The in situ vertical stress in the treatment stratum must be sufficient to enable the grout to displace the soil horizontally (if uncontrolled heave of the ground surface occurs densification will be minimized)
- The grout injection rate should be slow enough to allow pore pressure dissipation. Pore pressure dissipation should also be considered in hole spacing and sequencing
- Sequencing of grout injection is also important. If the soil is not near saturation, compaction grouting can usually be effective in most silts and sands

Compaction Grouting
Geotechnical Considerations, cont'd

- Collapsible soils can usually be treated effectively with the addition of water during drilling prior to compaction grout injection
- Stratified soils, particularly thinly stratified soils, can be cause for difficult or reduced improvement capability.

Compaction Grouting
Range of Improvable Soils



Compaction Grouting
QA/QC Methods

Quality control includes procedural inspection and documentation of the work activity, testing to ensure proper mix design/injection rates, and verification of ground improvement where applicable.

Ground improvement can be assessed by Standard Penetration Testing, Cone Penetrometer Testing, or other similar methods. Data recording of important grouting parameters has been utilized on sensitive projects.

Compaction Grouting
Advantages

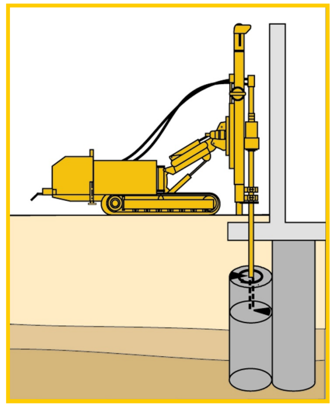
- Pinpoint treatment
- Speed of installation
- Wide applications range
- Effective in a variety of soil conditions
- Can be performed in very tight access and low headroom conditions
- Non-hazardous
- No waste spoil disposal
- No need to connect to footing or column

Compaction Grouting
Advantages, cont'd

- Non-destructive and adaptable to existing foundations
- Economic alternative to removal and replacement or piling
- Able to reach depths unattainable by other methods
- Enhanced control and effectiveness of in situ treatment with Denver System^{tm}
- Minimal impact to surface environment

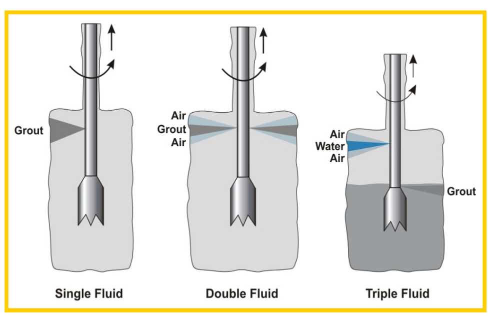
Jet Grouting

Jet Grouting is a useful Ground Modification system used to create in situ cemented geometries of soilcrete.



Jet Grouting Systems

There are three traditional jet grouting systems. Selection of a system is generally determined by the in situ soil, the application, and the physical characteristics of soilcrete (i.e. strength) required for that application.



Single Fluid Jet Grouting (Soilcrete S)

Grout is pumped through the rod and exits the horizontal nozzle(s) in the monitor at high velocity [approximately 650 ft/sec (200m/sec)].

This energy breaks down the soil matrix and replaces it with a mixture of grout slurry and in situ soil (soilcrete). Single fluid jet grouting is most effective in cohesionless soils.

Double Fluid Jet Grouting (Soilcrete D)

A two-phase internal fluid system is employed for the separate supply of grout and air down to different, concentric nozzles. The grout erodes in the same effect and for the same purpose as with Single Fluid.

Erosion efficiency is increased by wrapping the grout jet with air.

Soilcrete columns with diameters over 3 ft can be achieved in medium to dense soils, and more than 6 ft in loose soils. The double fluid system is more effective in cohesive soils than the single fluid system.

Triple Fluid Jet Grouting (Soilcrete T)

Grout, air and water are pumped through different lines to the monitor. Coaxial air and high-velocity water form the erosion medium. Grout emerges at a lower velocity from separate nozzle(s) below the erosion jet(s). This separates the erosion process from the grouting process and tends to yield a higher quality soilcrete. Triple fluid jet grouting is

the most effective s system for cohesive soils.

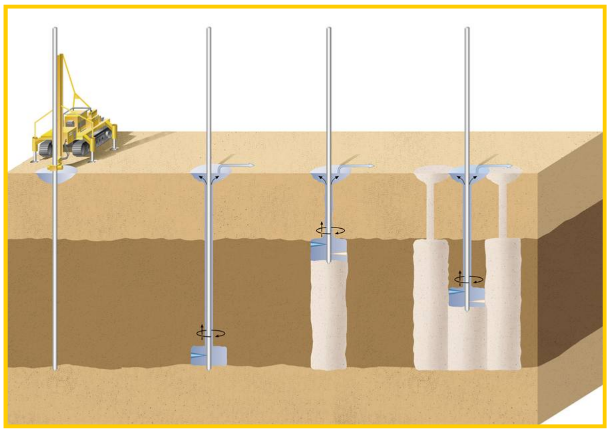
SuperJet Grouting

Grout, air and drilling fluid are pumped through separate chambers in the drill string. Upon reaching the design drill depth, jet grouting is initiated with high velocity, coaxial air and grout slurry to erode and mix with the soil, while the pumping of drilling fluid is ceased.

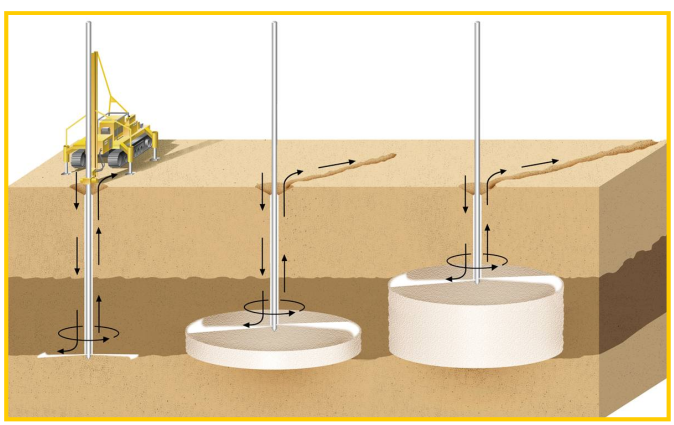
This system uses opposing nozzles and a highly sophisticated jetting monitor specifically designed for focus of the injection media. Using very slow rotation and lift, soilcrete column diameters of 10-16 ft (3-5m) can be achieved.

This is the most effective system for mass stabilization application or where surgical treatment is necessary.

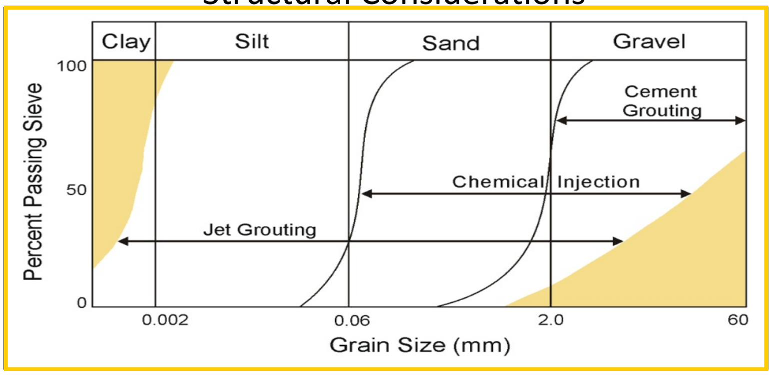
Jet Grouting
Process



SuperJet Grouting
Process



Jet Grouting
Important Geotechnical and Structural Considerations



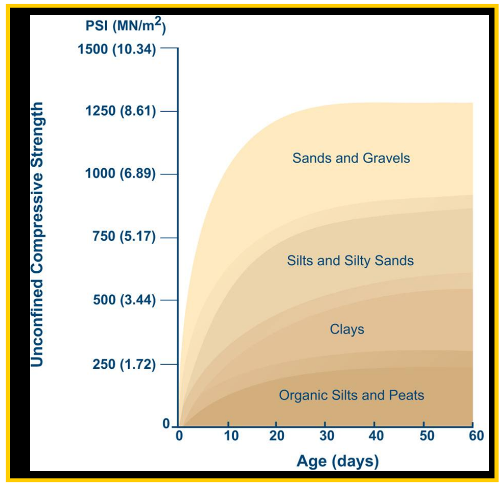
Jet grouting is effective across the widest range of soil types of any grouting system, including silts and some clays. Because it is an erosion based system, soil erodibility plays a major role in predicting geometry, quality and production. Cohesionless soils are typically more erodible than cohesive soils.

Jet Grouting
Soil Erodibility

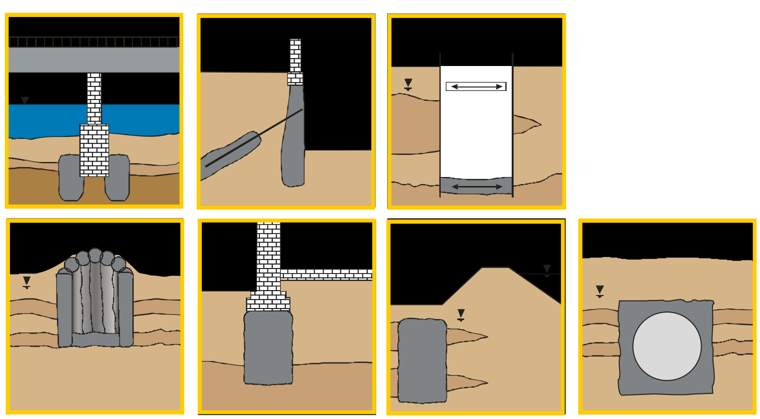
Since the geometry and physical properties of the soilcrete are engineered, the degree of improvement can be readily predicted.

Jet Grouting
Typical Soilcrete Strengths

Soilcrete strengths are variable and difficult to predict, particularly in layered soils. This chart represents an estimate of average results expected.



Jet Grouting
Applications



Jet Grouting
Design Considerations

Jet grouting systems can be designed to mix the soil with a grout or nearly replace it with grout.

For underpinning and excavation support (with groundwater control), the design consists of developing a contiguous soilcrete mass to resist overturning and sliding while maintaining the integrity of supported structures and nearby utilities.

Jet Grouting
Design Considerations

- Design Considerations for Underpinning
  - Bearing capacity of the system
  - Retaining system evaluation for lateral earth pressures and surcharge loads
  - Settlement review
  - Strength adequacy of the system
- Design Considerations for Excavation Support
  - What depth is necessary and what shear strength and geometry of soilcrete will resist the surcharge, soil and water pressure imposed after excavation?
  - Are soil anchors or internal bracing necessary?
- Design Considerations for Groundwater Control
  - What integrity is possible from interconnected soilcrete elements and how much water can be tolerated through the soilcrete barrier?

Jet Grouting
Soilcrete Design

Theoretically, treatment depth is unlimited, but Jet Grouting has rarely been performed in depths greater than 164 ft (50m).

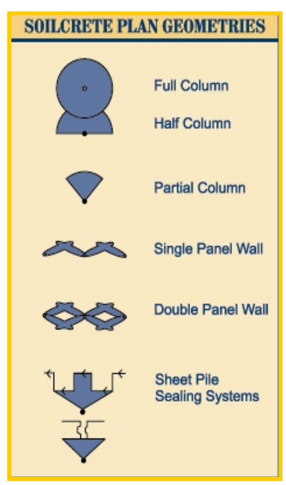
Treatment can also be pinpointed to a specific strata. The size of the soilcrete mass to be created is determined by the application. The width or diameter of each panel or column is determined during the design stage.

Jet Grouting
Soilcrete Design Geometries

The size of the soilcrete mass is determined by the application.

Accurate, detailed and frequent description of soil type, with reasonable assessment of strength or density allows this prediction to be made with confidence.

If required, shear and/or tensile reinforcement can be incorporated into the soilcrete.

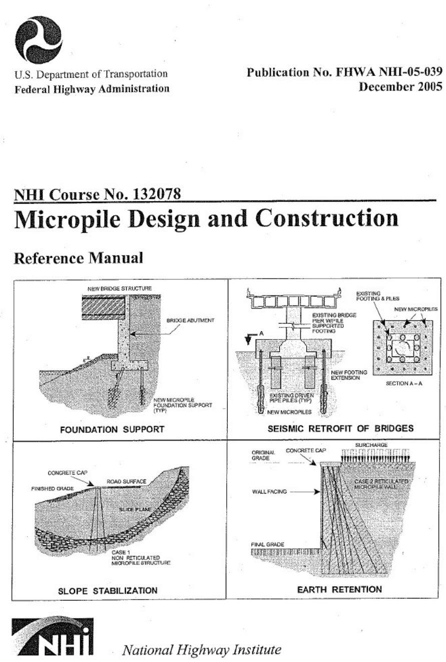


Jet Grouting
QA/QC Methods

- Sampling of waste materials -- conservative relative assessment of in situ characteristics
- Core samples
- Daily report forms -- parameters and procedures of treatment

Micropiles

FHWA-NHI-05-039 (December,2005) "Micropile Design and Construction";


U.S. Department of Transportation
Federal Highway Administration

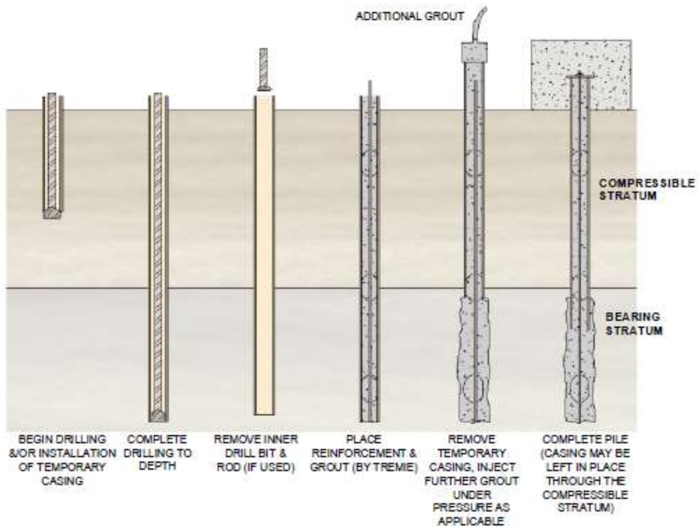
Publication No. FHWA NHI-05-039
December 2005

NHI Course No. 132078

Micropile Design and Construction

Reference Manual

National Highway Institute



Micropile Construction Sequence.

Definition - Micropile

- A small diameter (typically < 12 inches) pile,
- drilled and grouted;
- non-displacement;
- typically reinforced

Micropile Classification System

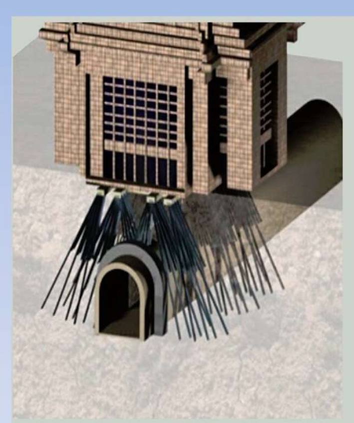
- Design Behavior (Case 1 and Case 2)
- Method of Grouting (Type A, B, C, D, *E*)
  - Affects grout/bond capacity
  - Sub Classes based on drilling method and reinforcement type

1) Based on Design Application

Classification of Micropiles

Case 1: Micropile elements, which are loaded directly & where the pile reinforcement resists the majority of the applied load.

Case 2: Micropile elements circumscribe and internally reinforce the soil to make a reinforced soil composite that resists the applied load.



Drilled Micropiles under a building

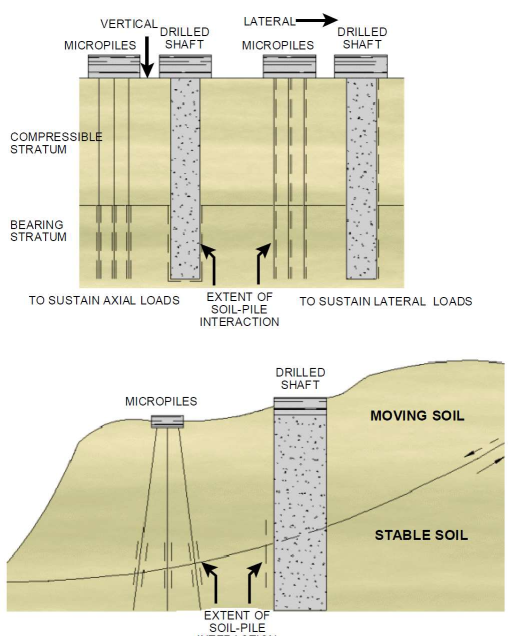
Applications

- **For Structural support (Case 1)**

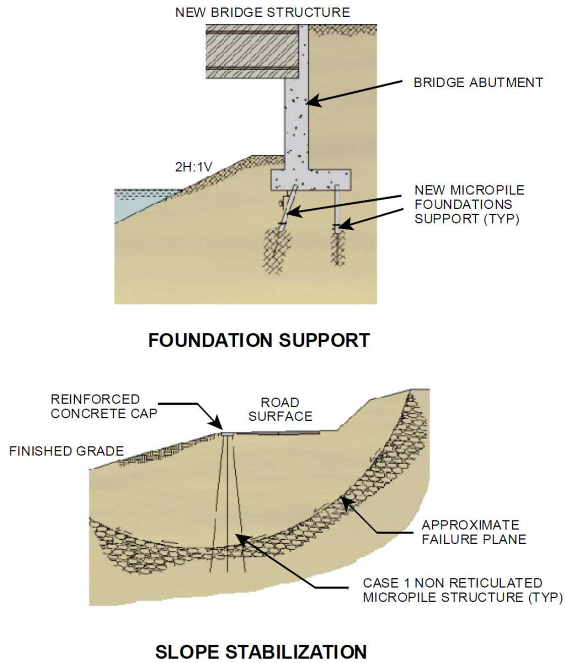
a) New Foundations
b) Under pinning of existing structures
c) Seismic retrofitting of existing structures
d) Scour protection
e) Earth retention

- **In situ Reinforcement (Case 2)**

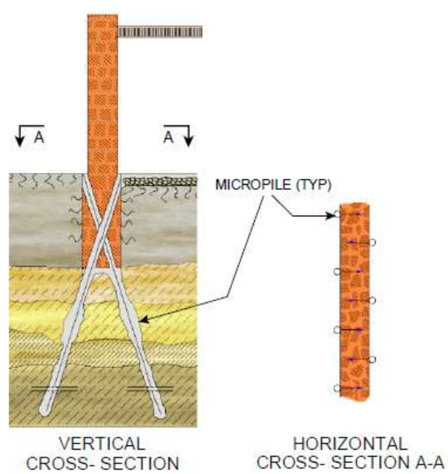
a) Slope Stabilization
b) Earth retention
c) Ground strengthening and protection
d) Settlement reduction



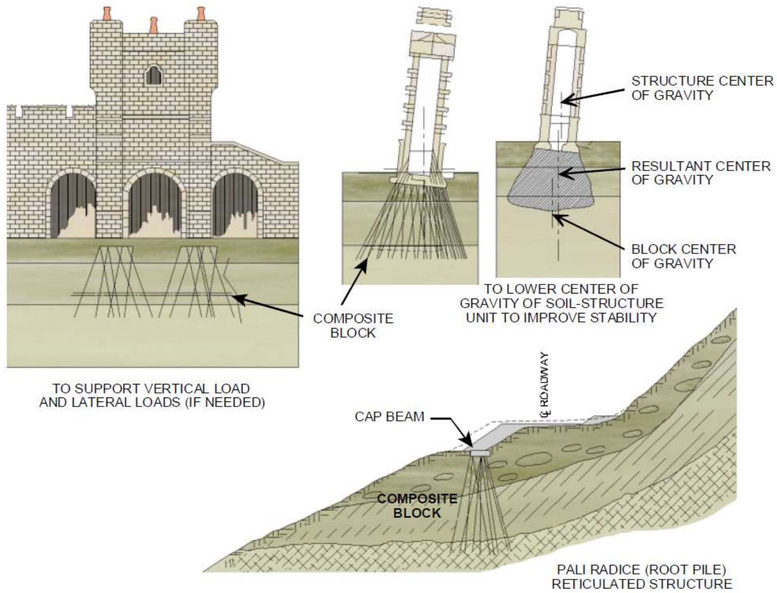
CASE 1 Micropiles (Directly Loaded)



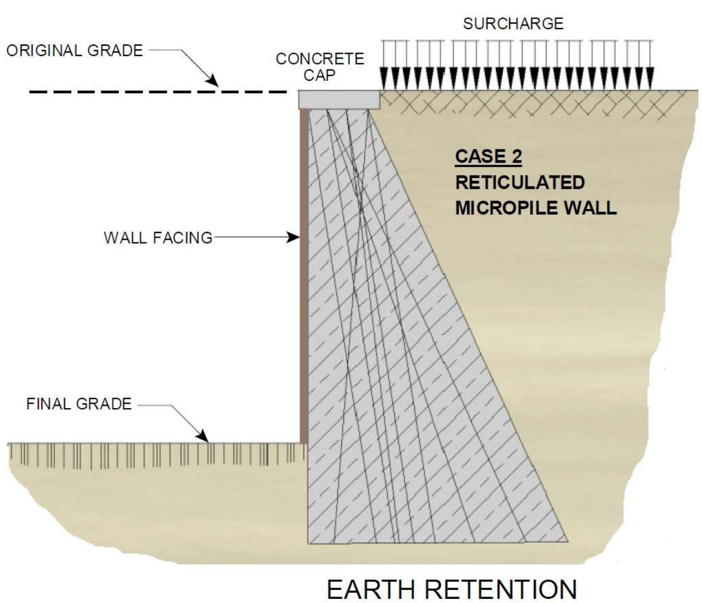
CASE 1 Micropiles (Directly Loaded)



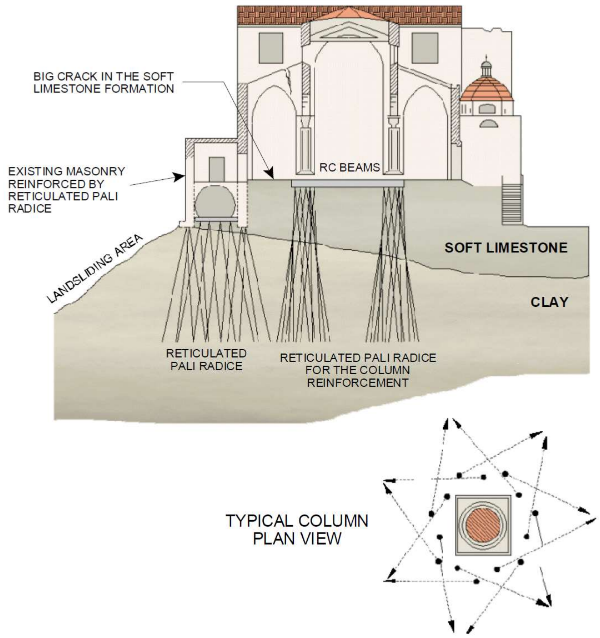
Classical arrangement of root piles for underpinning



CASE 2 Micropiles –Arranged Micropile Network.



