GROUND IMPROVEMENT

1.1 Introduction

Ground improvement has been both a science and art, with significant developments observed through ancient history. From the use of straw as blended infill with soils for additional strength during the ancient Roman civilizations, and the use of elephants for compaction of earth dams during the early Asian civilizations, the concepts of reinforced earth with geosynthetics, use of electrokinetics and thermal modifications of soils have come a long way. The use of large and stiff stone columns and subsequent sand drains in the past has now been replaced by quicker to install and more effective prefabricated vertical drains, which have also eliminated the need for more expensive soil improvement methods.

The early selection and application of the most appropriate ground improvement techniques can improve considerably not only the design and performance of foundations and earth structures, including embankments, cut slopes, roads, railways and tailings dams, but also result in their cost-effectiveness. Ground improvement works have become increasingly challenging when more and more problematic soils and marginal land have to be utilized for infrastructure development.

1.2 Need for Ground Improvement Techniques

As more engineering structures are built, it becomes increasingly difficult to find a site with suitable soil properties. The properties at many sites must be improved by the use of some form of soil improvement methods, such as: static or dynamic compaction, reinforcement, drainage or by the use of admixtures. Thus, it is important for the soil engineers to know the different soil improvement methods; the degree to which soil properties may be improved; and the costs and benefits involved. In this way, the soil engineer can gain knowledge in order to design ground improvement projects as well as to advise the client regarding value engineering to save cost and obtain maximum benefits for the specific project. The following are some of the methods used as ground improvement techniques:

Surface Compaction, Deep Compaction, Preloading, Vertical Drains, Stone Columns, Vacuum Drainage, Mechanically Stabilized Earth (Reinforced Earth), Granular Piles, Micropiles, Lime Stabilization, Cement Stabilization, Chemical Stabilization, Grouting, Geotextiles, Lightweight Embankment Materials.

1.3 Current status and the scope in the profession

Ground improvement has been both a science and art, with significant developments observed through ancient history. From the use of straw as blended infill with soils for additional strength during the ancient Roman civilizations, and the use of elephants for compaction of earth dams during the early Asian civilizations, the concepts of reinforced earth with geosynthetics, use of electrokinetics and thermal modifications of soils have come a long way. The use of large and stiff stone columns and subsequent sand drains in the past has now been replaced by quicker to install and more effective prefabricated vertical drains, which have also eliminated the need for more expensive soil improvement methods.

The early selection and application of the most appropriate ground improvement techniques can improve considerably not only the design and performance of foundations and earth structures, including embankments, cut slopes, roads, railways and tailings dams, but also result in their cost-effectiveness. Ground improvement works have become increasingly challenging when more and more problematic soils and marginal land have to be utilized for infrastructure development.

Rapid urban and industrial growth demands more land for further development. In order to meet this demand land reclamation and utilization of unsuitable and environmentally affected lands have been taken up. These, hitherto useless lands for construction have been converted to be useful ones by adopting one or more ground improvement techniques. Navi Mumbai is one such example. The field of ground improvement techniques has been recognized as an important and rapidly expanding one.

1.4 Some Techniques - an overview

The ground can be improved by adapting certain ground improvement techniques. Vibro-compaction increases the density of the soil by using powerful depth vibrators. Vacuum consolidation is used for improving soft soils by using a vacuum pump. Preloading method is used to remove pore water over time. Heating is used to form a crystalline or glass product by electric current. Ground freezing converts pore water to ice to increase their combined strength and make them impervious. Vibro replacement stone columns improve the bearing capacity of soil whereas Vibro displacement method displaces the soil. Electro osmosis makes water flow through fine grained soils. Electro kinetic stabilization is the application of electro osmosis. Reinforced soil steel is used for retaining structures, sloping walls, dams etc…. seismic loading is suited for construction in seismically active regions. Mechanically stabilized earth structures create a reinforced soil mass. The geo methods like Geosynthetics, Geogrid etc. are discussed. Soil nailing increases the shear strength of the in-situ soil and restrains its displacement. Micro pile gives the structural support and used for repair/replacement of existing foundations. Grouting is injection of pumpable materials to increase its rigidity.