CASE 2 Micropiles –Arranged Micropile Network.



Typical Network of arranged Micropiles

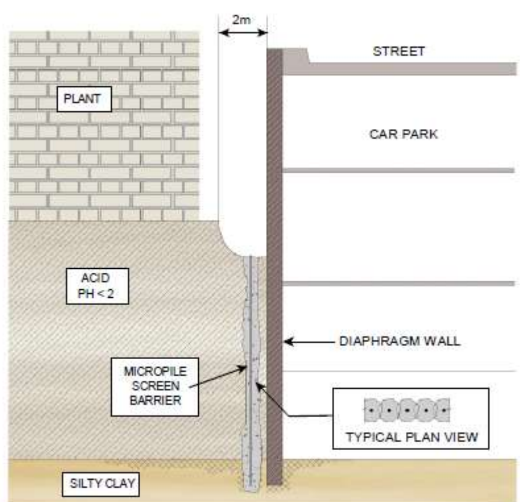


Figure 3-3. Protection of an Existing Diaphragm Wall with a Secant Micropile Screen using Anti-acid Mortar (after Bachy, 1992).

Case 2 Micropiles

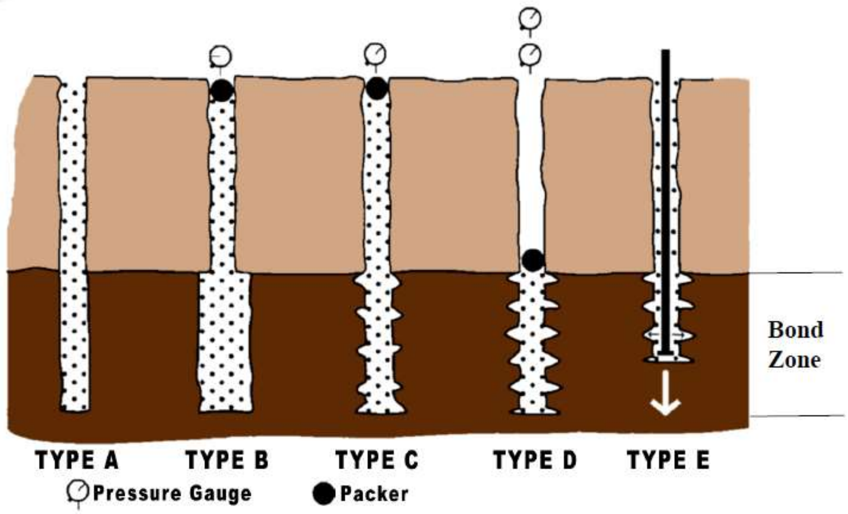
- Network of Micropiles
- Act As Group to Reinforce The Soil Mass
- Each Micropile is Lightly Reinforced
- Design Procedures Not Fully Developed

2) Based on Construction type

•The method of grouting is generally the most sensitive construction control over grout/ground bond capacity. Grout-to-grout capacity varies with the grouting method**.**

a) Type A: Gravity Grout
b) Type B: Pressure through Casing
c) Type C: Single Global Post Grout
d) Type D: Multiple Repeatable Post Grout

Micropile Classification Based on Grouting



Type A: the grout is placed under gravity head only using sand-cement motors or neat cement.

• **Type B:** In this type neat cement grout is placed in to the hole as the temporary steel casing is with drawn. Injection pressures varies from 0.5 to 1.0 MPa. The pressure is limited to avoid fracturing of the surrounding ground.

Type C: This is done in two step process:
1) As of Type A
2) Prior to hardening of the primary grout, similar grout is injected one time via a sleeve grout pipe at pressure of at least 1.0MPa.

• **Type D:** This is done in two step process of grouting similar to Type C with modifications to step 2 where the pressure is injected at a pressure of 2.0 to 8.0 MPa:

Relationship Between Micropile Application, Design Behavior and Construction Type

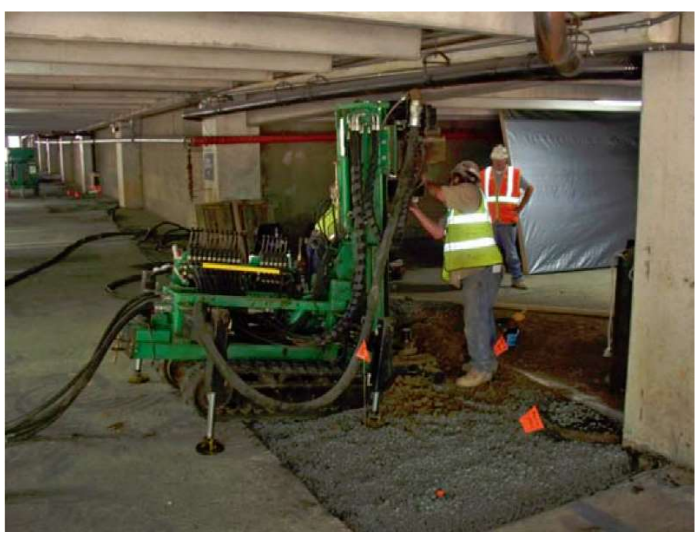
	STRUCTURAL SUPPORT	IN-SITU EARTH REINFORCEMENT			
Application	Underpinning of Existing Foundations, New Foundations, and Seismic Retrofitting	Slope Stabilization and Earth Retention	Ground Strengthening	Settlement Reduction	Structural Stability
Design Behavior	CASE 1	CASE 1 and CASE 2	CASE 2 with minor CASE 1	CASE 2	CASE 2
Construction Type	Type A (bond zones in rock or stiff clays) Type B, C, and D in soil	Type A and Type B in soil	Types A and B in soil	Type A in soil	Type A in soil
Frequency of Use	Probably 95 percent of total world applications	0 to 5 percent			

Micropile Materials

Permanent Steel Pipe
- API 5CT & ASTM A252
- 80 ksi yield
- Flush joint threads

- **Steel Reinforcement**
  - ASTM A615, Gr. 60 & 75
  - ASTM A722, Gr. 150
  - Mechanical coupling
  - Hollow bars
- **Cement Grout**
  - Neat cement – ASTM C150
  - W/C ratio of 0.45
  - 4000 psi (min)

Micropile Installation Equipments



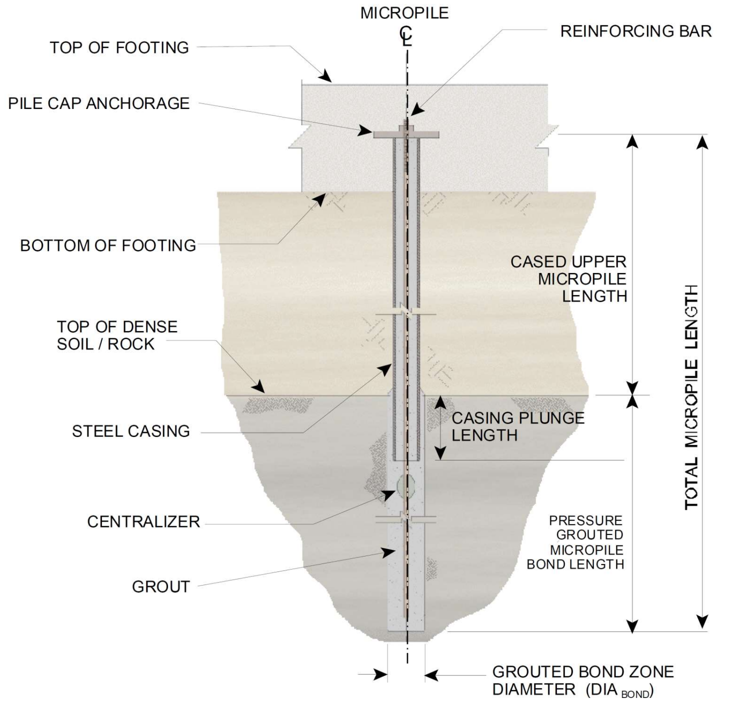
Micropile Installation Equipments

Micropile Installation Equipments

Drill Rods and
Various Casing bits
and Shoes.

Outline of Design steps

1) Review available project information
2) Review geotechnical data
3) Geotechnical design
4) Pile structural design
5) Combined geotechnical & structural design considerations
6) Additional micro pile system considerations



Detail of a composite Reinforced Micropile.

Structural design of micropile cased length

Allowable Compression Load for Cased Length

$$P_{c-allowable} = \left[0.4\, f'_{c-grout} \times A_{grout} + 0.47\, F_{y-steel} \left(A_{bar} + A_{ca\,\sin\,g}\right)\right]$$

$P_{c\text{-allowable}}$ = allowable compression load;

f'_c = unconfined compressive strength of grout (typically a 28-day strength);

A_{grout} = area of grout in micropile cross section (inside casing only, discount grout outside the casing);

$F_{y\text{-steel}}$ = yield stress of steel;

A_{bar} = cross sectional area of steel reinforcing bar (if used); and

A_{casing} = cross sectional area of steel casing.

Allowable Tension Load for Cased Length

$$P_{t-allowable} = 0.55\,F_{y-steel} \times \left(A_{bar} + A_{ca\sin g}\right)$$

Allowable compression load for the uncased length of a micropile

$$P_{c-allowable} = \left(0.4\,f_c^{'} \times A_{grout} + 0.47\,F_{y-bar} \times A_{bar}\right)$$

allowable tension load for the uncased length of a micropile

$$P_{t-allowable} = 0.55\,F_{y-bar} \times A_{bar}$$

The ultimate structural capacity

$$P_{ult-compression} = \left[0.85\,f_{c-grout}^{'} \times A_{grout} + f_{y-ca\sin g} \times A_{ca\sin g} + f_{y-bar} \times A_{bar}\right]$$

$$P_{ult-tension} = \left[f_{y-ca\sin g} \times A_{ca\sin g} + f_{y-bar} \times A_{bar}\right]$$

Evaluate Geotechnical Capacity of Micropile

$$P_{G-allowable} = \frac{\alpha_{bond}}{FS} \times \pi \times D_b \times L_b$$

where:

α_{bond} = grout to ground ultimate bond strength;

FS = factor of safety applied to the ultimate bond strength;

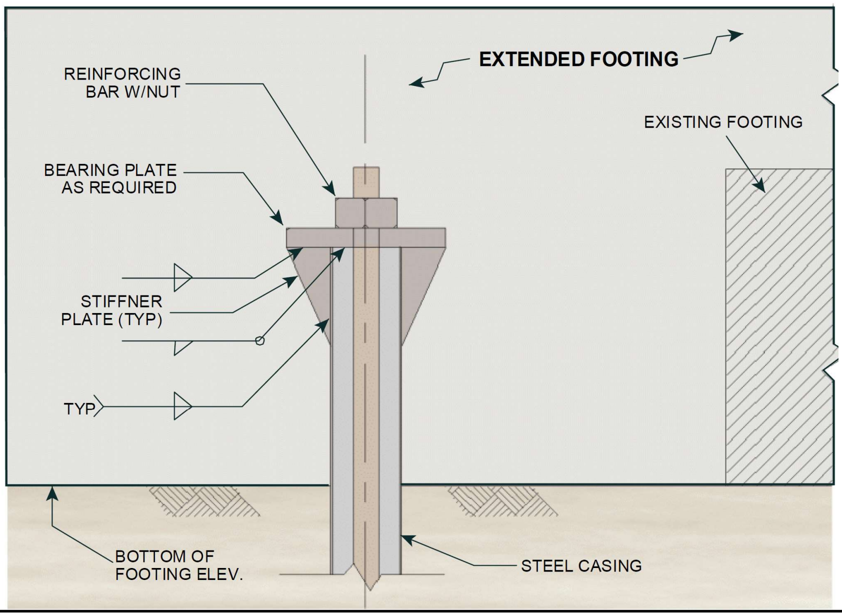
D_b = diameter of the drill hole; and

L_b = bond length

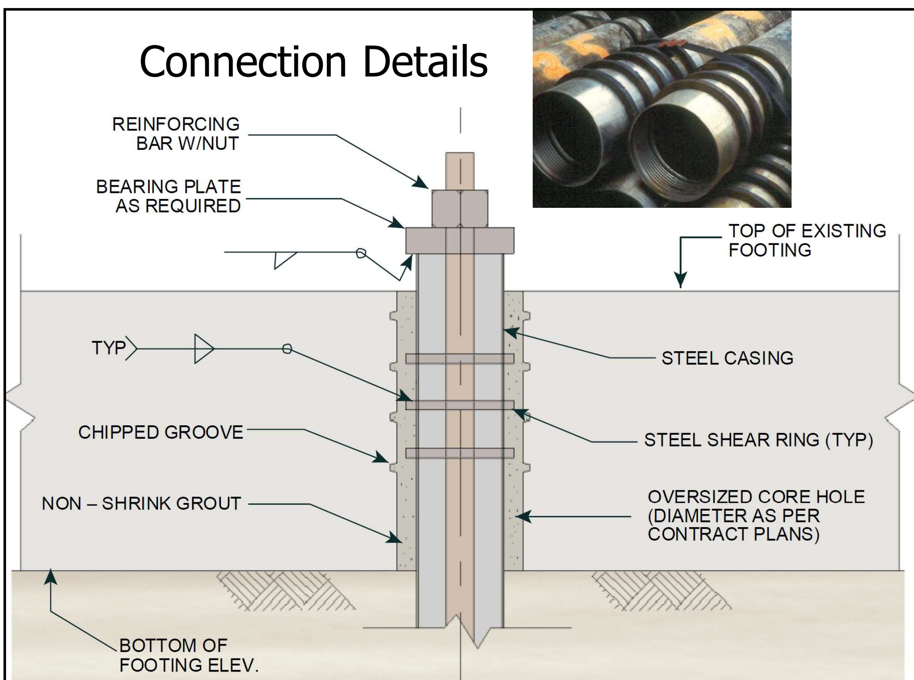
Table:1(a): Summary of typical $\alpha_{bond\ nominal\ strength}$ (kPa)values (Grout-to-ground bond) for micropile design

Soil/Rock Description	Type A	Type B	Type C	Type D
Silt&clay(some sand) (Soft, medium plastic)	35-70	35-95	50-120	50-145
Silt&clay(some sand) (Stiff, dense to very dense)	50-120	70-190	95-190	95-190
sand (some silt) (fine, loose medium dense)	70-145	70-190	95-190	95-240
sand (some silt,gravel) (fine coarse,medium -very dense)	95-215	120-360	145-360	145-385
gravel(some sand) (medium-very dense)	95-265	120-360	145-360	145-385
Glacial till(silt, sand gravel) (medium very dense cemented)	95-190	95-310	120-310	120-335

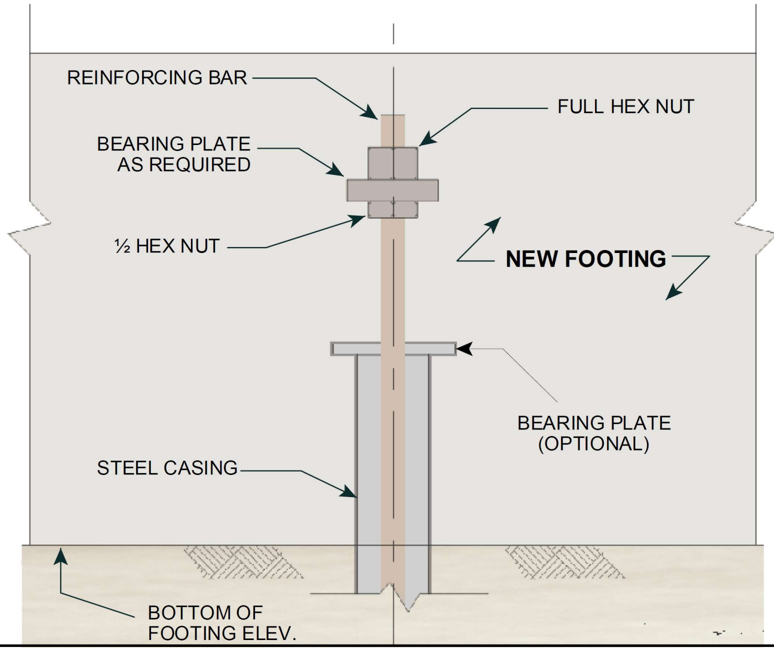
Connection Details



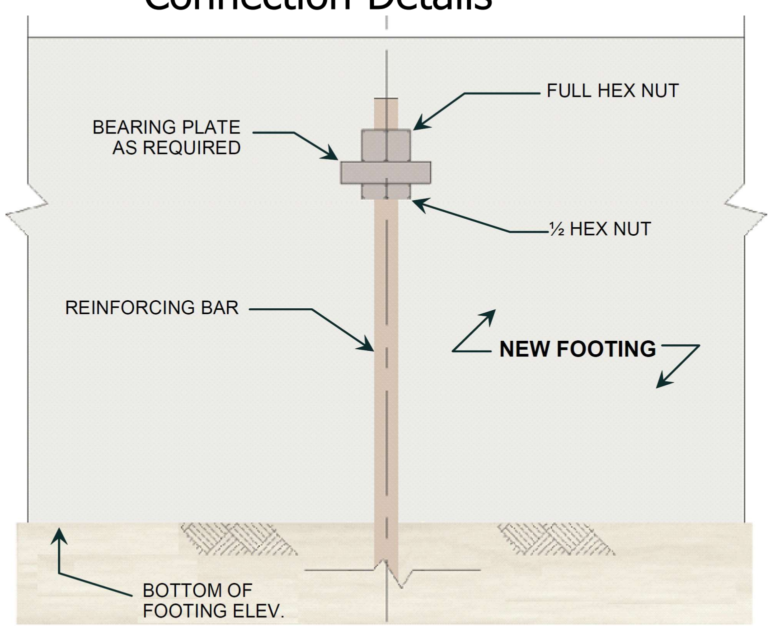
Connection Details



Connection Details



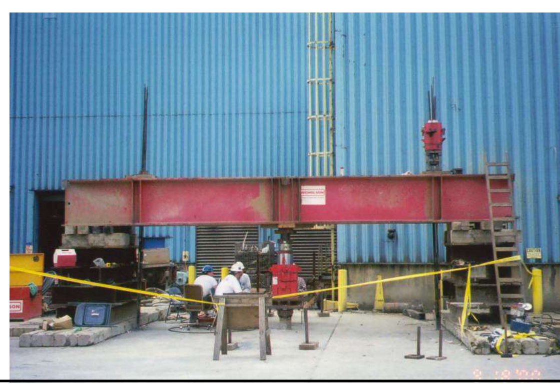
Connection Details



Develop Load Test Program

Scope of Program

- Include or not include??
- FS min for verification and proof testing is 2.0
- Max test load should not exceed 80% of ultimate structural capacity



Load Test Program

Verification Test

- Verifies design assumptions regarding bond zone strength/deformation (taken to design load x FS or can be taken to failure);
- Verifies adequacy of Contractor’s installation methods;
- May include creep tests, if conditions apply;
- Performed prior to installation of production piles;
- Authorization to proceed on production pile after successful verification tests;
- May require modification of installation procedures if results unsuitable ;
- *If installation procedures change, perform addition testing*

Load Test Program

Proof Load Testing

- “Proof” load testing on selected production piles provides qa to confirm installation procedures
- *Performed on specified number of pile*
- *Confirm capacity of suspect piles*

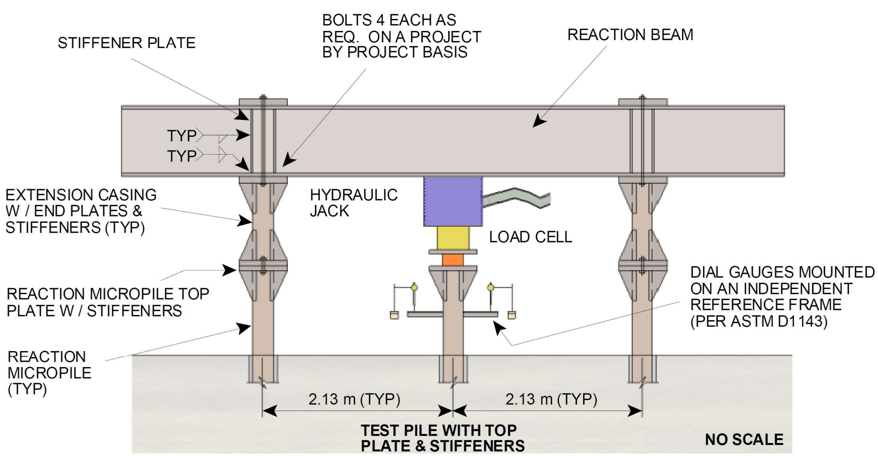
Load Test Frequency

Verification Load Testing

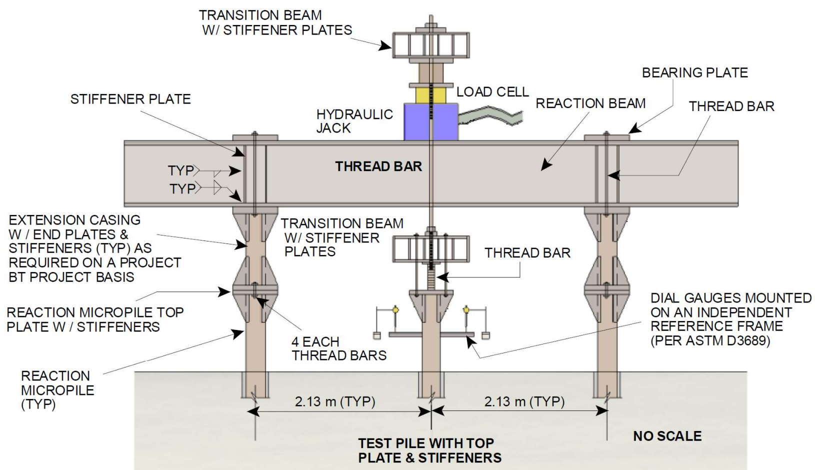
- *Compression/Tension - Minimum one/project*
- *Lateral Loads – If design requires*

"Proof" Load Testing

- Underpinning >> 1 per substructure unit
- Seismic Retrofit >> 1 per substructure unit
- New construction >> 1 per substructure unit but not less than 5% of total production piles

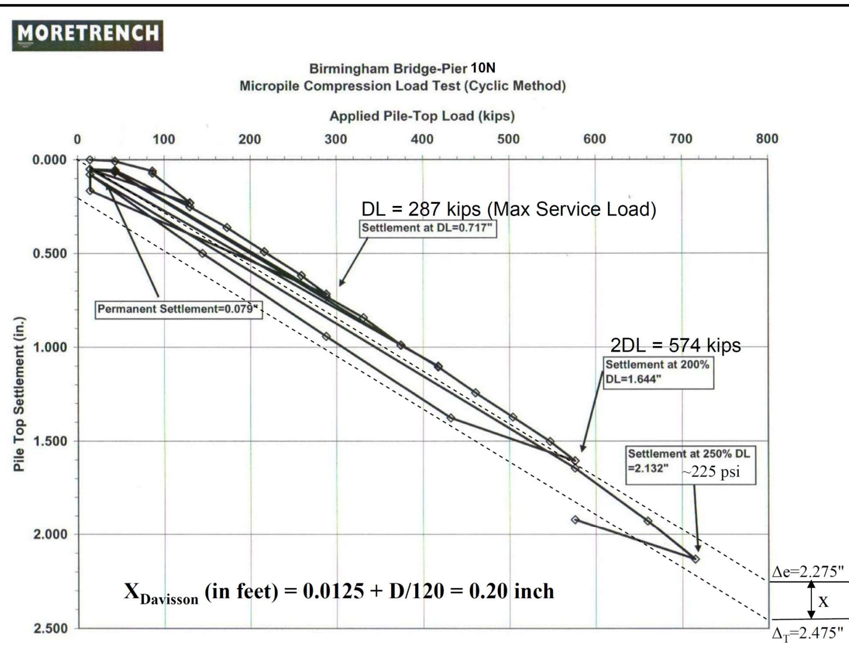


Schematic of Compression Load Test Arrangement (ASTM D1143).

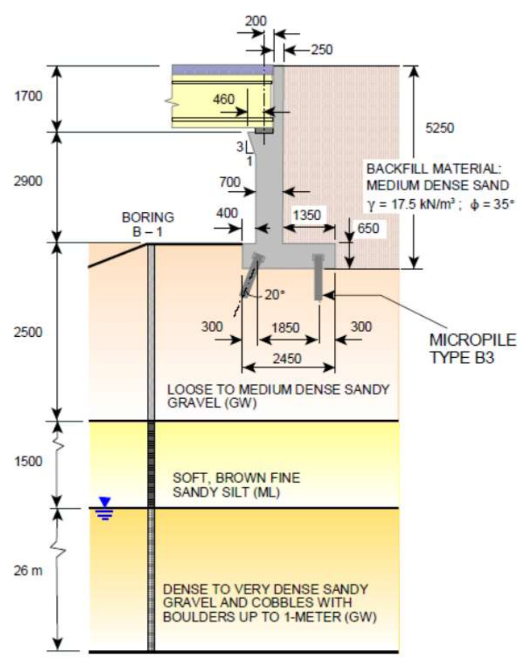


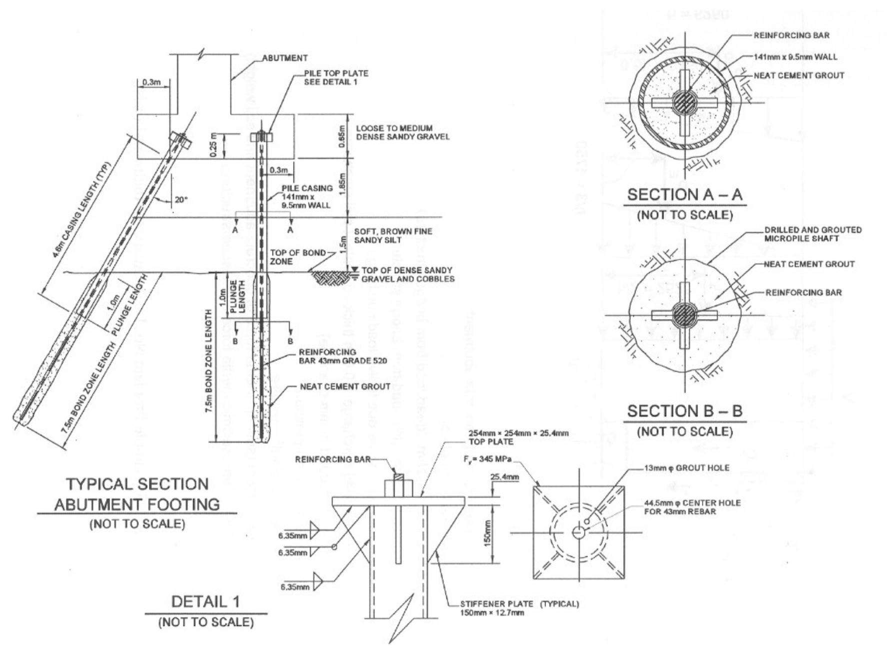
Note: 2.13 m = 7 ft

Schematic of Tension Load Test Arrangement (ASTM D3689).



Design Example





STEP 1 – ABUTMENT DESIGN LOADS

Table S1-1. Sample Problem No. 1- Summary of Abutment Loads Per Meter Length

Load	Description	Type	Load		Moment Arm		Moment*
			F_x (kN)	F_y (kN)	X (m)	Y (m)	M (kN-m)
D_c	Dead load of concrete abutment	D		97.00	0.27		26.19
D_S	Dead load of soil	E		108.68	-0.55		-59.77
V_{DL}	Dead load from bridge superstructure	D		178.70	0.58		103.65
V_{LL}	Live load from bridge superstructure	L		73.00	0.58		42.34
H_L	Earth pressure due to live load surcharge	L	14.91			2.63	39.13
P_E	Earth pressure	E	65.32			1.75	114.31
P_{EQ-H}	Seismic earth pressure	EQ	15.91			3.15	50.12
I_A	Seismic inertial force of concrete & soil weight	EQ	30.9			2.35	72.50
I_S	Seismic inertial force of the superstructure	EQ	26.8			3.55	95.14

STEP 2 – DETERMINE PILE DESIGN LOADS PER METER LENGTH

Group I Pile Design Loads

$$\text{Rear Pile Vertical Load} = \left[\frac{457.4}{1.111} - \frac{[266 - 457.4 \times 0.185]\,1.11}{0.9127}\right] = 191\,k\text{N}$$

$$\text{Front Pile Vertical Load} = \left[\frac{457.4}{1.111} + \frac{[266 - 457.4 \times 0.185]\,0.74}{0.9127}\right] = 559\,k\text{N}$$

$$\text{Front Pile Axial Load} = \frac{559}{\cos(20°)} = 595\ k\text{N} \ \text{compression}$$

STEP 3 – EVALUATE ALLOWABLE STRUCTURAL CAPACITY OF CASED LENGTH

Pile Cased Length Allowable Load

Material dimensions and properties

Casing - Use 141 mm outside diameter x 9.5 mm wall thickness.

Reduce outside diameter by 1.6 mm to account for corrosion.

Casing outside diameter OD_{casing} = 141 mm - 2 x 1.6 mm = 137.8 mm

Pile casing inside diameter ID_{casing} = 141 mm - 2 x 9.5 mm = 122 mm

Pile casing steel area $A_{casing} = \frac{\pi}{4}\left[OD^2_{casing} - ID^2_{casing}\right] = 3{,}224\,mm^2$

Casing yield strength $F_{y-casing} = 241\text{MP}a$

Reinforcing bar - Use 43 mm grade 520 steel reinforcing bar.

Bar area $A_{bar} = 1{,}452\ mm^2$

Bar steel yield strength $F_{y\text{-}bar} = 520\ MPa$

Grout area $A_{grout} = \frac{\pi}{4} ID^2_{ca\sin g} - A_{bar} = 10{,}240\ mm^2$

Grout compressive strength $f'_{c-grout} = 34.5\ MPa$

For strain compatibility between casing and rebar, use for steel yield stress:

$F_{y\text{-}steel}$ = the minimum of $F_{y\text{-}bar}$ and $F_{y\ casing}$ = 241 MPa

Allowable Tension Load

$$P_{t-allowable} = 0.55 F_{y-steel}\left(A_{bar} + A_{ca\sin g}\right) = 620\,kN$$

Allowable Compression Load

$$P_{c-allowable} = \left[0.4 f'_{c-grout} \times A_{grout} + 0.47 F_{y-steel}\left(A_{bar} + A_{ca\sin g}\right)\right] = 671\,kN$$

STEP 4 – EVALUATE ALLOWABLE STRUCTURAL CAPACITY OF UNCASED LENGTH

Soil conditions and the method of pile installation can affect the resulting diameter of the pile bond length. For this example, assume a drill-hole diameter of 50 mm greater than the casing outside diameter (OD).

Using a casing OD = 141mm

Therefore, Grout D_b = 141 mm + 50 mm = 191 mm (0.191 m)

Bond length grout area $$A_{grout} = \frac{\pi}{4} D^2{}_b - A_{bar} = 27{,}200\ mm^2$$

Allowable Tension Load

$$P_{t-allowable} = 0.55 F_{y-bar} \times A_{bar} = (0.55 \times 520\,MPa \times 1{,}452\,mm^2) = 415\,kN$$

Allowable Compression Load

$$P_{c-allowable} = \left(0.4 f_c^{'} \times A_{grout} + 0.47 F_{y-bar} \times A_{bar}\right)$$
$$P_{c-allowable} = \left(0.4 \times 34.5\,MPa \times 27{,}200\,mm^2 + 0.47 \times 520\,MPa \times 1{,}452\,mm^2\right) = 730\,kN$$

STEP 5 – EVALUATE ALLOWABLE GEOTECHNICAL CAPACITY

From Table 5-3 select an ultimate unit grout-to-ground bond strength α_{bond} = 265 kPa. This represents an approximate average value for gravels.

The controlling non-seismic micropile loading is 595 kN per pile. Therefore, an allowable geotechnical bond load $P_{G\text{-}allowable} \geq$ 595 kN/pile must be provided to support the structural loading.

Provide: $P_{G\text{-}allowable} \geq$ 595 kN/pile

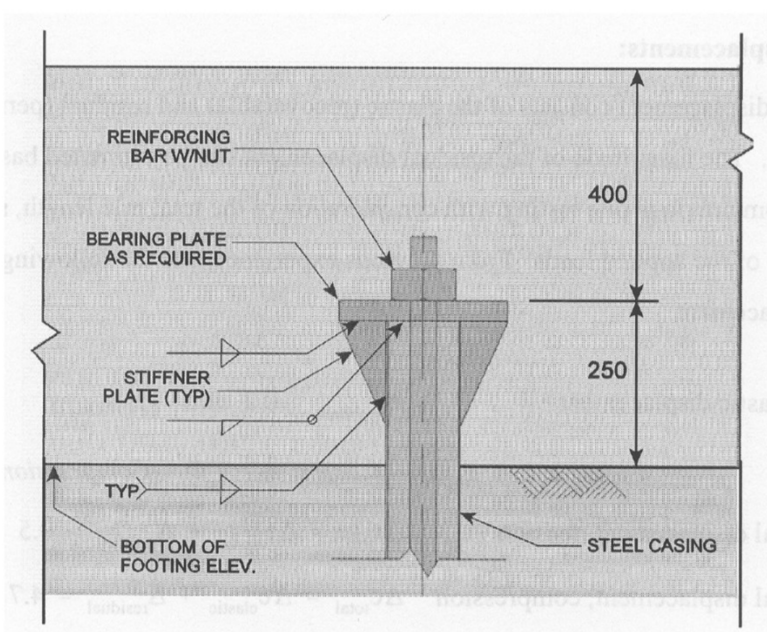
Compute the bond length, L_b, required to provide $P_{G\text{-}allowable}$ as follows:

$$L_b = \frac{P_{G-allowable} \times FS}{\alpha_{bond} \times \pi \times D_b}$$

$$L_b = \frac{595\,kN \times 2.0}{265\,kPa \times \pi \times 0.191\,m} = 7.48\,m$$

Select Bond Length = 7.5 m

$$P_{G-allowable} = \frac{265\,kPa}{2.0} \times 3.14 \times 0.191\,m \times 7.5\,m = 596\,kN$$



STEP 9 – CHECK STRUCTURAL CAPACITY TO RESIST TEST LOADS

Cased Length		**Uncased Length**	
OD*	= 141mm		
ID	= 122 mm (9.5 mm wall)		
A_{casing}	= 3,925 mm²	A_{grout}	= 27,200 mm²
$F_{y\text{-}casing}$	= 241 MPa (use for casing and bar)	$f'_{c\text{-}grout}$	= 34.5 MPa
A_{bar}	= 1,452 mm²	A_{bar}	= 1,452 mm²
$F_{y\text{-}bar}$	= 520 MPa	$F_{y\text{-}bar}$	= 520 MPa
A_{grout}	= 10,240 mm²		
$f'_{c\text{-}grout}$	= 34.5 MPa		

* Do not reduce by 1.6 mm for corrosion.

$$P_{c-allowable} = \left[0.68 f'_{c-grout} A_{grout} + \frac{F_{y-casing}}{1.25}\left(A_{bar} + A_{casing}\right)\right]$$

$$P_{c-allowable} = \left[0.68 \times 34.5 MPa \times 10{,}240 mm^2 + \frac{241 MPa}{1.25}\left(1{,}452 mm^2 + 3{,}925 mm^2\right)\right] = 1{,}277 kN$$

Pile Uncased Length Allowable Load

$$P_{c-allowable} = 0.68 f'_{c-grout} A_{grout} + 0.80 F_{y-bar} A_{bar}$$

$$P_{c-allowable} = 0.68 \times 34.5 MPa \times 27{,}200 mm^2 + 0.80 \times 520 MPa \times 1{,}452 mm^2 = 1{,}242 kN$$

The design pile is OK for the proof test at 952 kN and the verification test at 1,190 kN.

Dewatering

Purposes for Dewatering

- **The purpose of dewatering is to control the surface and subsurface hydrologic environment in such a way as to permit the structure to be constructed "in the dry."**

- **Dewatering means "the separation of water from the soil," or perhaps "taking the water out of the particular construction problem completely."**

- **This leads to concepts like pre-drainage of soil, control of ground water, and even the improvement of physical properties of soil.**
- **Permanent dewatering systems are far less commonly used than temporary or construction dewatering systems**

Common Dewatering Methods

- Sumps, trenches, and pumps
- Well points
- Deep wells with submersible pumps

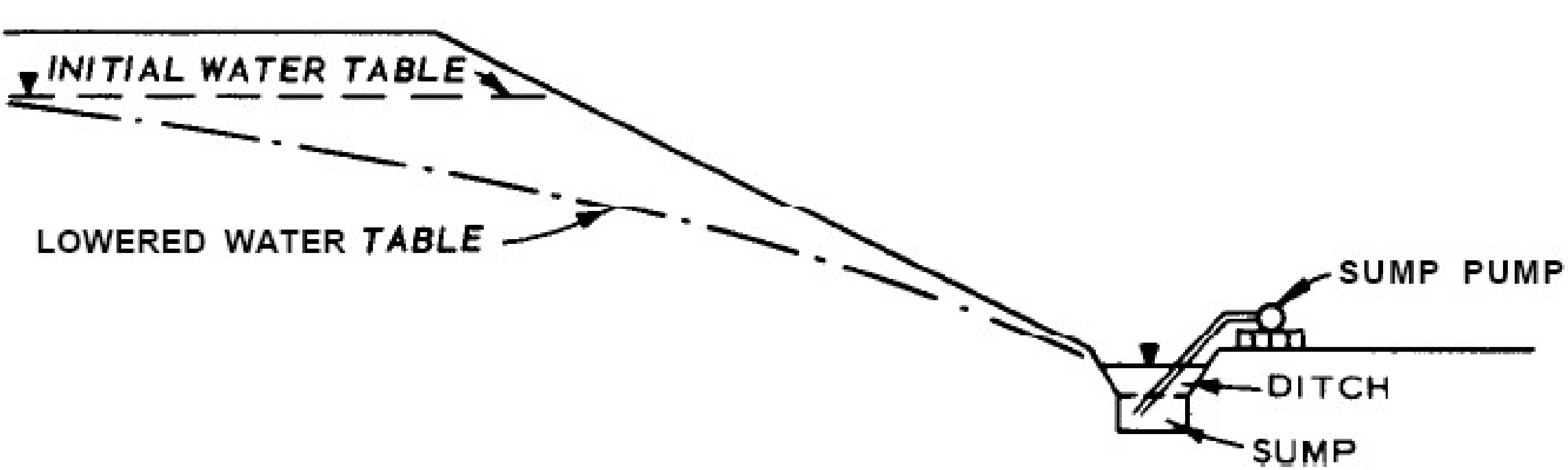
Sumps, Trenches, and Pumps

- Handle minor amount of water inflow
- The height of groundwater above the excavation bottom is relatively small (5ft or less)
- The surrounding soil is relatively impermeable (such as clayey soil)

Wet Excavations

- Sump pumps are frequently used to remove surface water and a small infiltration of groundwater
- Sumps and connecting interceptor ditches should be located well outside the footing area and below the bottom of footing so the groundwater is not allowed to disturb the foundation bearing surface
- In granular soils, it is important that fine particles not be carried away by pumping. The sump(s) may be lined with a filter material to prevent or minimize loss of fines

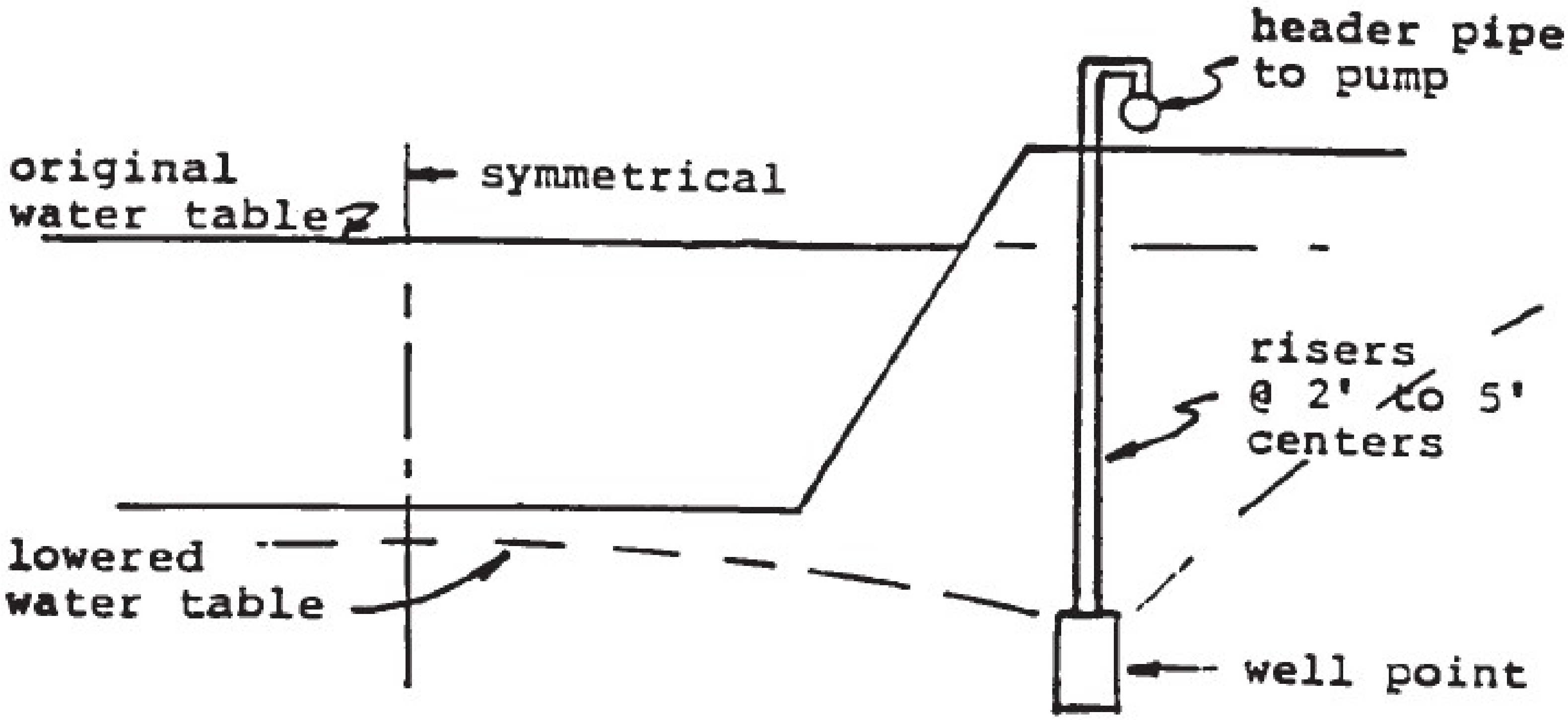
Dewatering Open Excavation by Ditch and Sump



Well Point Method

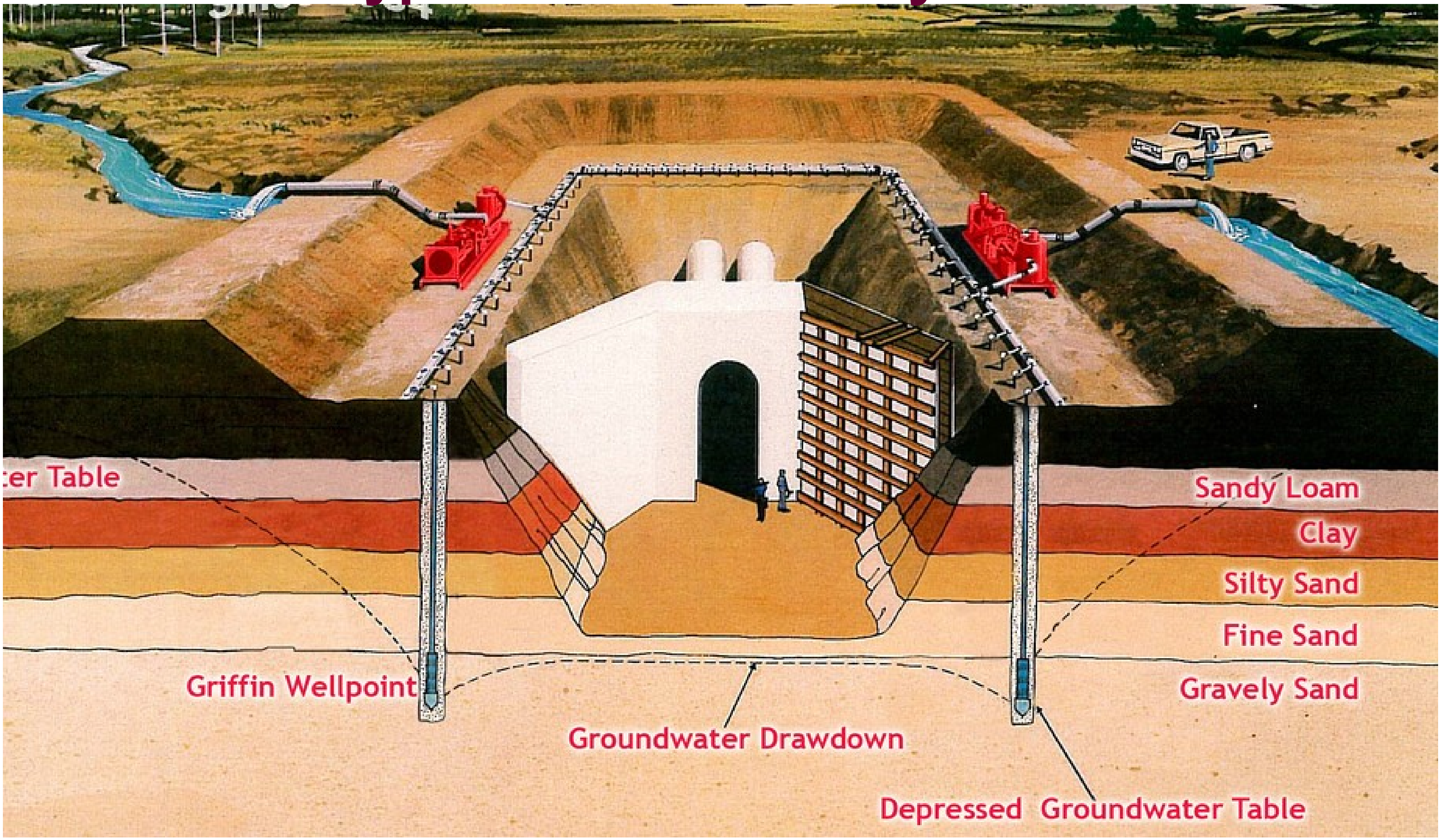
- **Multiple closely spaced wells connected by pipes to a strong pump**
- **Multiple lines or stages of well points are required for excavations more than 5m below the groundwater table**