The jet grouting is quite advanced in speed as well as techniques when compared with the general grouting.

COMPACTION

2.1 Introduction

Many types of earth construction, such as dams, retaining walls, highways, and airport, require man-placed soil, or fill. To compact a soil is to place it in a dense state. The dense state is achieved through the reduction of the air voids in the soil, with little or no reduction in the water content.

2.2 Objectives

- Decrease future settlements
- Increase shear strength
- Decrease permeability

2.3 General Compaction Methods

	Coarse-grained soils	**Fine-grained soils**
Laboratory	Vibrating hammer	Falling weight and hammers Kneading compactors Static loading and press
Field	Hand-operated vibration plates Motorized vibratory rollers Rubber-tired equipment Free-falling weight; dynamic compaction (low frequency vibration, 4~10 Hz)	Hand-operated tampers Sheepsfoot rollers Rubber-tired rollers

2.4 Laboratory Compaction

The purpose of a laboratory compaction test is to determine the *proper amount of mixing water* to use when compacting the soil in the field and the *resulting degree of denseness* which can be expected from compaction at this optimum water.

The *proctor test* is an impact compaction. A hammer is dropped several times on a soil sample in a mold. The mass of the hammer, height of drop, number of drops, number of layers of soil, and the volume of the mold are specified.

Standard Proctor Test		**Modified Proctor Test**	
Weight of hammer =	2.6 kg	Weight of hammer =	4.9 kg
Height of fall =	310 mm	Height of fall =	450 mm
No. of Impacts =	25	No. of Impacts =	25
No. of layers =	3	No. of layers =	3

2.4.1 Procedure

- Several samples of the same soil, but at different water contents, are compacted according to the compaction test specifications.
- The total or wet density and the actual water content of each compacted sample are measured.

$$\rho = \frac{M_t}{V_t}, \ \rho_d = \frac{\rho}{1+w}$$

- Plot the dry densities ρ_d versus water contents w for each compacted sample. The curve is called as a *compaction curve*.

2.5 Field Compaction Equipment

- **Smooth-wheel roller (drum)**
  - 100% coverage under the wheel
  - Contact pressure up to 380 kPa
  - Can be used on all soil types except for rocky soils.
  - Compactive effort: static weight
  - The most common use of large smooth wheel rollers is for proof-rolling subgrades and compacting asphalt pavement.

- **Pneumatic (or rubber-tired) roller**
  - 80% coverage under the wheel
  - Contact pressure up to 700 kPa
  - Can be used for both granular and fine-grained soils.
  - Compactive effort: static weight and kneading.
  - Can be used for highway fills or earth dam construction.

- **Sheepsfoot rollers**
  - Has many round or rectangular shaped protrusions or "feet" attached to a steel drum
  - 8% ~ 12 % coverage
  - Contact pressure is from 1400 to 7000 kPa

- It is best suited for clayed soils.
- Compactive effort: static weight and kneading.

- **Tamping foot roller**
  - About 40% coverage
  - Contact pressure is from 1400 to 8400 kPa
  - It is best for compacting fine-grained soils (silt and clay).
  - Compactive effort: static weight and kneading.

- **Mesh (or grid pattern) roller**
  - 50% coverage
  - Contact pressure is from 1400 to 6200 kPa
  - It is ideally suited for compacting rocky soils, gravels, and sands. With high towing speed, the material is vibrated, crushed, and impacted.
  - Compactive effort: static weight and vibration.

- **Vibrating drum on smooth-wheel roller**
  - Vertical vibrator attached to smooth wheel rollers.
  - The best explanation of why roller vibration causes densification of granular soils is that particle rearrangement occurs due to cyclic deformation of the soil produced by the oscillations of the roller.
  - Compactive effort: static weight and vibration.
  - Suitable for granular soils

2.6 Field Compaction Control and Specifications

- *Dry density* and *water content* correlate well with the engineering properties, and thus they are convenient construction control parameters.
- Since the objective of compaction is to stabilize soils and improve their engineering behavior, it is important to keep in mind the desired engineering properties of the fill, not just its dry density and water content. This point is often lost in the earthwork construction control.
- 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 are written. Field compaction *control tests* are specified, and the results of these become the standard for controlling the project.
- 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 are written. Field compaction *control tests* are specified, and the results of these become the standard for controlling the project.