Single Stage Well Point System



Caltrans

Typical Well Point System



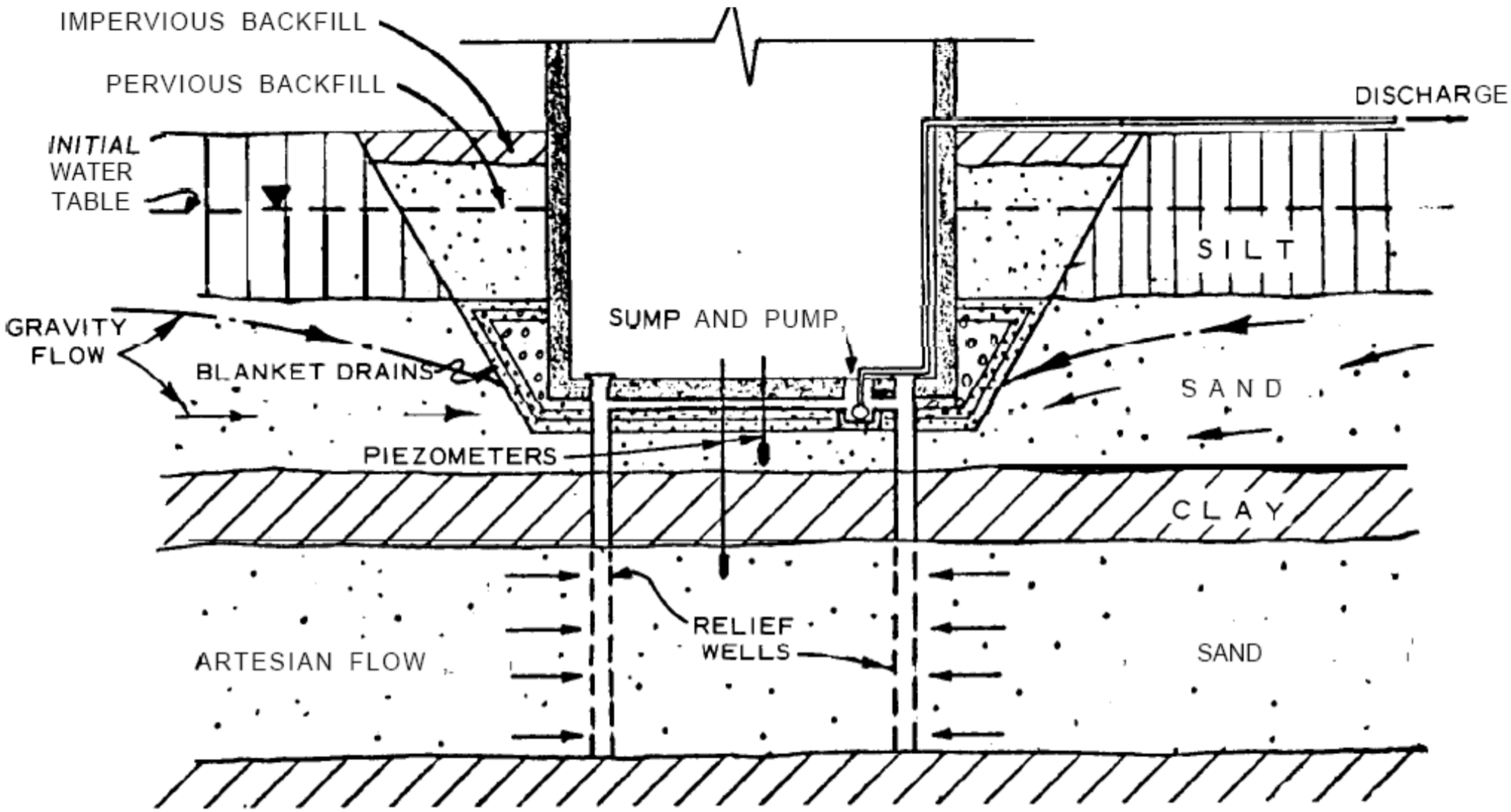
Small pipes, up to 2.5 inches in diameter, connected to screens at the bottom and to a vacuum header pipe at the surface constitute a wellpoint system.

Deep Wells with Submersible Pumps

- Pumps are placed at the bottom of the wells and the water is discharged through a pipe connected to the pump and run up through the well hole to a suitable discharge point
- They are more powerful than well points, require a wider spacing and fewer well holes
- Used alone or in combination of well points

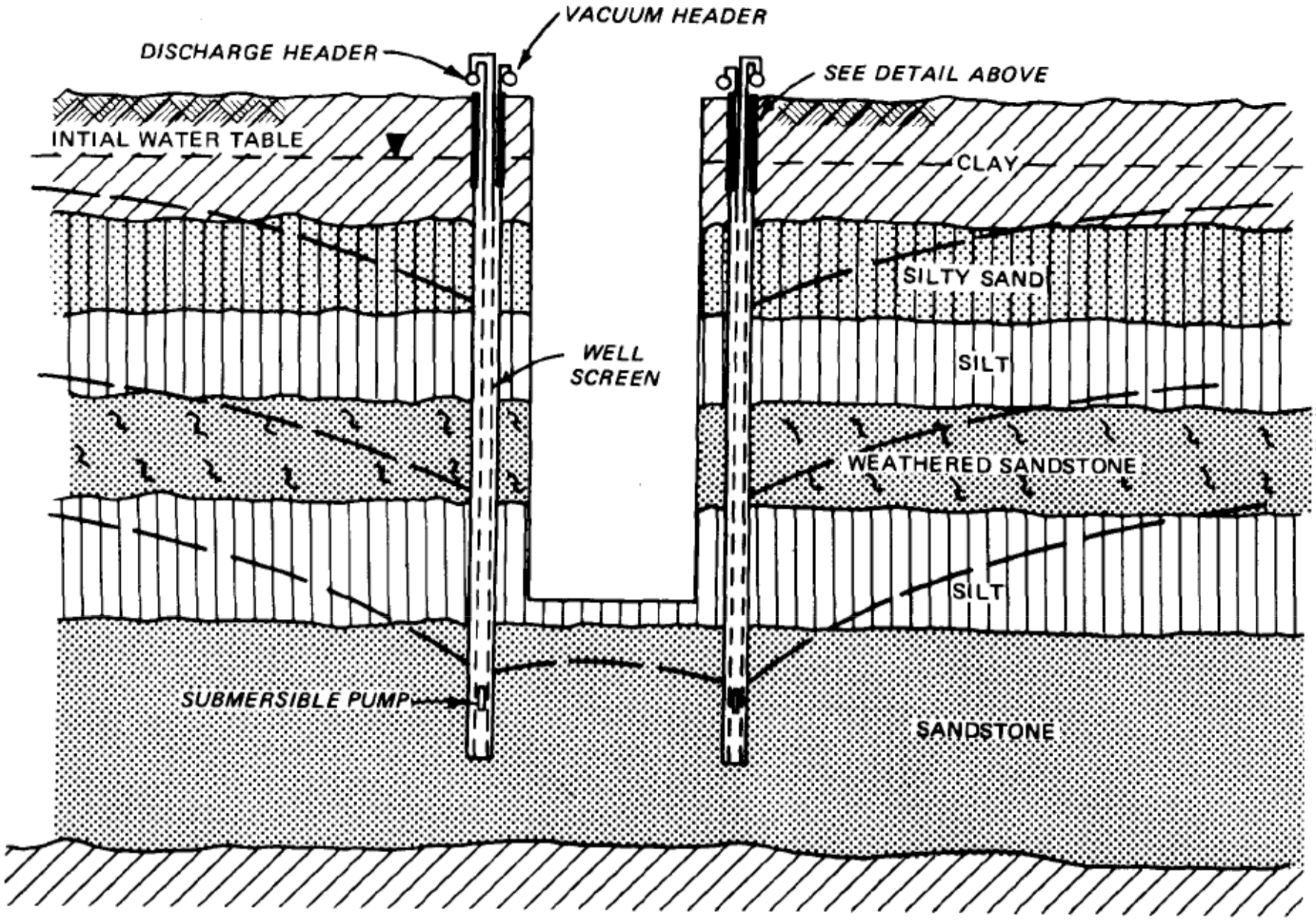
Applications

Permanent Groundwater Control System



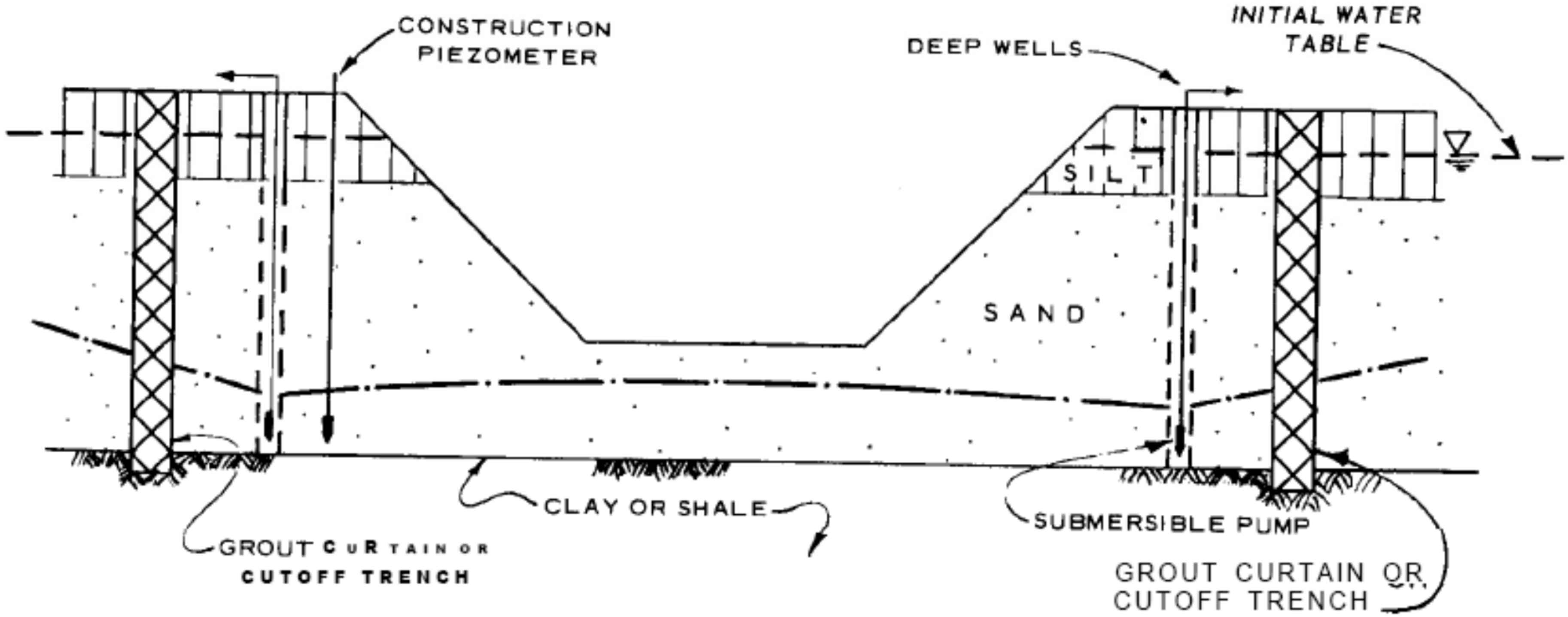
Army TM 5-818-5

Deep Wells with Auxiliary Vacuum System

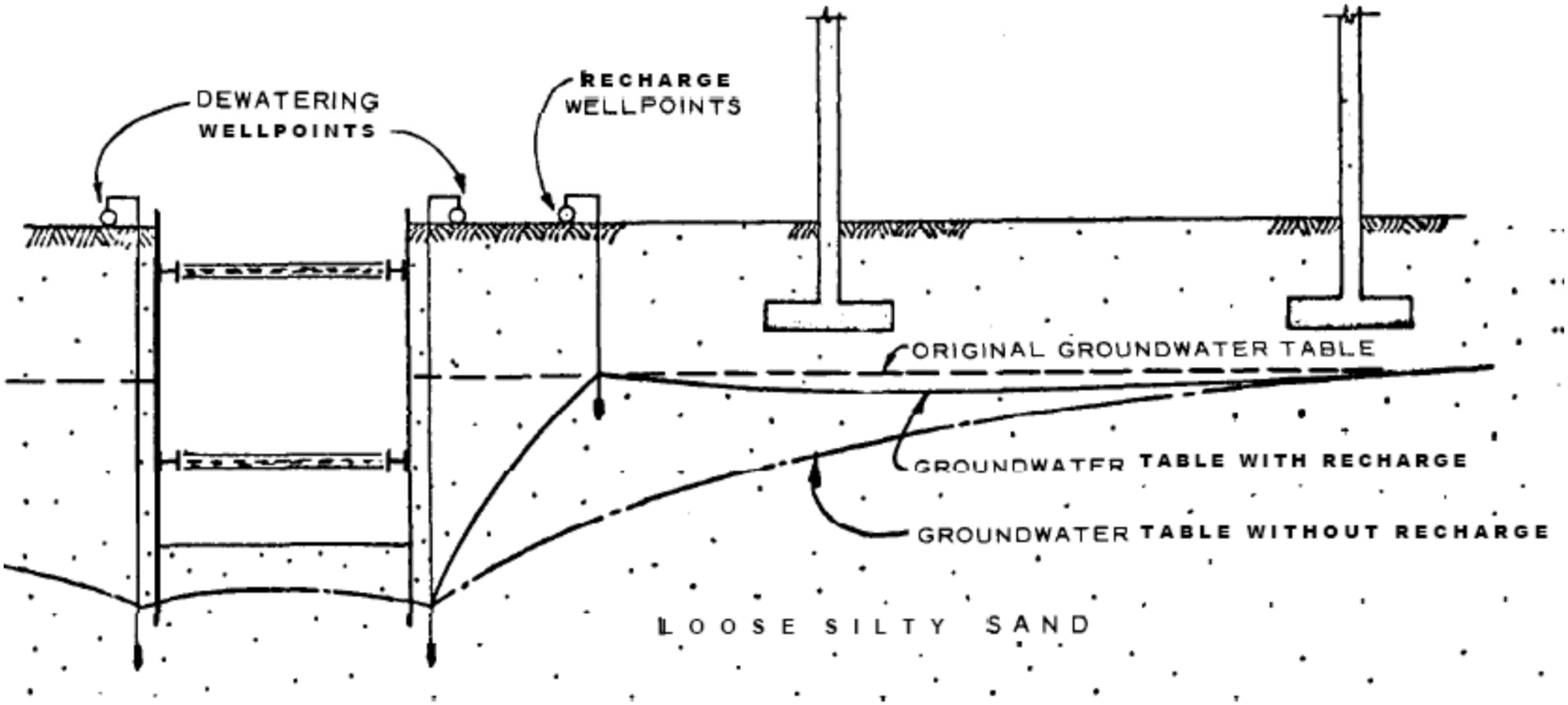


Army TM 5-818-5

Grout Curtain or Cutoff Trench around An Excavation



Recharge Groundwater to Prevent Settlement



Settlement of Adjacent Structures

$$\delta = \frac{H}{1+e_0} C_c \log \frac{\sigma'_{vo} + \Delta\sigma}{\sigma'_{vo}}$$

$$\Delta\sigma = \Delta h \gamma_w$$

Δh = reduction of groundwater level

Design Input Parameters

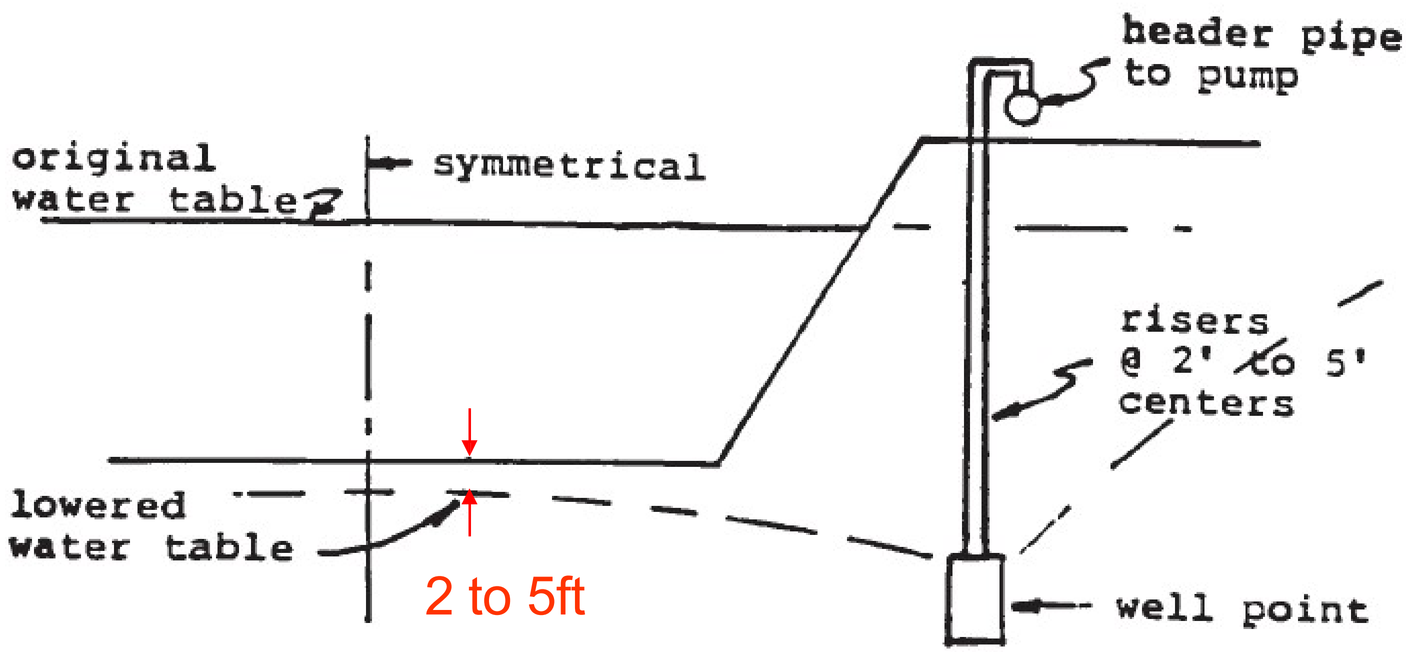
- **Most important input parameters for selecting and designing a dewatering system:**

  -the height of the groundwater above the base of the excavation

  -the permeability of the ground surrounding the excavation

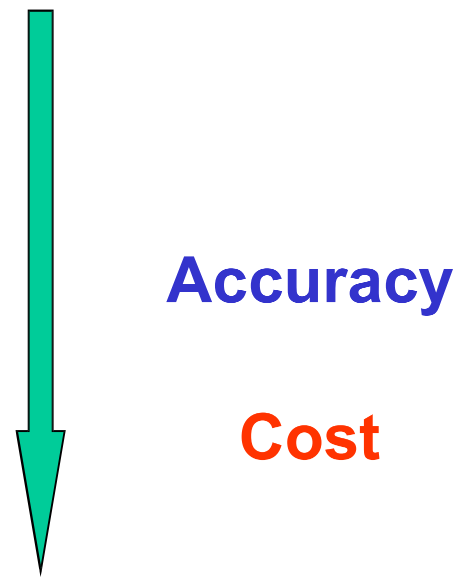
Depth of Required Groundwater Lowering

- The water level should be lowered to about 2 to 5 ft below the base of the excavation



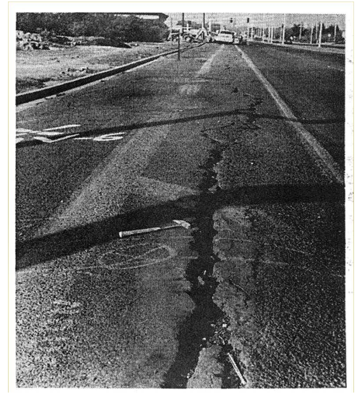
Methods for Permeability

- Empirical formulas
- Laboratory permeability tests
- Borehole packer tests
- Field pump tests



**GROUND
TREATMENT WITH
LIME**

Lime treatment can be used to improve soft soils and expansive soils



Problems with expansive soils

Pavement Cracking in swelling ground

INTRODUCTION

- Stabilization using lime is an established practice to improve the characteristics of fine grained soils.
- The first field applications in the construction of highways and airfields pavements were reported in 1950-60. With the proven success of these attempts, the technique was extended as for large scale soil treatment using lime for stabilization of subgrades as well as improvement of bearing capacity of foundations in the form of lime columns

Mechanism of stabilization

Stabilization using lime is an established practice to improve the characteristics of fine grained soils.

The addition of lime affects the shear strength, compressibility, and the permeability of soft clays. These beneficial changes occur due to the diffusion of lime.

Soil-lime reaction

- Cation-exchange
- Flocculation
- Pozzolanic reaction

1(a) Cation Exchange

- It is an important reaction and mainly responsible for the changes occurring in the plasticity characteristics of soil.
- The cation replacement takes place in order of their replacing power

$Li^{+}<Na^{+}<H^{+}<K^{+}<NH4^{+}<Mg^{2+}<Ca^{2+}<Al^{3+}$

- CEC highly depends on the pH of the soil water and the type of clay mineral in the soil.

Montmorillonite (highest); Koalinite (Lowest).

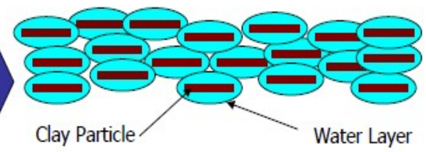
- $Ca(OH)_2$ [formed either due to hydration of quicklime or when it is used directly] dissociates in the water.

$$CaO+H_2O \rightarrow Ca(OH)_2 +15.6 \text{ kcal/mole}$$

- It increases the electrolytic concentration and p_H of the pore water and dissolves the silicates (SiO_2) and aluminates (Al_2O_3) from the clay particles.
- Na+ and other cations adsorbed to the clay mineral surfaces are exchanged with Ca^{++} ions.

1(b) Flocculation

Untreated clays have a molecular structure similar to some polymers, and give plastic properties. The structure can trap water between it's molecular layers, causing volume and density changes.



Flocculation/Agglomeration

In treated clays Calcium and Magnesium atoms (from Lime) have replaced Sodium and Hydrogen atoms producing a soil with very friable characteristics

Lime flocculating clay

1(c) Pozzolanic

the addition of lime to soil alters the properties of soil and this is mainly due to the formation of various compounds such as calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) and micro fabric changes(Pozzolanic reaction).

$$Ca^{2+} + 2(OH^{-}) + siO_2 \rightarrow CSH$$

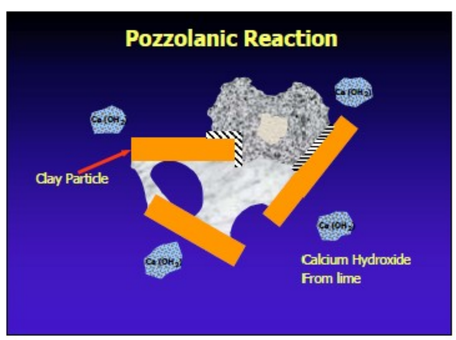
$$Ca^{2+} + 2(OH^{-}) + Al_2O_3 \rightarrow CAH$$

The reaction is much slower reaction than the hydration of cement and hence some times cement is added to increase the rate of reaction.

Pozzolanic Reactions Using Lime (Clay Soil)

On-going reaction with available silica and alumina in the soil forms complex cementitious materials (the POZZOLANIC effect.)

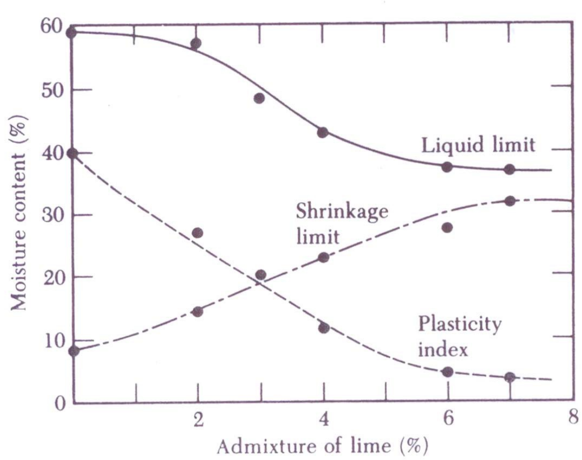
Add lime and fly ash to stabilize soil low in clay.



Factors controlling the characteristics of lime treated clay

- ➢Type of lime (Quick lime or Hydrated lime)
- ➢Lime content
- (Lime Fixation Point and Optimum lime content)
- ➢Curing time
- ➢Type of soil
- ➢Clay mineral
- ➢Soil pH
- ➢Curing temperature

Variation of index properties with addition of lime



W/D studies

Changes in soil sample (untreated) with Wetting and Drying Cycles

At the start | **After Wetting** | **After Drying** | **After 1 cycle of wetting and drying**

Untreated Clay

W/D studies

Changes in soil sample (treated) with W/D Cycles

At the start	After 3 cycles	After 5 cycles	After 7 cycles

Lime Treated Clay

Preparation of the soil: to remove large elements which might delay the mixing-in of lime, and it also helps to modify the humidity of the soil. It may be carried out with a ripper.

Spreading: the lime is dispersed using a spreader fitted with a weighing device. The lime is supplied pneumatically to the spreader.

Mixing: the purpose of this operation is to spread out the soil while at the same mixing the lime evenly into it.

Compaction: when grading, the layer thickness that can be compacted by rolling should be taken into account. After grading, the treated soil has to be compacted using a compacting machine (pneumatic-tyre roller or tamping roller). In warm weather, mixing should be done after two hours to allow for reactions.

Roadway and Subgrade Soil Characteristics

County	Route Number	Age at Time of Study (yrs)	Plasticity Index Range of Untreated Subgrade (%)	Amount of Lime Added (%) *	In Situ CBR of Untreated Subgrade (avg)	In Situ CBR of Lime Stabilized Subgrade (avg)
Anderson	US 127	11	6 - 21	4	2.0	40.5
Boyle	US 127	12	24 - 41	5	2.4	40.2
Fayette	US 125	8	16 - 45	5	3.1	31.7
Hardin	US 62	13	11 - 33	6	3.0	101.4
Owen	US 127	12	14 - 20	5	3.0	41.3
Shelby	KY 55	10	17 - 26	5	3.1	25.9
Trigg	US 68	9	14 - 23	5	6	91.7

*By dry weight of soil

Table 1: Roadway and Subgrade Soil Characteristics

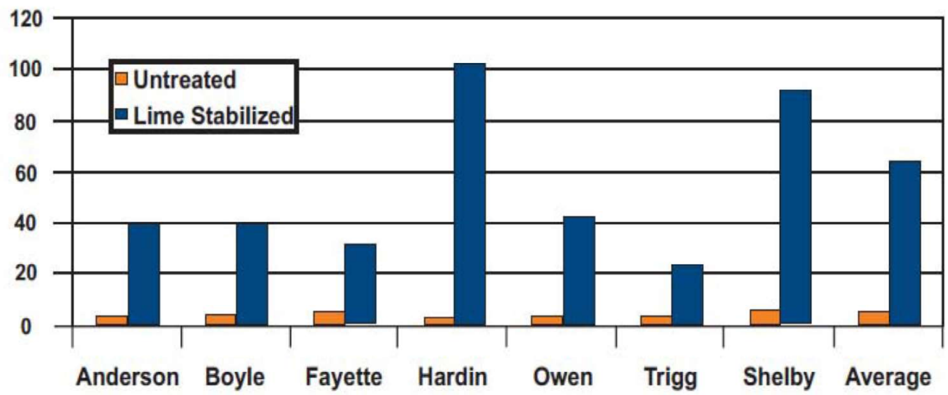
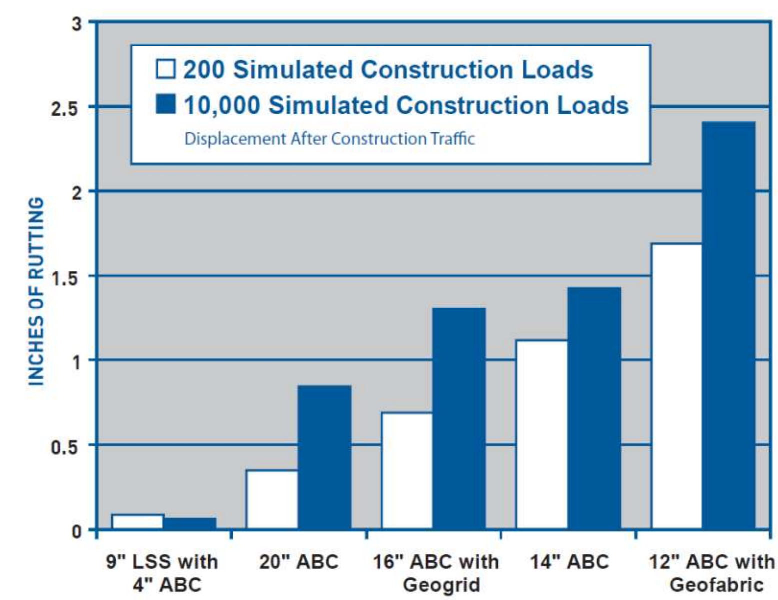


Figure 2: In Situ CBR Values of Untreated and Lime Stabilized Pavement Subgrade

Comparing Lime Treatment to Remove-and-Replace for Construction Site Soil Improvement

Cost Comparison of Soil Improvement Options

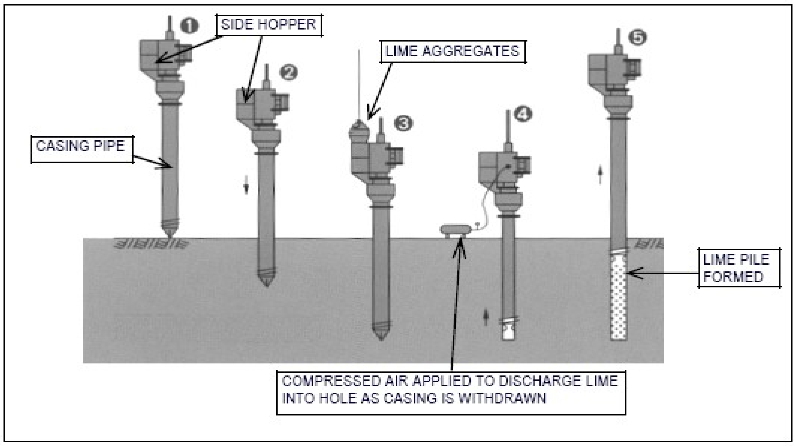
Test Configuration	Unit Cost ($/SY)
12" Lime Treated Soil*	$5.40
9" Lime Treated Soil with 4" ABC	$10.44
14" Agg Base Course	$20.18
12" Agg Base Course with Geofabric	$22.59
16" Agg Base Course with Geogrid	$24.34
20" Agg Base Course	$28.82



Lime Columns

- Broms and Bomans (1975, 1979) used a special type of auger to form the bores in which lime was mixed with the soil in-situ.
- In this technique it was assumed that the improved soil column in the bore was acting as a pile to support the superstructure.
- Later is was found that lime can diffuse in to the surrounding soil and can stabilize a greater volume of soil.

Typical installation process of lime piles.



This method produces both a consolidation and strength gain effect on the treated soil, without additional loading, via lateral expansion of the lime columns as they absorb water from the soft soil.

These lime columns have the following effects on the adjacent soil.

a) Consolidation / dewatering effect

Quick lime, CaO, absorbs water from the surrounding ground, causing the lime to swell and forms slaked lime ($Ca(OH)_2$) as per the following chemical reaction

$$CaO + H_2O \rightarrow Ca(OH)_2 + 15.6 \text{ Kcal/mol}$$

b) Ion exchange effect

As the surface of fine particles of clay is negatively charged, calcium ions (Ca^{++}) from the slaked lime are absorbed by the surface of clay particles. As a result, clay particles are bonded with each other and the weak clay is improved with a resultant increase in shear strength.

C) Pozzolanic effect

Among all the three effects only consolidation/dewatering effect is the main process by which the strength and stiffness of the soil mass is improved in the shorter term. Other two effects ion exchange effect and pozzolanic effect are ignored.

Design of Foundation on lime columns

Laboratory investigations are generally required to estimate the amount of lime required to reach the desired column strength and the required reduction of the compressibility of the soil. Normally 5%-8% unslaked lime is added.

Stabilization using cement and cementitious materials

Stabilization using cement and other admixtures such as fly ash, blast furnace slag has been adopted in many geotechnical and highway engineering projects. These applications include

a)Shallow depth applications in the case of improvement of subgrade, sub-base and base course of highways and embankment material

b) Stabilization of deep soil deposits such as soft soils and peaty soils.

Factors influencing the strength and stiffness improvement

- Cement content, water content combined into water/cement(w/c) ratio.
- Method of compaction.
- Time elapsed between mixing and compaction.
- Length of curing.
- Temperature and humidity.
- Specimen size and boundary effects.

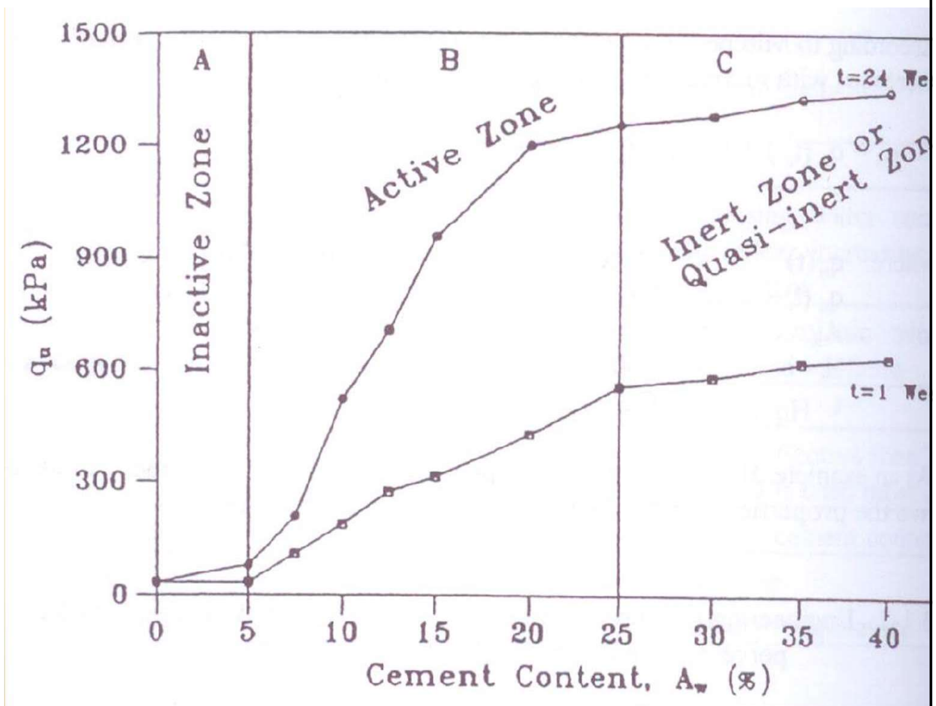
Strength gain is given by:

$$q_u(t) = q_u(t_0) + k \log \frac{t}{t_o}$$

$q_u(t)$ = the UCC (unconfined compression) strength at t days
$q_u(t_0)$ = the UCC strength at t_0 days
k = 480C for granular soils; 70C for fine grained soils
C = Cement content by weight

Effect of adding cement and blast furnace slag leads to the following chemical reactions:

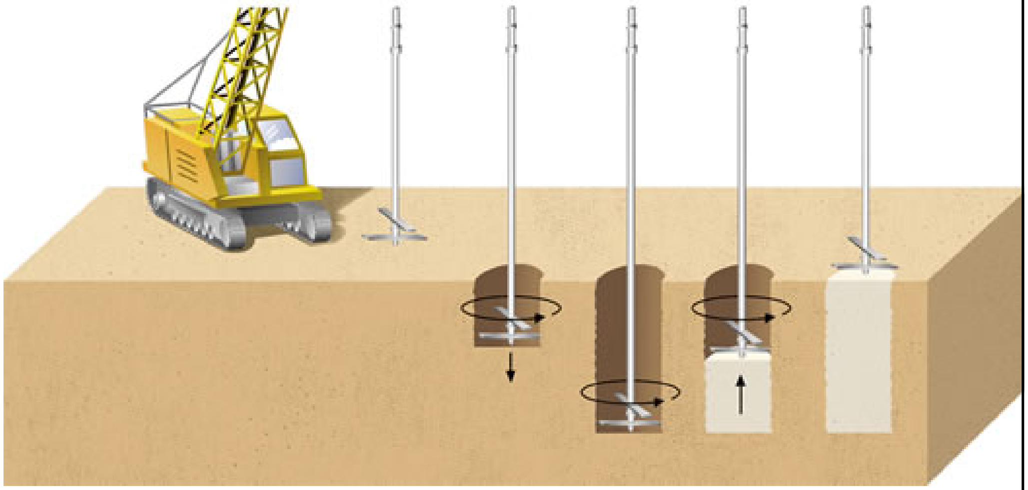
- Hydration of cement produces Ca(OH)2. The calcium hydroxide generated is upto 25% of the weight of cement.
- Adsorption of Ca(OH)2 by the clay, cation exchange reaction
- If the clay is saturated with Ca(OH)2, a pozzolonic reaction between the components occurs.



Influence of cement content on unconfined compression strength Bergado et al (1996)

Deep Mixing Methods

- Mixing soil with cement, lime or other binders has been a common soil stabilization method. For fills, the mixing can be done before placement with or without compactions.
- Most frequently, soils are mixed in-situ with cement and/or lime using a specially made machine. This method was developed in Japan and in the Scandinavian countries independently in the 1970s. The method has been called in different names, but commonly referred to as deep cement mixing (DCM or DMM).



"Wet" and "Dry" Deep Mixing Methods

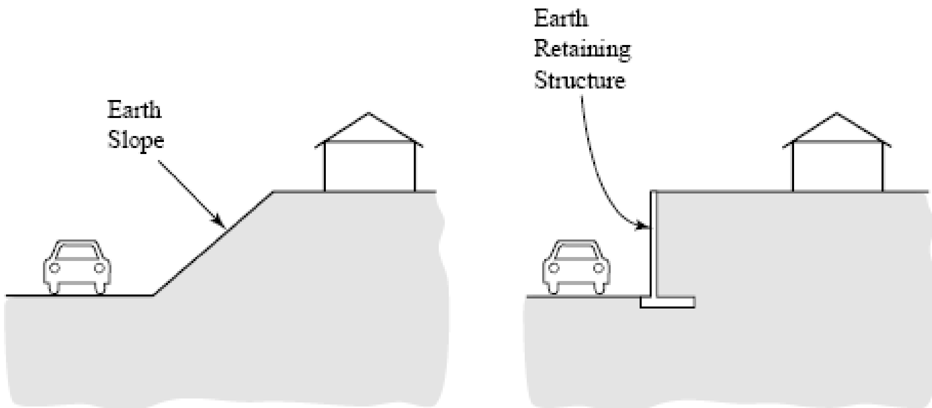
Wet Method:	Dry Method:
Larger & heavier equipment	Smaller & lighter equipment
Used in sands, silts, and clays	Used in soft, wet ground
Significant spoils produced	No significant spoils produced
0.3 m to 3 m diameter	0.3 m to 1 m diameter

Applications: Excavation Support

Applications: Bridge Foundation Support

95 m dia. Oil Storage Tanks, Louisiana

Earth slopes and earth retaining structures



Used to maintain two different ground surface elevations

EARTH RETAINING STRUCTURES

Types of Retaining Wall

Retaining Wall

The various types of earth-retaining structures fall into three broad groups.

Gravity Walls

Embedded walls

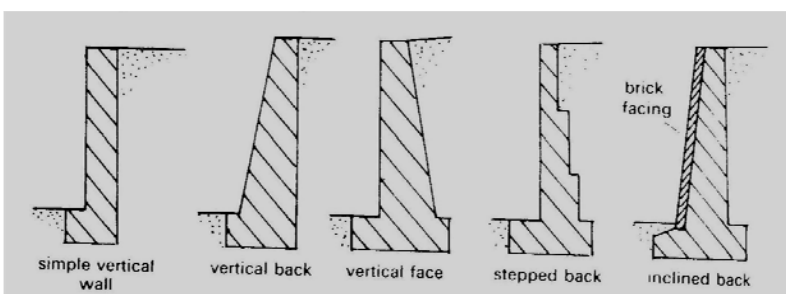
Reinforced and anchored earth

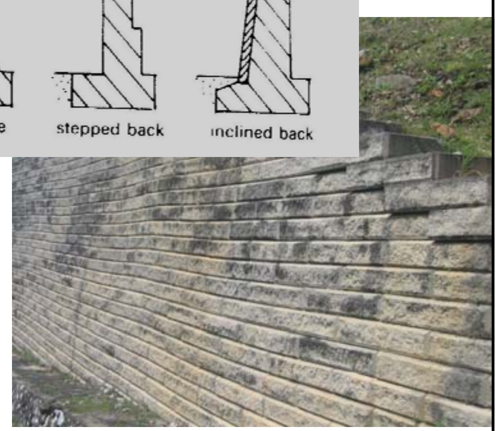
EARTH RETAINING STRUCTURES

Gravity Walls

- **Masonry walls**
- **Gabion walls**
- **Crib walls**
- **RC walls**
- **Counterfort walls**
- **Buttressed walls**

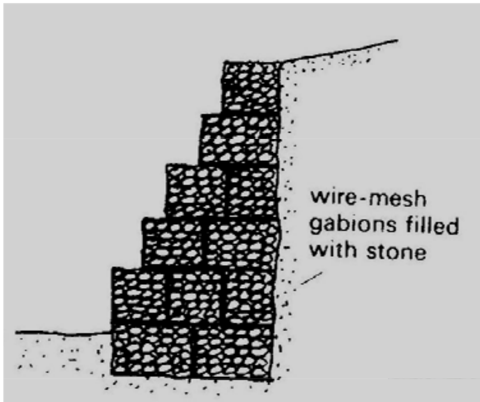
EARTH RETAINING STRUCTURES
Gravity Walls





Unreinforced masonry wall

EARTH RETAINING STRUCTURES
Gravity Walls



Gabion wall

Gabion

Gabion

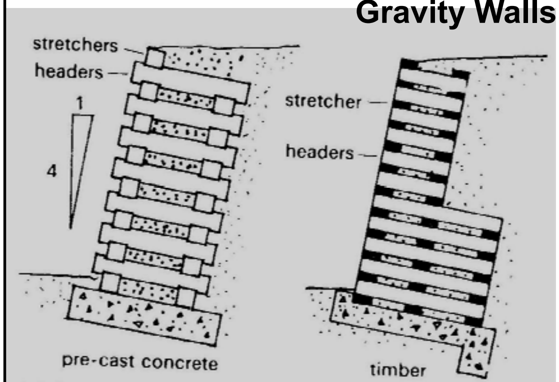
Gabion Wall

- **General**
  1. Typical Application: Retaining walls, Slope stabilization
  2. Size requirements: Base width of ranges from 0.5 to 0.7 of the wall height
  3. Typical Height Range: 2-8m

- **Advantages**
  1. Wall System is flexible and can accommodate large and differential settlements without distress
  2. Wall pervious, therefore, well suited for bank stabilization applications

EARTH RETAINING STRUCTURES

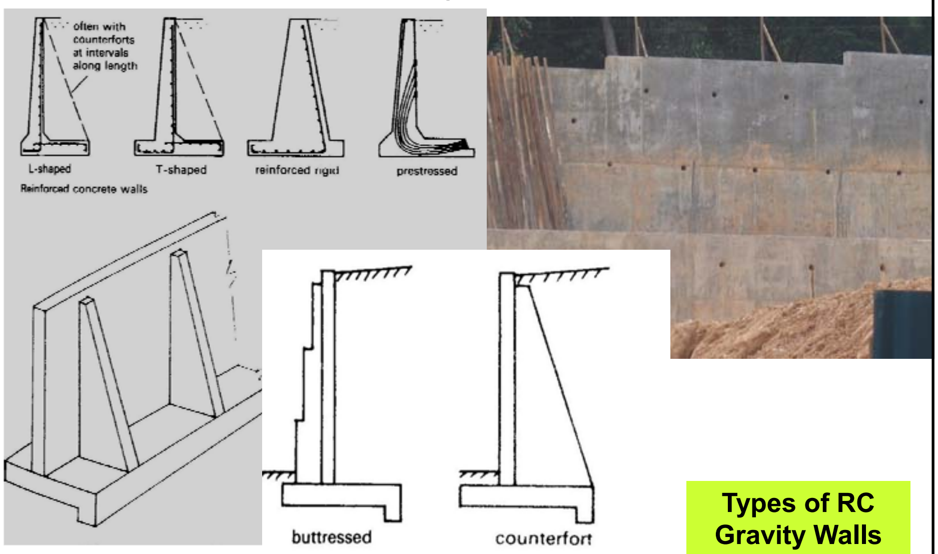
Gravity Walls



Crib wall

Crib Wall

EARTH RETAINING STRUCTURES
Gravity Walls



Types of RC Gravity Walls

CIP (Cast in Place) Concrete Wall

- **General**
  1. Typical Application: Bridge abutments, retaining walls, soil stabilization
  2. Size requirements: Base width of ranges from 0.4 to 0.7 of the wall height
  3. Typical Height Range: 2-9 m Cantilever wall; 9-18 m (counter forth Wall)
  - **Advantages**
    1. Conventional Wall System with Well established design procedure & performance characteristics
    2. Concrete is very durable in many environments
    3. Concrete can be formed, textured, and colored to meet visual requirements

CIP Concrete Wall Cont.