2.6.1 Specifications

<u>End-product specifications</u>

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. *Care the results only !*

<u>Method specifications</u>

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.

2.6.2 Field control tests

Field control tests, measure the dry density and water content in the field can either be *destructive* or *nondestructive*.

<u>Destructive Methods</u>

(a) Sand cone
(b) Balloon
(c) Oil (or water) method

Calculations

- Know M_s and V_t
- Get $\rho_{d\ field}$ and w (water content)
- Compare $\rho_{d\ field}$ with $\rho_{d\ max\text{-}lab}$ and calculate relative compaction R.C.

<u>Nondestructive Methods</u>

Nuclear density meter

(a) Direct transmission
(b) Backscatter
(c) Air gap

Principles

<u>Density</u>

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.

<u>Water content</u>

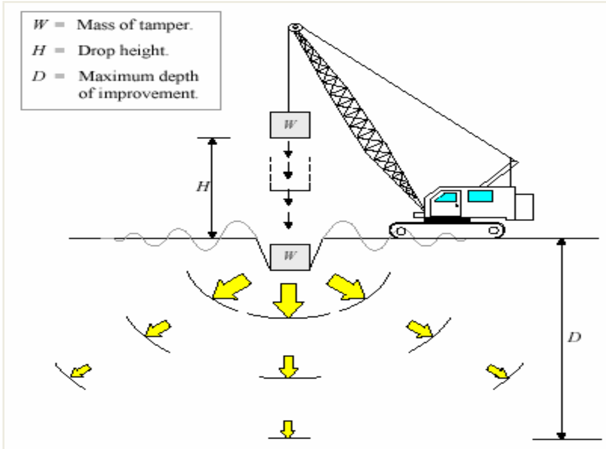
The water content can be determined based on the neutron scatter by hydrogen atoms. Typical neutron sources are americium-beryllium isotopes.

DYNAMIC COMPACTION

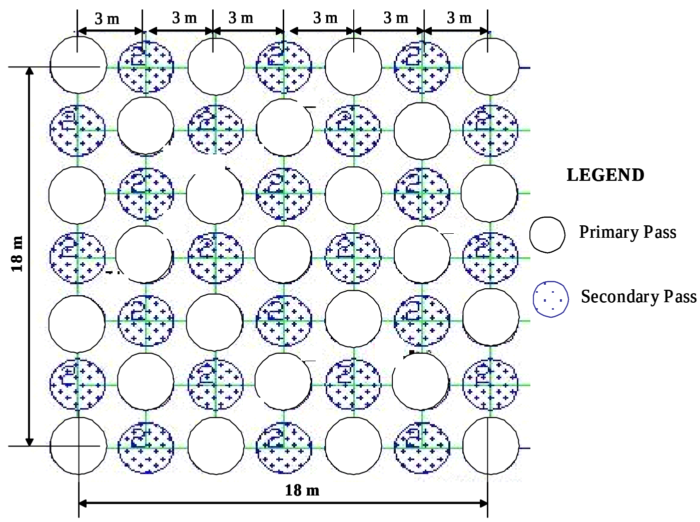
3.1 Introduction

Soil is compacted by repeated, systematic application of high energy using a heavy weight (pounder). The imparted energy is transmitted from the ground surface to the deeper soil layers by propagating shear and compression waves types, which force the soil particles into a denser state. In order to assure effective transfer of the applied energy, a 1 to 2 m thick stiff layer usually covers the ground surface. Pounders can be square or circular in shape and made of steel or concrete. Their weights normally range from 5 to 25 tons and drop heights of up to 25 m have been used. Heavier weights and larger drop heights have been used for compaction of deep soil deposits, but are not very common.