- **Disadvantages**

1. Requires relatively long construction period: formwork must be erected & concrete poured and allowed to cure before backfill loads

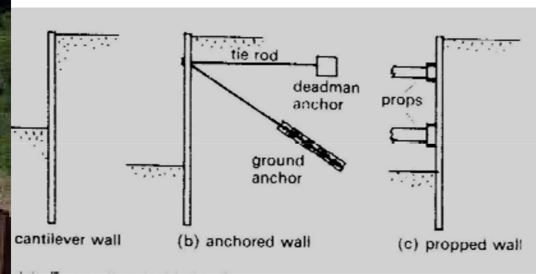
2. **Costly :**
   a) Required selected backfill if not available near the site
   b) May need temporary excavation support
   c) Deep foundation support

3. Wall system is rigid and its sensitive to total and differential settlements

Embedded walls

- **Driven sheet-pile walls**
- **Braced or propped walls**
- **Anchored wall**
- **Tangent or secant bored-pile walls**

EARTH RETAINING STRUCTURES



Types of embedded walls

Sheet Pile Wall

- **Description**

  Consist of driven, vibrated, or pushed, interlocking steel or concrete sheet pile sections. The required depth of embedment (i.e. length of sheet pile below final excavated grade) is evaluated based on the assumption that the passive resistance of the soil in front of the wall plus flexural strength of the sheet pile can resist the lateral forces from the soil behind the wall

- **Advantages**

  1. Conventional Wall System with Well established design procedure & performance characteristics
  2. Wall system can be used for application in which wall can penetrates below ground water table
  3. Wall system is suitable for temporary applications

Sheet Pile Wall Cont.

- **Disadvantages**

1. Requires specialized equipment
2. Driven sheet pile is noisy and it can be introduce vibration
3. Difficult to drive sheet in hard or dense or gravelly soil
4. Wall height is limited based on required structural sections
5. Wall system may undergo relatively movements which may be detrimental to nearby structure

Sheet Pile Wall

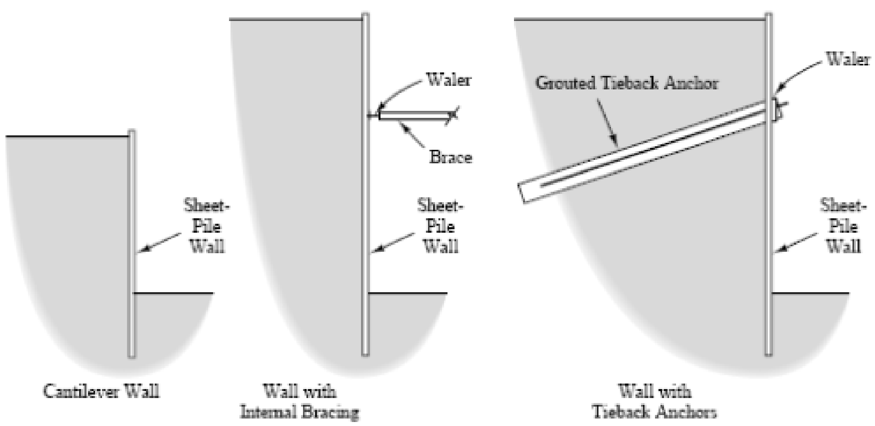
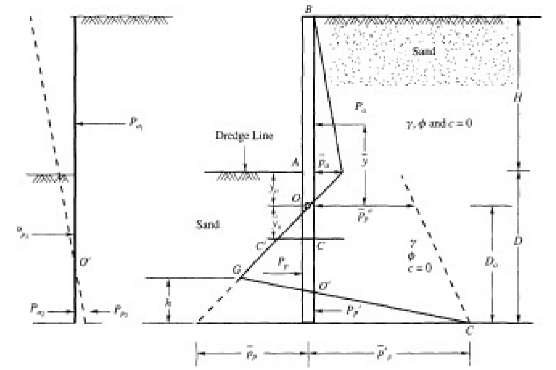
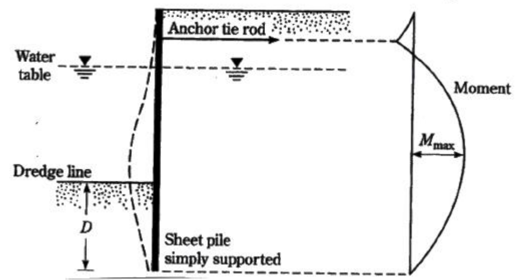


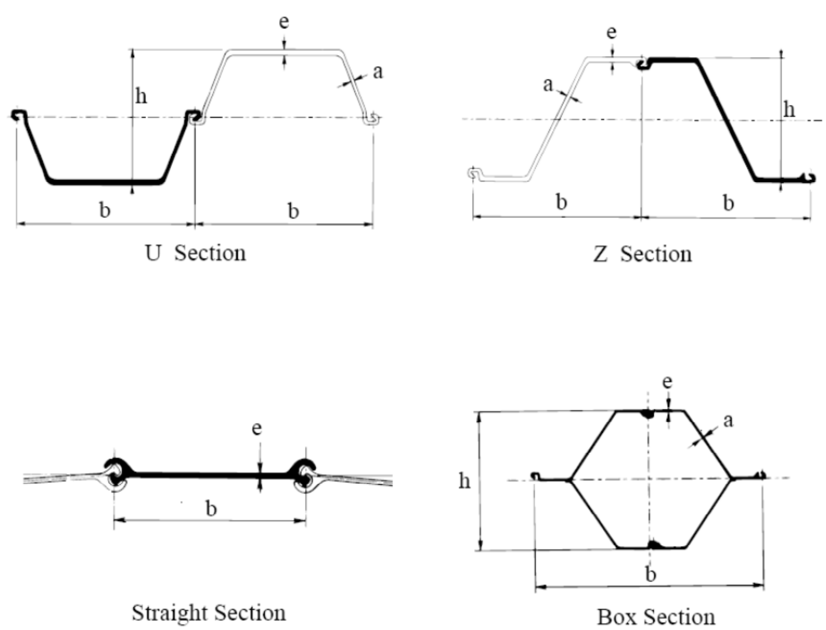
Figure 22.9 Short sheet pile walls can often cantilever, taller walls usually require internal bracing or tieback anchors.



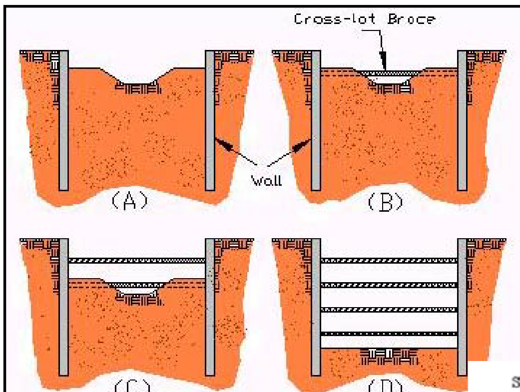
Deformation and moment distribution over the sheet pile.

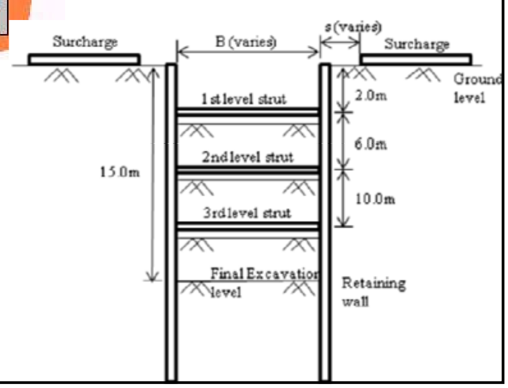


Sheet Pile Wall

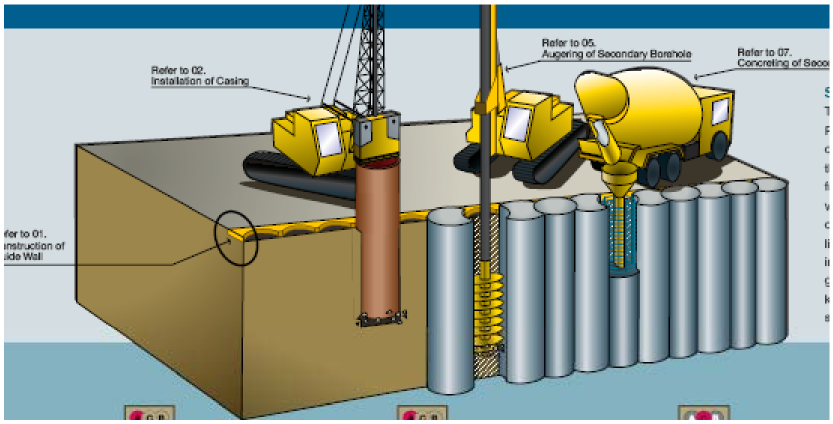


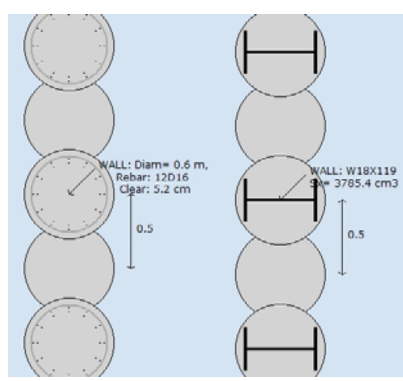
Braced Excavation





CONSTRUCTION OF SECANT PILE WALL





EARTH RETAINING STRUCTURES

Reinforced and Anchored Earth

Reinforced earth wall

Soil nailing

Ground anchors

Soil Nailed Wall

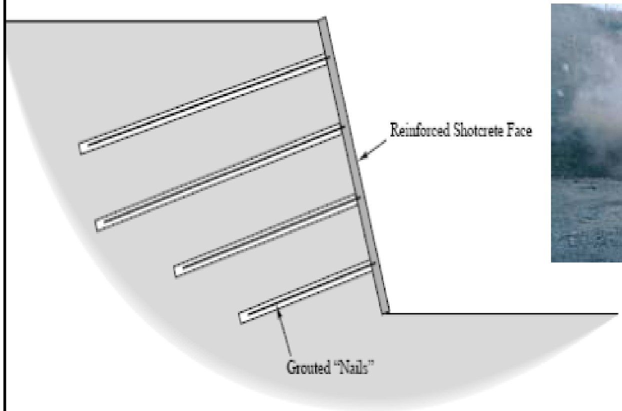


Figure 22.15 A soil nail wall.

Soil Nailed Wall

- **Description**

In Situ soil reinforcement technique wherein passive inclusions (soil nails) are placed into the natural ground at relatively close spacing (1-2 m) to increase the strength of the soil mass. Construction staged from top to down and after each stage of excavation, the nails are installed, drainage system are constructed and shotcrete are applied to the excavation face.

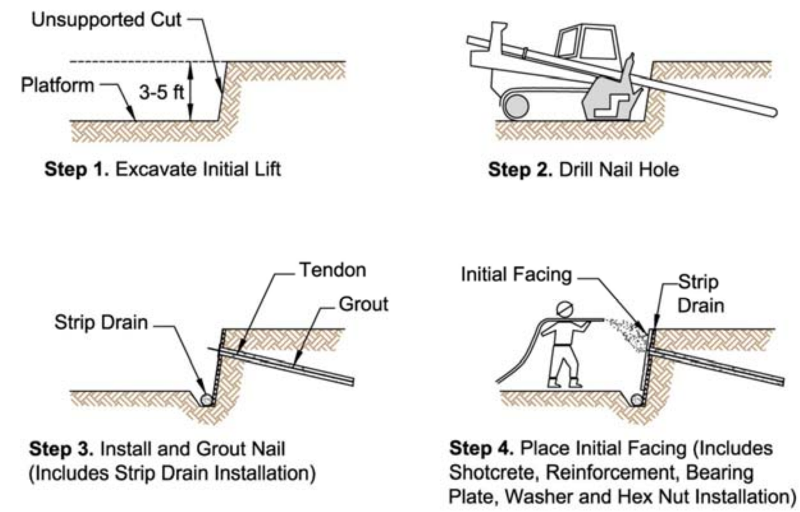
- **Advantages**

1. An unobstructed working space can be achieved on the excavation side of the wall
2. Surface movements can be limited by installing additional nails or by stressing nails in upper level to small percentage of working loads
3. Wall system is adaptable to varying site conditions
4. Is well suited for construction in areas of limited head room
5. Suitable for temporary applications

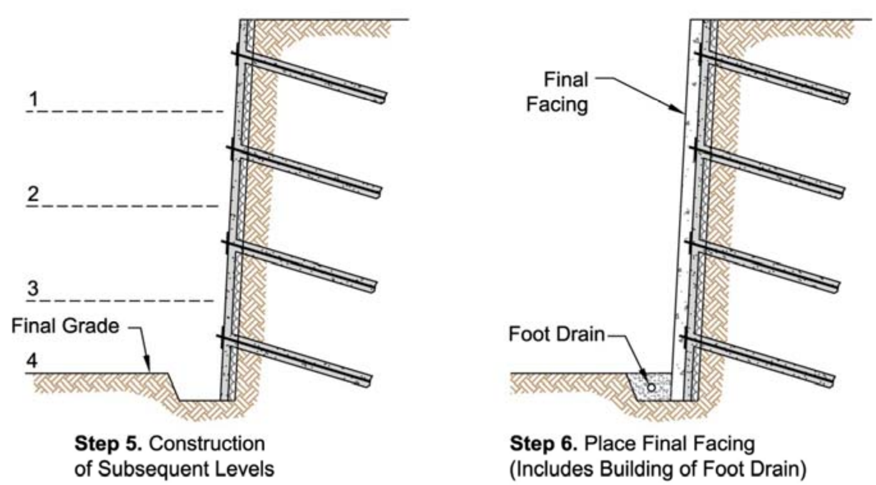
Soil Nailed Wall

- **Disadvantages**

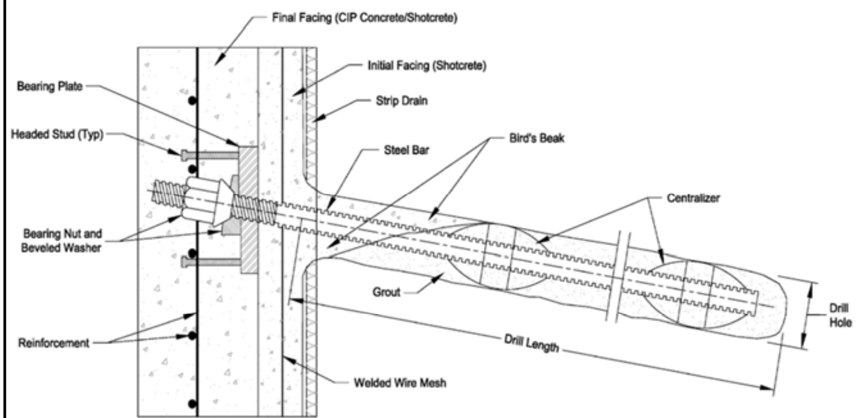
1. Construction of wall system requires specialty contractor
2. Required permanently dewatering in case of the present of ground table
3. Closed space nail May interface underground utilities
4. Nail capacity may be difficult to develop in some cohesive soil



Typical soil nail wall construction sequence.

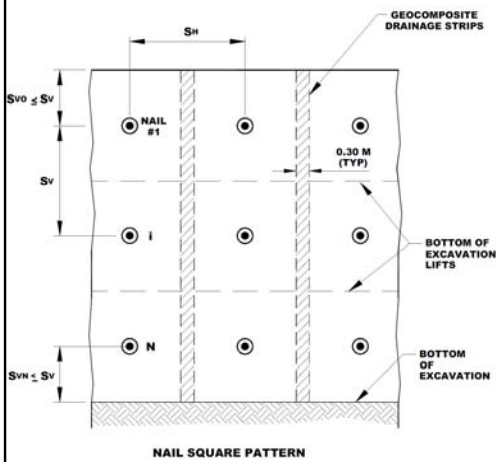


Typical soil nail wall construction sequence.



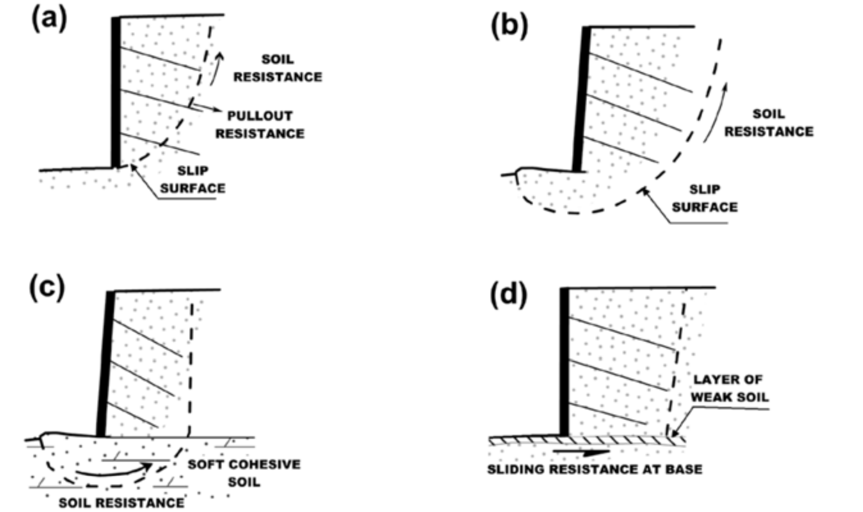
Main components of a solid bar soil nail Wall

Threaded solid tendon with steel plate, washer, and nut. Note headed studs for connection to final facing.

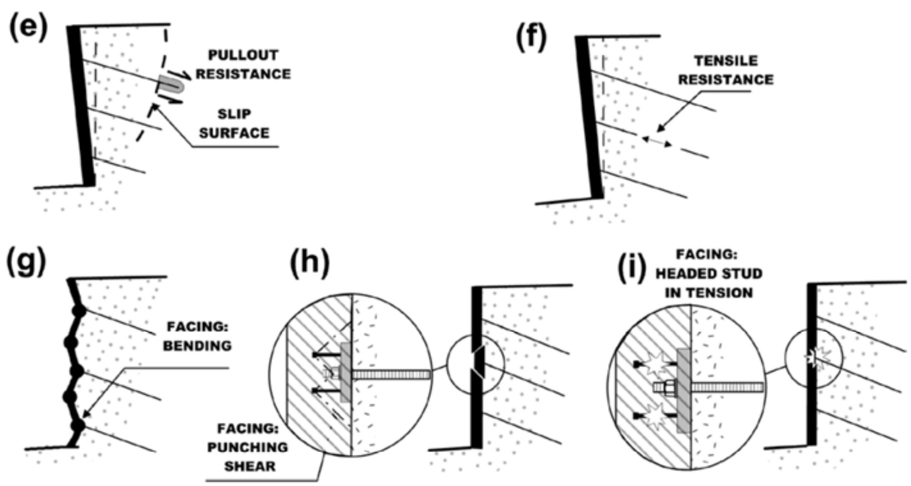


Strip drain prior to initial shotcrete placement.

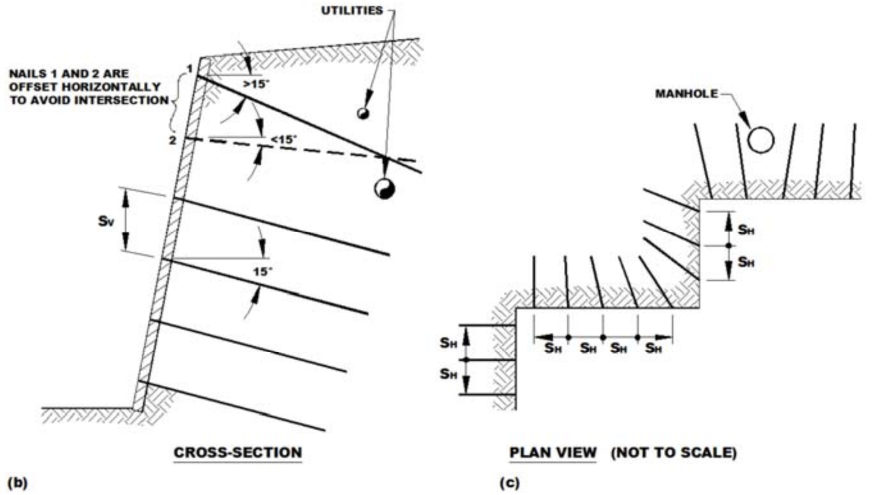
Precast panel facing



Potential limit states in soil nail walls: (a) internal stability (slip surface intersecting soil and nails); (b) global stability (slip surface not intersecting nails); (c) global stability: basal heave; (d) geotechnical strength: lateral sliding;



Potential limit states in soil nail walls: (e) geotechnical strength: pullout; (f) structural strength: nail in tension; (g) facing structural strength: bending; (h) facing structural strength: punching shear; (i) facing structural strength: headed stud in tension.