- Technique involves repeatedly dropping a large weight from a crane
- Dynamic Compaction is most often utilized as an economic alternative to excavation and replacement and/or deep foundations
- Weight may range from 6 to 172 tons
- Drop height typically varies from 10 m to 40 m
-
- degree of densification achieved is a function of the energy input (weight and drop height) as well as the saturation level, fines content and permeability of the material.
- 6 – 30 ton weight can densify the loose sands to a depth of 3 m to 12 m.
- Typical area that can be compacted with single crane 300-600 m^2.
- Done systematically in a rectangular or triangular pattern in phases
- Each phase can have no of passes; primary, secondary, tertiary, etc.
- Spacing between impact points depend upon:
    - Depth of compressible layer
    - Permeability of soil
    - Location of ground water level
- Deeper layers are compacted at wider grid spacing, upper layer are compacted with closer grid spacing
- Deep craters are formed by tamping
- Craters may be filled with sand after each pass
- Heave around craters is generally small



(a)

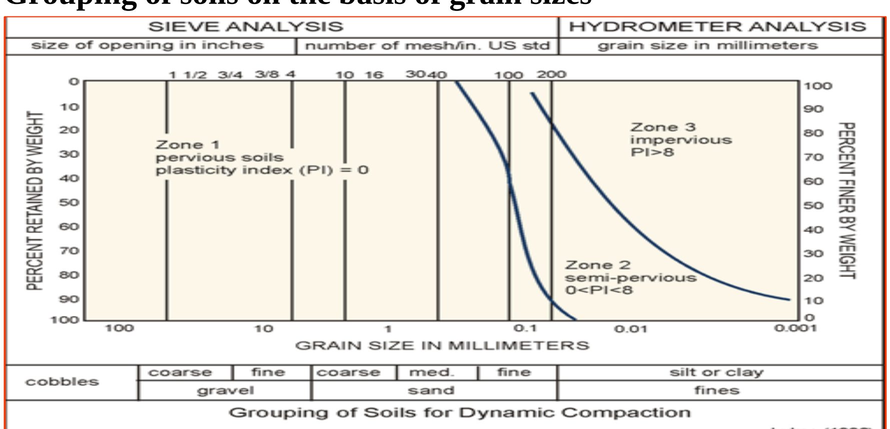


(b)

3.2 Application

- Applicable to wide variety of soils

Grouping of soils on the basis of grain sizes



Zone 1: Best
Zone 3: Worst (consider alternate methods)
Zone 2: Must apply multiple phases to allow for pore pressure dissipation

- Mainly used to compact granular fills
- Particularly useful for compacting rockfills below water and for bouldery soils where other methods can not be applied or are difficult
- Waste dumps, sanitary landfills, and mine wastes
- In sanitary fills, settlements are caused either by compression of voids or decaying of the trash material over time, DDC is effective in reducing the void ratio, and therefore reducing the immediate and long term settlement.
- DDC is also effective in reducing the decaying problem, since collapse means less available oxygen for decaying process.
- For recent fills where organic decomposition is still underway, DDC increases the unit weight of the soil mass by collapsing voids and decreasing the void ratio.
- For older fills where biological decomposition is complete, DDC has greatest effects by increasing unit weight and reducing long term ground subsidence.

3.3 Evaluation of Improvement (Control)

- The depth of improvement is proportional to the energy per blow
- The improvement can be estimated through empirical correlation, at design stage and is verified after compaction through field tests such as Standard Penetration Tests (SPT), Cone Penetration Test (CPT), etc.

3.4 Grid Spacing

- Significant effect on depth of improvement (Typical values 5 to 10 m)
- 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

3.5 Merits

- It is one of the most basic methods of compacting lose soils.
- Depth of compaction can reach upto 20 m.
- All types of soils can be compacted.
- Produces equal settlements more quickly than surcharge type loading.
- It can be used to treat soils both above and below water table.
- Cost effective and applied to all soil types and varied field conditions.