Varying nail patterns: (b) varying nail inclination and lengths around utilities, and (c) nail splaying at corners.

Soil nail load testing setup

GROUND IMPROVEMENT

USING GEOSYNTHETICS

Geosynthetic (GS) Materials

- Geotextiles (GT)
- Geogrids (GG)
- Geonets (GN)
- Geomembranes (GM)
- Geosynthetic clay liners (GCL)
- Geopipe (GP)
- Geofoam (GF)
- Geocomposites (GC)

Geotextiles

Geotextiles (GT)

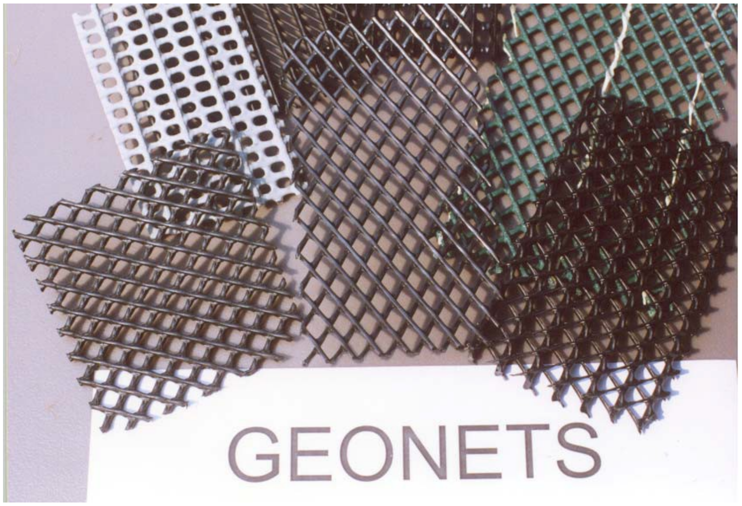
- majority are made from polypropylene fibers
- standard textile manufacturing
- woven (slit film, monofilament or multifilament)
- nonwoven (needle punched or heat bonded)
- characterized by an open and porous structure
- mechanical and hydraulic properties vary widely
- very versatile in their primary function

Uniaxial Stretched PE-Geogrid

Biaxial Stretched PP-Geogrid

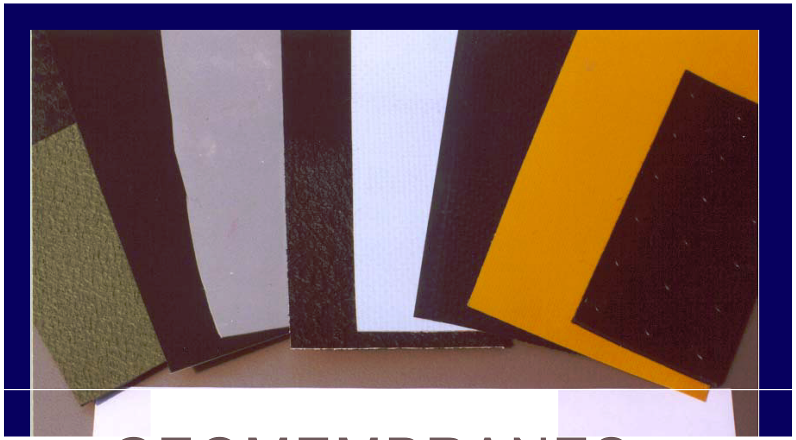
Geogrids (GG(

- unitized, woven strings or bonded straps
- structure allows for soil “strike-through”
- bidirectional –equal strength in both directions
- unidirectional – main strength in machine direction
- focuses entirely on reinforcement applications, e.g.,walls, steep slopes, base and foundation reinforcement



Geonets (GN)

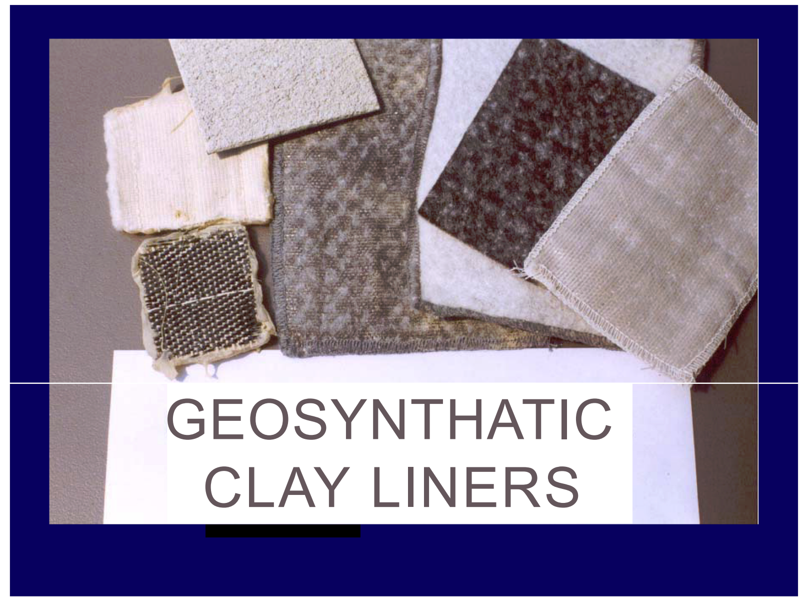
- all are made from high density polyethylene
- results in parallel sets of ribs as a integral unit
- biplanar – flow is equal in all directions
- triplanar – flow much greater in machine direction
- function is always in-plane drainage
- surfaces must be covered; usually with GTs



GEOMEMBRANES

Geomembranes (GM)

- function is always containment
- represents a barrier to liquids and gases
- many types: HDPE, LLDPE, fPP, PVC, EPDM, etc.
- required by regulations for waste containment
- new applications in hydraulics and private development



GEOPIPE

GEOFOAM

Geocomposites (GC)

- array of available products
- GT/GM; GT/GG; GT/GN; etc.
- considerable ongoing innovation
- primary function depends on final product

Function vs. Geosynthetic Type

Type of Geosynthetic	Separation	Reinforcement	Filtration	Drainage	Containment
Geotextile	√	√	√	√	
Geogrid		√			
Geonet				√	
Geomembrane					√
Geosynthetic clay liner					√
Geopipe				√	
Geofoam	√				
Geocomposite	√	√	√	√	√

Functions of Geosynthetics

- **Filtration**
    - Allow the passage of fluids preventing the migration of soil particles(geotextiles, geocomposites)
- **Drainage**
    - Transport of fluids geonets, geocomposites

Functions of Geosynthetics

- **Separation**
  - Prevent the mixing of two different soils or materials using geotextiles, geocomposites
- **Protection**
  - Avoid damages to a structure, a material or another geosynthetic using nonwoven geotextiles, geonets, geocomposites

Functions of Geosynthetics

- **Impermeabilization**
  - Fluid barrier using Geomembranes, geocomposites
- **Reinforcement of walls/steep slopes**
  - Provide tensile forces in the soil using geogrids, and geotextiles

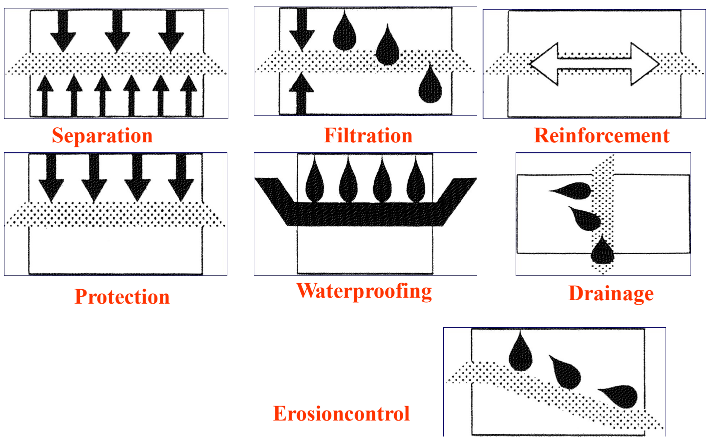
Functions of Geosynthetics

- **Reinforcement of soft soil**
  - Increase the bearing capacity using bidirectional geogrids, geotextiles, geocomposites
- **Reinforcement of concrete, asphalt**
  - Provide tensile and fatique resistance bidirectional geogrids

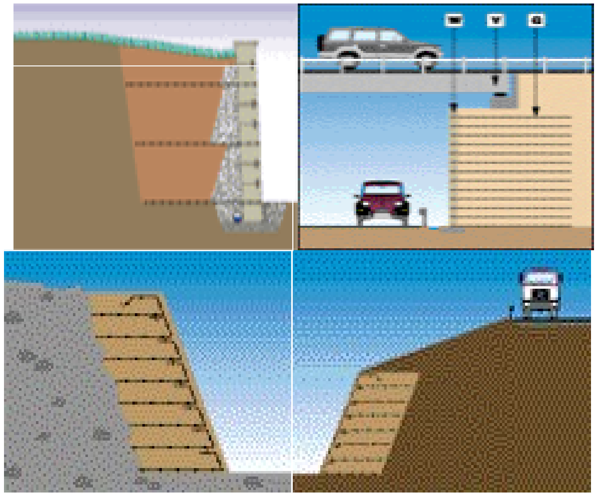
Functions of Geosynthetics

- **Erosion control or surfacial stabilisation**
  - Avoid the detachment and transport of soil particles by rain, runoff and wind; root anchorage using geomats, geocells, biomats, bionets
- **Confinement**
  - Restrain the lateral movement of a soil mass geocells

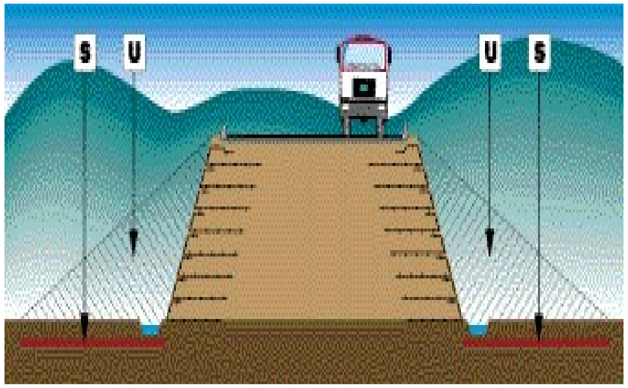
Functions of Geosynthetics



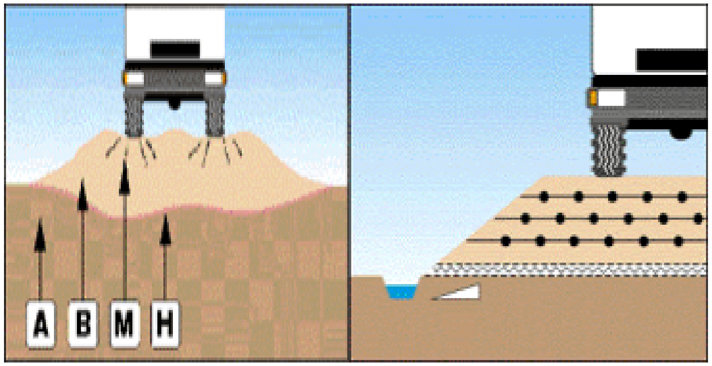
Retaining Walls, Slopes

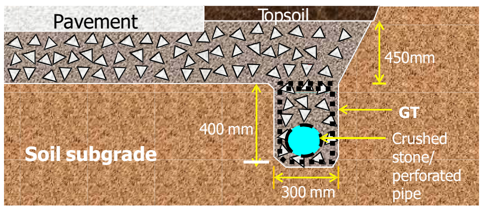


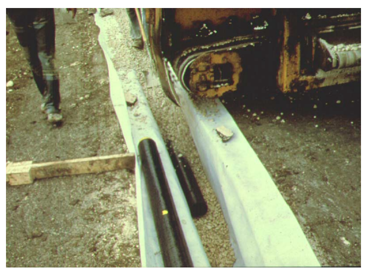
Highway Embankments



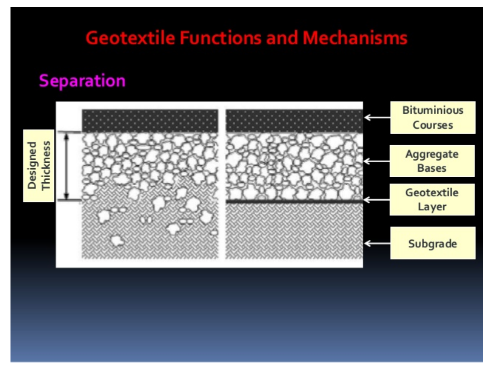
Reinforced Pavements



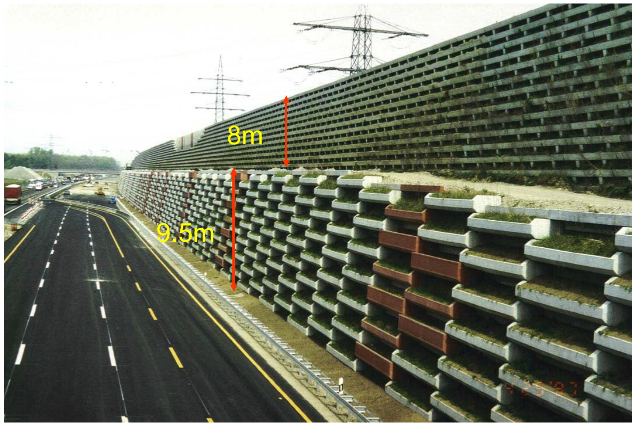

Pavement
Topsoil
450mm
GT
400 mm
Soil subgrade
Crushed stone/ perforated pipe
300 mm



Separation

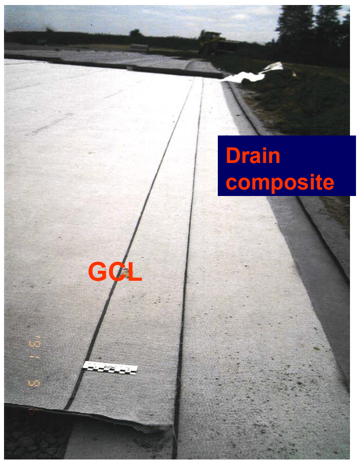

Geotextile Functions and Mechanisms
Separation
Designed Thickness
Bituminious Courses
Aggregate Bases
Geotextile Layer
Subgrade

Reinforcement



Reinforcement

Lining and Drainage



Capping of an old wastedump

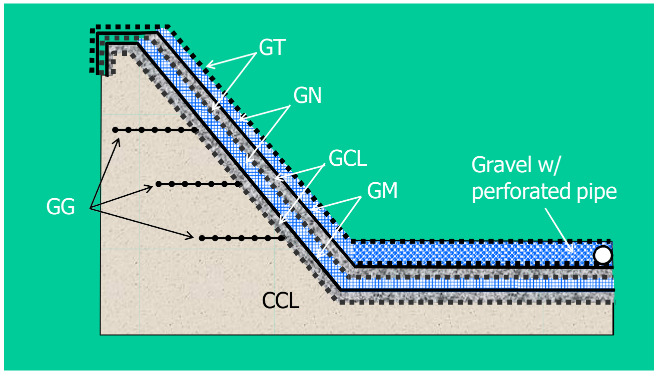
Geoenvironmental Applications

- Landfill liner systems
- Landfill cover systems
- Vertical Cutoff Barriers
- Liners for Surface Impoundments
- Liners for Heap Leach Ponds

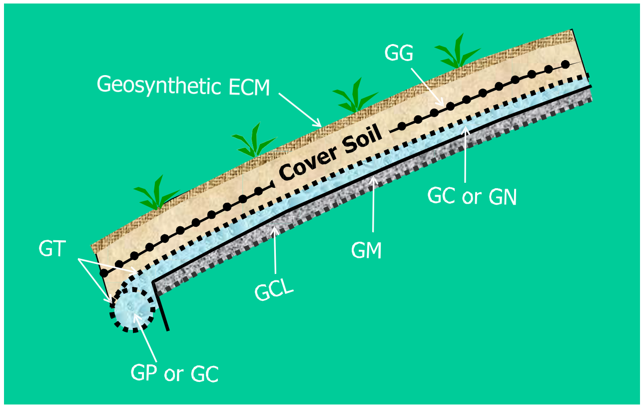
Nature of Waste Problem

- moisture within and precipitation on the waste generates leachate
- leachate takes the characteristics of the waste, thus leachate is very variable and is site-specific
- flows gravitationally downward, enters groundwater unless a suitable barrier layer and collection system is provided

Double Liner System
)with leak detection layer(

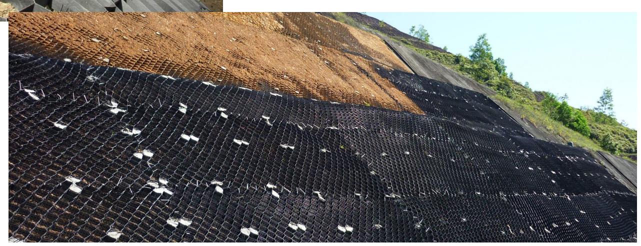


Final Cover System



Erosion Control

Erosion Control

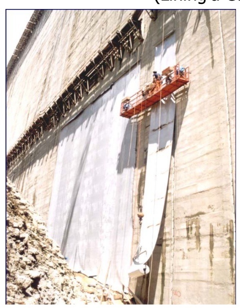


Waterproofing of Dams

- masonry, concrete, earth and RCC dams
- GM is not a structural element, its waterproofing
- many dams over 50-years old often have leakage; sometimes excessive leakage

(Lining a Concrete Dam)

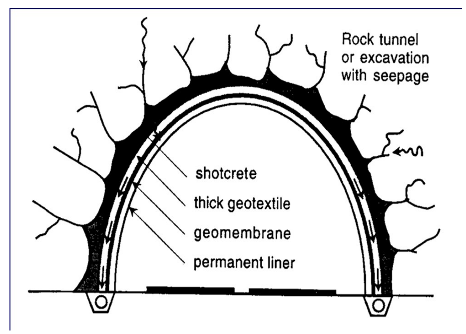
(Concrete Dam Leaking!)

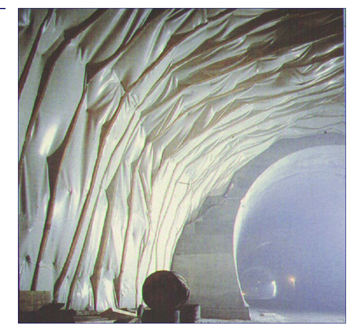


(Lined Earth Dam: Before Rip-Rap)

New Tunnel Waterproofing

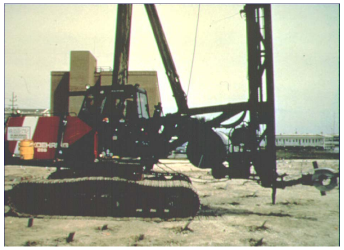
- many old tunnels without GMs are leaking
- white staining on surface is the “tell-tale”
- key is to use a GT and GM behind the permanent concrete surfacing
- in turn, this requires a GP drainage system





Geocomposite Wick Drains

- also called prefabricated vertical drains (PVDs(
- used for rapid consolidation of saturated fine grained soils
- consists of a drainage core with a GT filter/separator wrapped completely around it
- typically 100 mm wide, by 2to 10 mm thick, by ±100 m long)in roll or coil form(



Design Methods

(a) "Cost"-based on experience/availability
(b) "Specification" – for common applications
(c) "Function" – for specialty, critical and/or permanent applications

Design-by-Function

$$FS = \frac{Allowable\ (Test)\ Property}{Required\ (Design)\ \ Property}$$

where

- test Methods are from ASTM, ISO or GRI
- design Models from the Literature
- factor-of-Safety is Application Specific

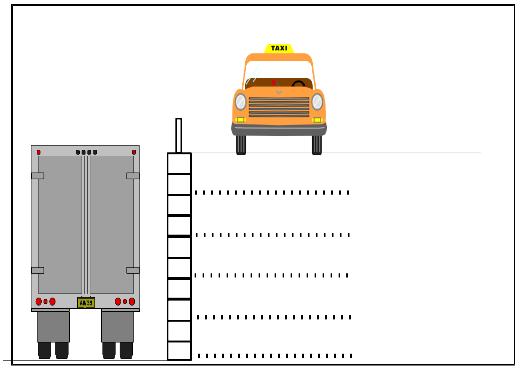
Mechanically Stabilized Earth

Mechanically Stabilized Earth (MSE)

- **Mechanically stabilized earth walls and slopes are constructed with** “reinforced soil” **and consist of horizontal soil reinforcing elements including such things as steel strips, steel or** polymeric grids**, and** geotextile sheets **and a *facing* to prevent erosion.**

Mechanically Stabilized Earth
(MSE)

- Placement of horizontal reinforcing elements of this type significantly strengthens the soil and allows construction of **very steep slopes**. Even vertical walls can be constructed without support from a massive structural system at the face.