VIBRO-COMPACTION

4.1 Introduction

Vibro-compaction, sometimes referred to as Vibrofloation, is the rearrangement of soil particles into a denser configuration by the use of powerful depth vibration**.** Vibrocompaction is a ground improvement process for densifying loose sands to create stable foundation soils. The principle behind vibrocompaction is simple. The combined action of vibration and water saturation by jetting rearranges loose sand grains into a more compact state. Vibrocompaction is performed with specially-designed vibrating probes 12 to 16 inches in diameter which vibrates at frequencies typically in the range of 30 to 50 Hz. The probe is first inserted into the ground by both jetting and vibration. After the probe reaches the required depth of compaction, granular material, usually sand, is added from the ground surface to fill the void space created by the vibrator. A compacted radial zone of granular material is created.

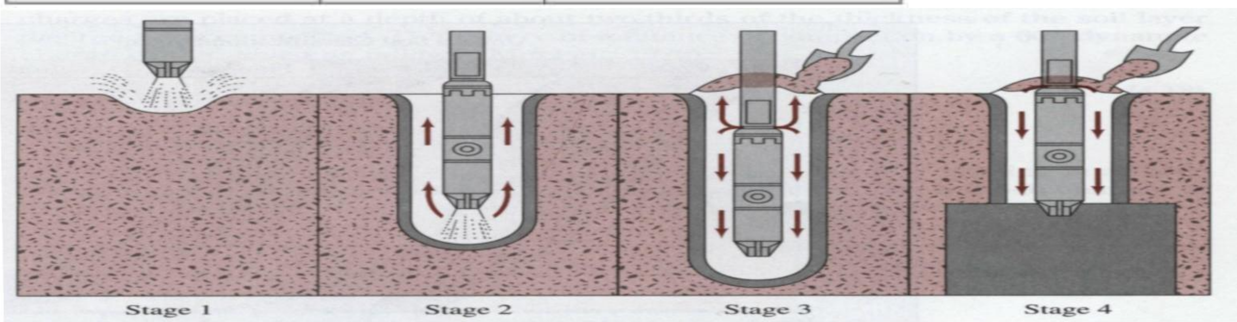
4.2 Applications

- Reduction of risk of liquefaction due to seismic activity.
- Permit construction on granular fills.
- Reduce foundation settlements
- Prevent soil liquefaction during earthquakes
- Increase in-situ density of land reclamation fills
- Increase shear strength to improve slope stability
- Reduce water permeability to facilitate dewatering

4.3 Suitability

- Suitable if less than 10% fine are there

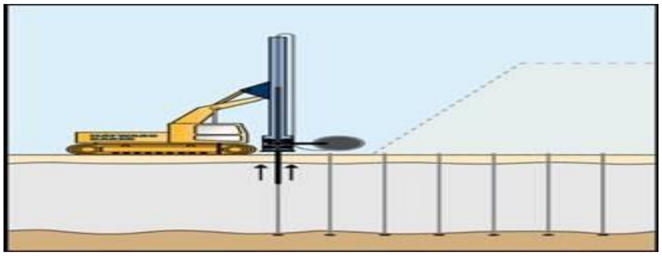
Soil Type	Effectiveness	When to get expert advice
Sands with < 5% fines	excellent	Grain size curve very steep. High carbonate or mica content
Sands with < 12 % fines	Marginal to good	Success depends on many factors, such as clay content, grain shape, grain size curve, water table.
Sands with over 12% fines	Poor to marginal	Ask for expert advice if VC may work. Method may work in combination with -> Wick drains
Clay	Not applicable	
Land reclamation	Excellent, if spec for fill material is appropriate	Get advice at early stage to assure that the specs for the fill material are amenable to VC



PRELOADING

5.1 Introduction

Preloading has been used for many years without change in the method or application to improve soil properties. Preloading or pre-compression is the process of placing additional vertical stress on a compressible soil to remove pore water over time. The pore water dissipation reduces the total volume causing settlement. **Surcharging** is an economical method for ground improvement. However, the consolidation of the soils is time dependent, delaying construction projects making it a non-feasible alternative.