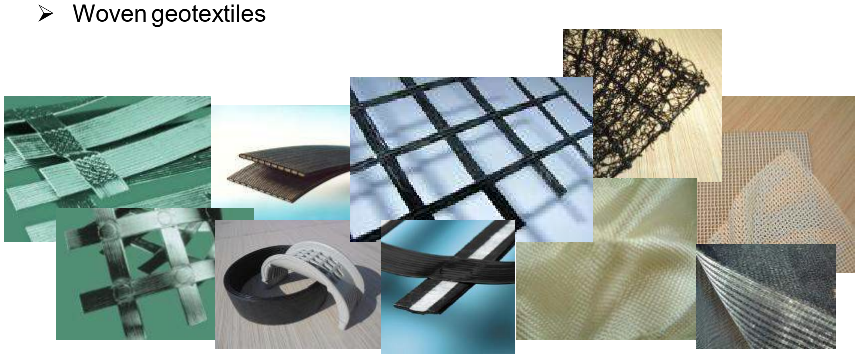
CONCEPT OF REINFORCED SOIL

without soil reinforcement

with soil reinforcement

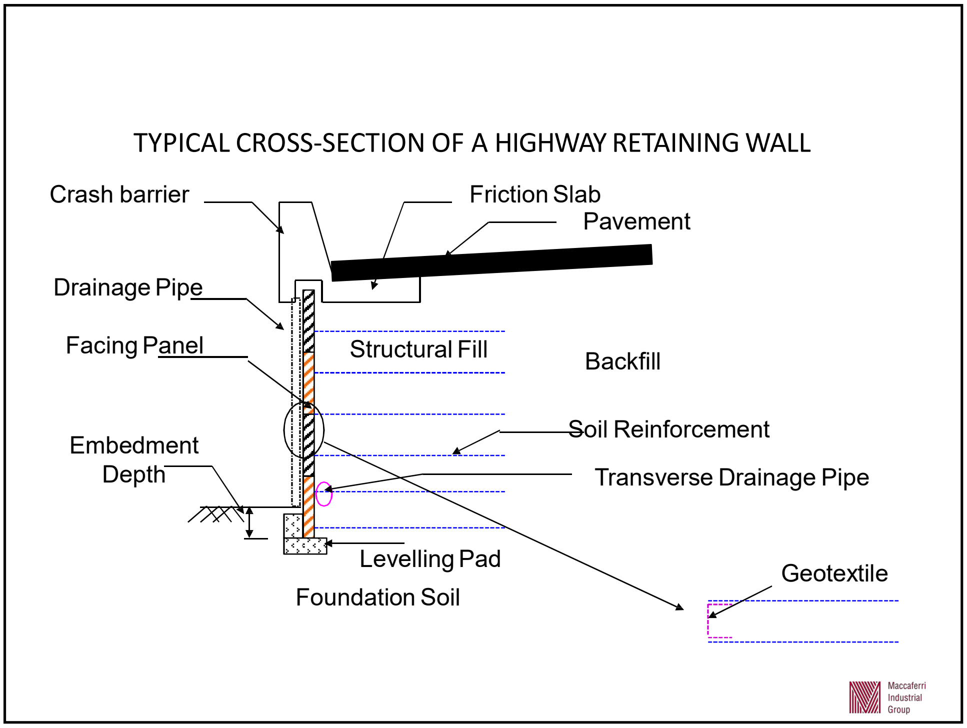
TYPES OF SOIL REINFORCEMENTS

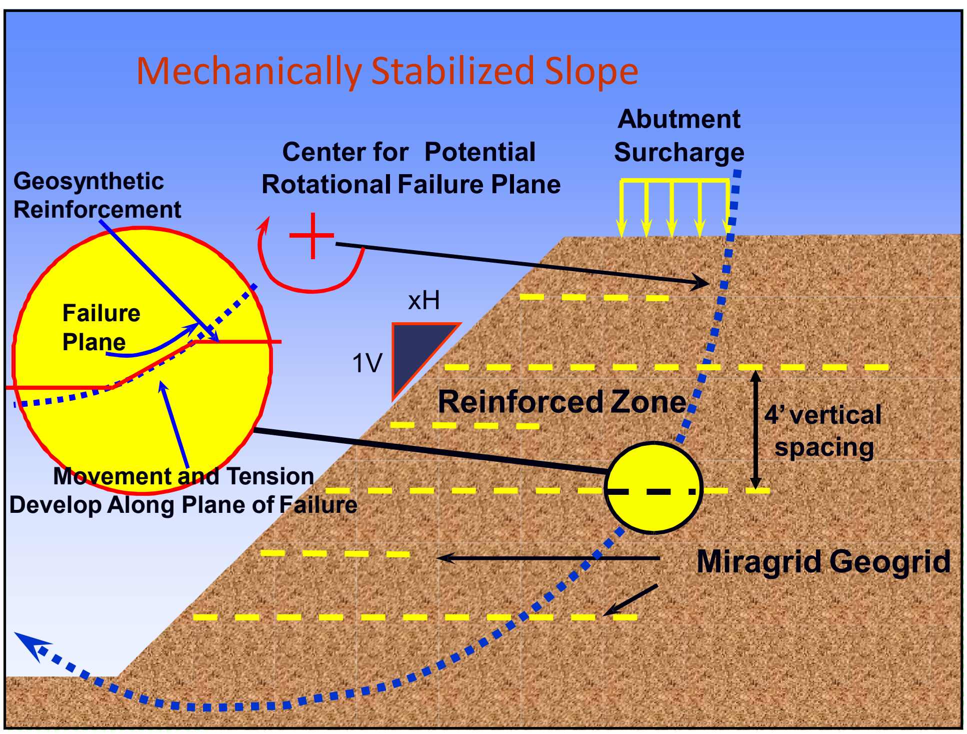
- Steel strip
- Geostrip
- Various types Geogrids (extruded, bonded, woven etc)
- Woven geotextiles



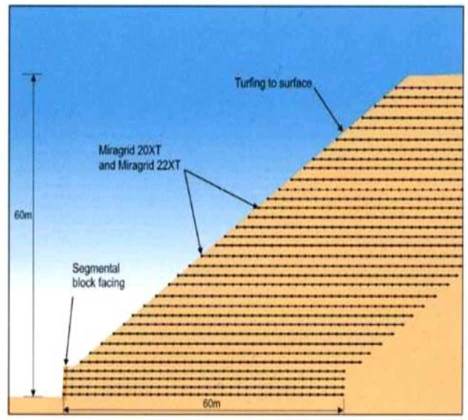
Major applications of Soil Reinforcement as per design codes

- Retaining Walls & Bridge Abutments
- Retaining Slopes
- Soil Nailing
- Embankments
  - On soft soil (like Sabkha in gulf countries)
  - Over piles
  - Over areas prone to subsidence


TYPICAL CROSS-SECTION OF A HIGHWAY RETAINING WALL
Crash barrier
Friction Slab
Pavement
Drainage Pipe
Facing Panel
Structural Fill
Backfill
Soil Reinforcement
Embedment
Depth
Transverse Drainage Pipe
Levelling Pad
Foundation Soil
Geotextile
Maccaferri
Industrial
Group


Mechanically Stabilized Slope
Abutment
Surcharge
Center for Potential
Rotational Failure Plane
Geosynthetic
Reinforcement
Failure
Plane
xH
1V
Reinforced Zone
4' vertical
spacing
Movement and Tension
Develop Along Plane of Failure
Miragrid Geogrid

- Laguna Beach Area, CA



How Steep Can a MSE Slope Go?

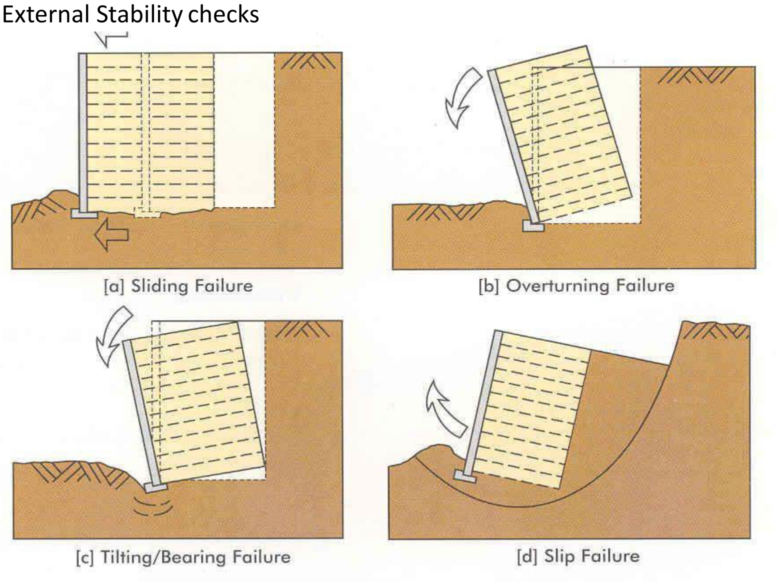
- **> 70 deg. is a retaining wall**

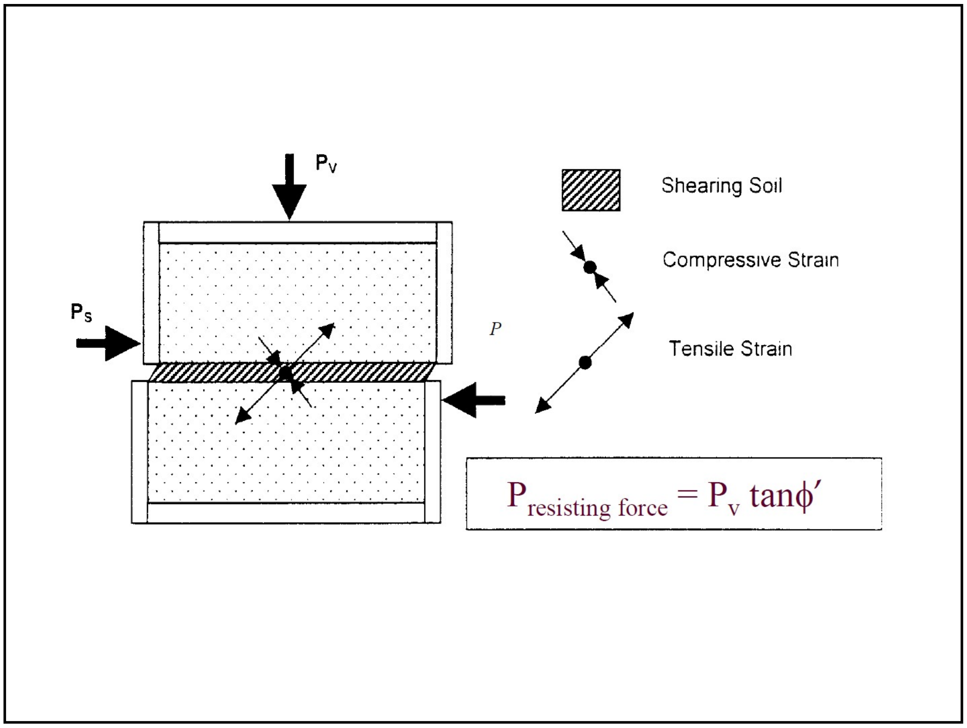
Design of Soil Reinforced Retaining Wall

Stability Checks :

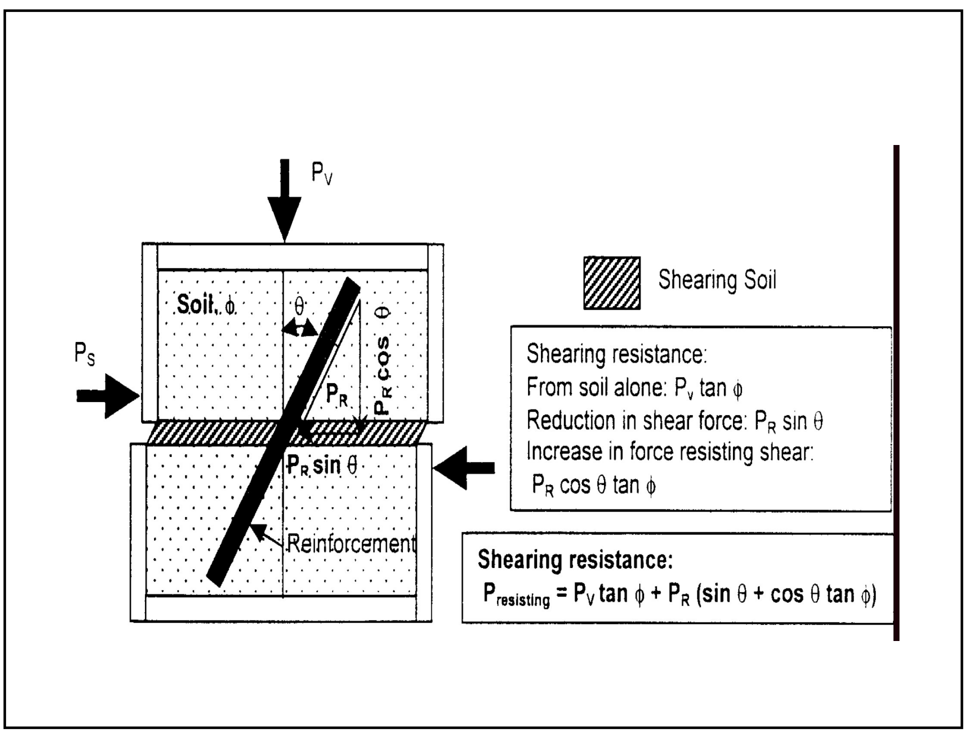
1. External Stability is addressed to check against over-turning, sliding and foundation failure
2. Internal Stability is addressed to determine soil reinforcement spacing, strength & length

External Stability checks





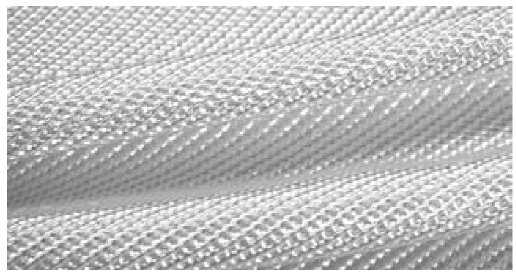
P_V
P_S
Shearing Soil
Compressive Strain
Tensile Strain
P
$P_{resisting\ force} = P_v \tan\phi'$



P_V
P_S
Soil, ϕ
θ
P_R
$P_R \cos\theta$
$P_R \sin\theta$
Reinforcement
Shearing Soil
Shearing resistance:
From soil alone: $P_v \tan\phi$
Reduction in shear force: $P_R \sin\theta$
Increase in force resisting shear:
$P_R \cos\theta \tan\phi$
Shearing resistance:
$P_{resisting} = P_V \tan\phi + P_R (\sin\theta + \cos\theta \tan\phi)$

PET / HS Woven Polyester

- Low creep behavior for long term structural stability and more economical design.
- Geotextile comprised of high tenacity polyester fibers.

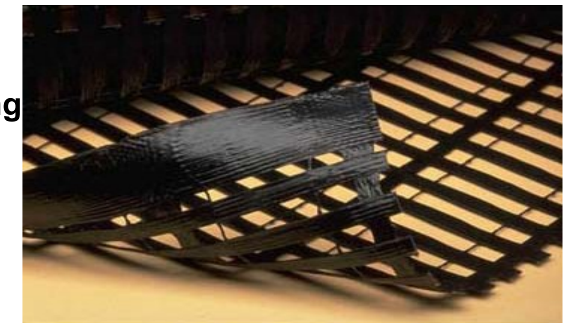


Polypropylene Geotextiles

- **For High Strength Short-Term Loading**
- **For Low Strength Long-Term Loading**

Geogrids

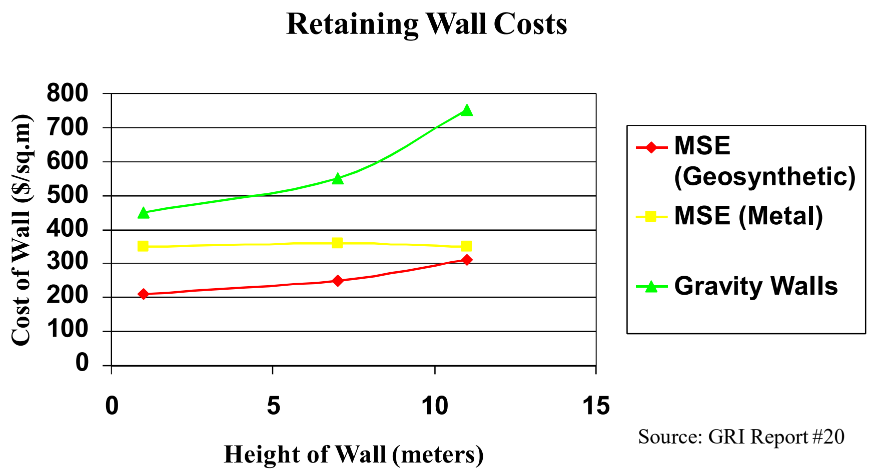
- **High Strength Polyester Coated Geogrid or HDPE Uniaxial grids for Long-Term Projects**
- **Polypropylene Biaxial for Short-Term Loading**



Installation Damage Testing

- Measures the installation damage effects on the geogrid
- In general, the lighter the geogrid, the lower the resistance to installation damage
- Most geogrid companies will report LTDS for three soil types
- Default soil type is sand

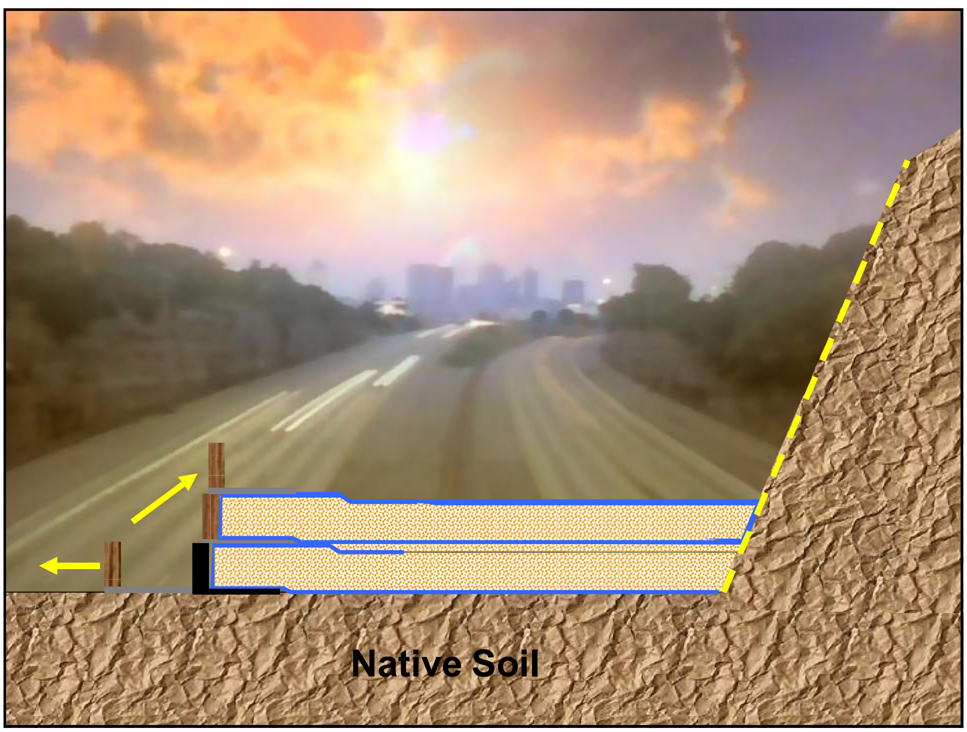
Mechanically Stabilized *Earth Walls*



3 Main Types of MSE *Abutment Walls*

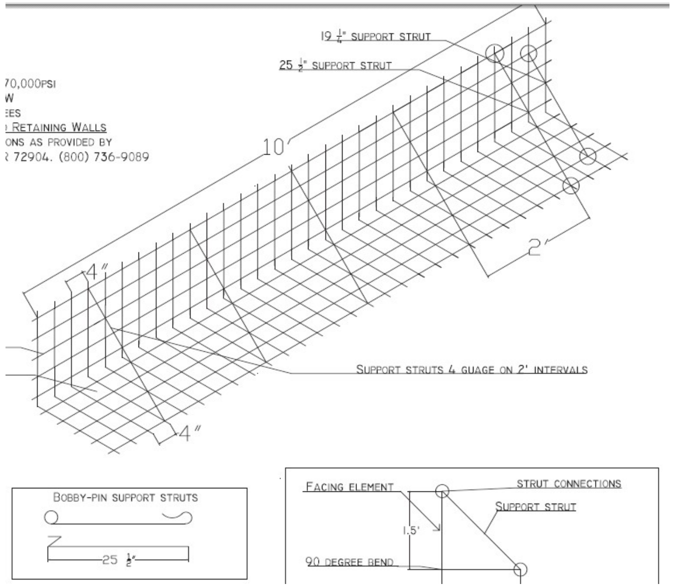
- **Traditional Fabric Faced (wood formed).**
- **Wire Basket Faced (Baskets left in place).**
- **Segmental Block Walls**

Traditional Wood Formed
Fabric Wrapped Face Walls




Wooden Forms

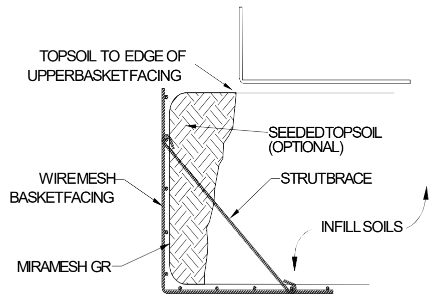
Welded Wire Baskets



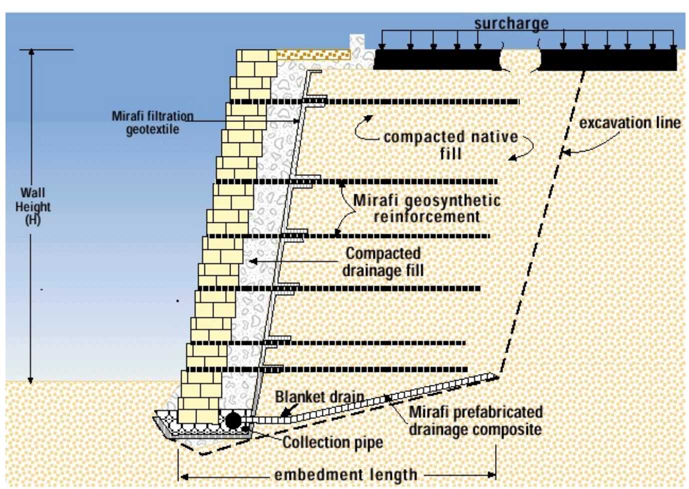
Facing Options

Wire Basket

- Vegetated wall system



Segmental Block Retaining *Walls/Abutments*



Project:
CalTrans PGR Wall – 74' Tall!
Location:
5/805 freeways San Diego,

Highest 1:1 MSE slope in America 242' high

Extension of Runway 5 at Yeager Airport in Charleston, WV

Mechanically Stabilized Earth Walls

❑ **Description**

mechanically stabilized earth wall employs metallic (strip or bar mat) or geosynthetic (geogrid or geotextile) reinforcement that is connected to a precast concrete or prefabricated metal facing a panel to create a reinforced soil mass.

❑ General

1. Typical Application: Bridge abutments, retaining wall, slope stabilization
2. Size requirements: minimum reinforcement length of 0.7 m of the wall height

❑Advantages

1. Rapid construction; does not required specialized labor
2. Limited foundation preparation
3. Flexible; accommodate large differential settlement
4. Reinforcement is light and easily to handle
5. Flexibility in choice facing and architectural finishes
6. Suitable for regions in high seismicity

Mechanically Stabilized Earth Walls Cont.

❑ **Disadvantages**

1. Not economical for cut application due to additional cost in temporary excavation
2. Requires relatively large base width
3. Use of metallic reinfrorcment requires a minimum electrochemical requirements for corrosions
4. Allowable loads for geosynthetic reinforcement must be reduced to account for creep, durability, and construction damage
5. Not appropriate for
   - If we need access to underground utilities
   - Locations subjected to scour
   - Place involving significant horizontal curvature
6. Not cost effective for temporary applications