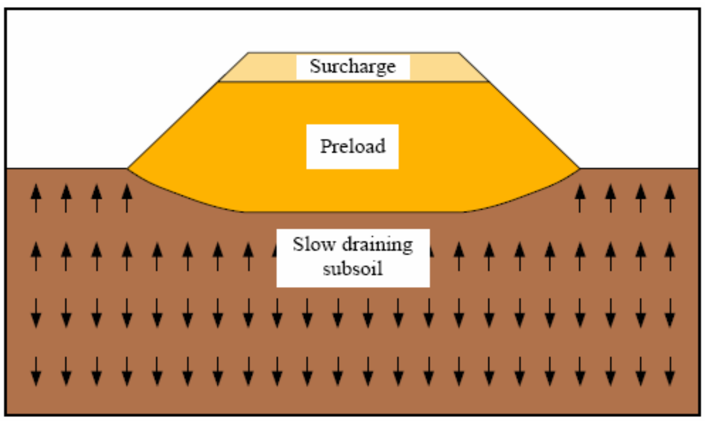


The soils treated are Organic silt, Varved silts and clays, soft clay, Dredged material The design considerations which should be made are bearing capacity, Slope stability, Degree of consolidation.

The two common preloading techniques are conventional preloading, e. g.

- by means of an embankment, and
- vacuum induced preloading.

5.2 Preloading by means of an Embankment



Preloading by means of an embankment

5.2.1 The Technique

- 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.
- Surcharge fills are typically 3-8 m thick and generally produces settlements of 300 mm – 1000 mm.

5.2.2 Limitations

- Surcharge fill must extend horizontally atleast 10 m beyond the perimeter of the planned construction, which may not be possible at confined sites.
- Transport of large quantities of soil on and off the site may not be practical, or may have unacceptable environmental (noise, traffic, dust) impacts on adjacent areas.
- Surcharge must remain in place for months or years thus delaying construction.

5.3 Vacuum Preloading

- In its simplest form the method of vacuum consolidation consists of a system of vertical drains and a drainage layer (sand) on top (150 mm).
- It is sealed from atmosphere by an impervious membrane. Horizontal drains are installed in the drainage layer and connected to a vacuum pump.
- To maintain air tightness, the ends of the membrane are placed at the bottom of a peripheral trench filled e. g. with bentonite.
- Negative pressure (60 to 80 kPa) is created in the drainage layer by means of the vacuum pump. The applied negative pressure generates negative pore water pressures, resulting in an increase in effective stress in the soil, which in turn is leading to an accelerated consolidation.

5.3.1 Advantages of vacuum preloading

- There is no extra fill material needed, the construction times are generally shorter and it requires no heavy machinery.
- No chemical admixtures will penetrate into the ground and thus it is an environmental friendly ground improvement method
- Isotropic consolidation eliminates the risk of failure under additional loading of the permanent construction, there is no risk of slope instability beyond boundaries and it allows a controlled rate and magnitude of loading and settlement

5.4 Prefabricated Vertical Drains and Pre-loading

With increased thickness of the soft clay where the consolidation period is too long for full consolidation of primary settlements, vertical drainage may be incorporated in conjunction with preloading in order to accelerate the settlement. Vertical drains may be proposed in the areas where the thickness of soft soils is limited to less than 10 m and embankment height are low. The anticipated primary and secondary settlements in such areas are limited.

5.4.1 Vertical Drains

Vertical drains are artificially-created drainage paths which are inserted into the soft clay subsoil. Thus, the pore water squeezed out during consolidation of the clay due to the hydraulic gradients created by the preloading, can flow faster in the horizontal direction towards the vertical drains.

Therefore, the vertical drain installation reduces the length of the drainage path and, consequently, accelerates the consolidation process and allows the clay to gain rapid strength increase to carry the new load by its own.

5.4.2 Types of Vertical Drains

- Sand Drains
- Prefabricated Drains

5.4.2.1 Sand drains

Sand drains are basically boreholes filled with sand. Are of two types:

- Displacement Sand Drains

As for the displacement type of sand drains, a closed mandrel is driven or pushed into the ground with resulting displacement in both vertical and horizontal directions. The installation causes therefore disturbances, especially in soft and sensitive clays, which reduces the shear strength and horizontal permeability.

- Non Displacement Sand Drains

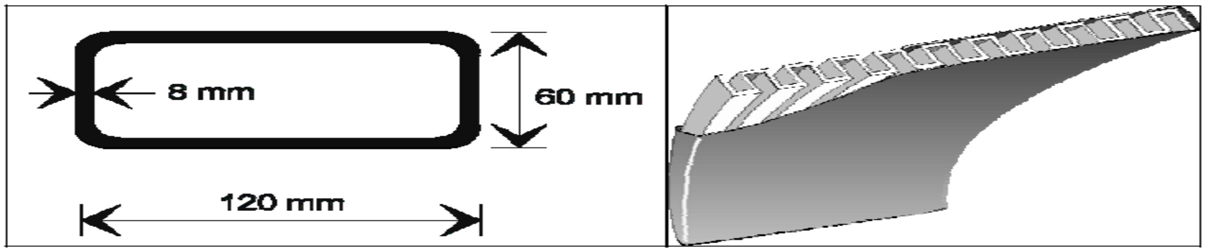
The low- or non-displacement installations are considered to have less disturbing effects on the soil. Drilling of the hole is done by means of an auger or water jets. In terms of jetting, however, installation is very complex.

Disadvantages of sand drains

- To receive adequate drainage properties, sand has to be carefully chosen which might seldom be found close to the construction site.
- Drains might become discontinuous because of careless installation or horizontal soil displacement during the consolidation process.
- During filling bulking of the sand might appear which could lead to cavities and subsequently to collapse due to flooding.
- Construction problems and/or budgetary burdens might arise due to the large diameter of sand drains.
- The disturbance of the soil surrounding each drain caused by installation may reduce the permeability, the flow of water of water to the drain and thus the efficiency of the system.
- The reinforcing effect of sand drains may reduce the effectiveness of preloading the subsoil.

5.4.2.2 Prefabricated Drains

The installation of prefabricated vertical drains is also done by a mandrel and it is a displacement installation. Figure shows a typical mandrel and the typical shape of a prefabricated drain. The dimensions of the prefabricated drains are much smaller compared to sand drains and subsequently are the dimensions of the mandrel. Thus, the degree of soil disturbance caused by the size of the mandrel during installations is lower.



These may be -

- **Cardboard Drains**

Cardboard draıns are drıven ınto the ground by purpose-made mandrel whıch ıs then removed.

- **Plastic Drains**

These are the new generatıon draıns whıch are very sımılar to cardboard draıns

- **Sandwicks**

These are ready-made small dıameter sand draıns whıch are contaıned ın long canvas bags (approximately 10 cm ın diameter). They are usually ınstalled by close mandrel technıque. They are relatıvely cheap.

Advantages

- Low cost.
- Fast Installation
- Ensured drain continuity
- Clean site
- High permeability
- Negligible soil disturbance
- Positive Drainage

5.4.2.3 Guidelines for spacing, depth

The design of any vertical drain project involves the determination of drain spacing which will give the required degree of consolidation in a particular period of time for a known type of drain.

- The vertical grids are installed in triangular or square grid pattern.
- Spacing ranging from 1 to 4 m.
- The depth of clay is often taken as the full depth of soft clay.
- For depth of 5-20 m of soft clay, full depth vertical depths prove to be economical. Beyond 20 m the installation costs rise markedly.

5.4.2.4 Design Procedures (General)

- All design procedures for vertical drains require a proper estimate of the coefficient of radial consolidation c_h. This parameter links vertical compressibility and horizontal compressibility and horizontal permeability and controls the radial flow of water into the drain.
- c_h varies from 2-10 times the c_v.
- monograph for estimating the average degree of percent consolidation for various values of c_h, drain diameter and spacing and time is used.

STONE COLUMNS

6.1 Introduction

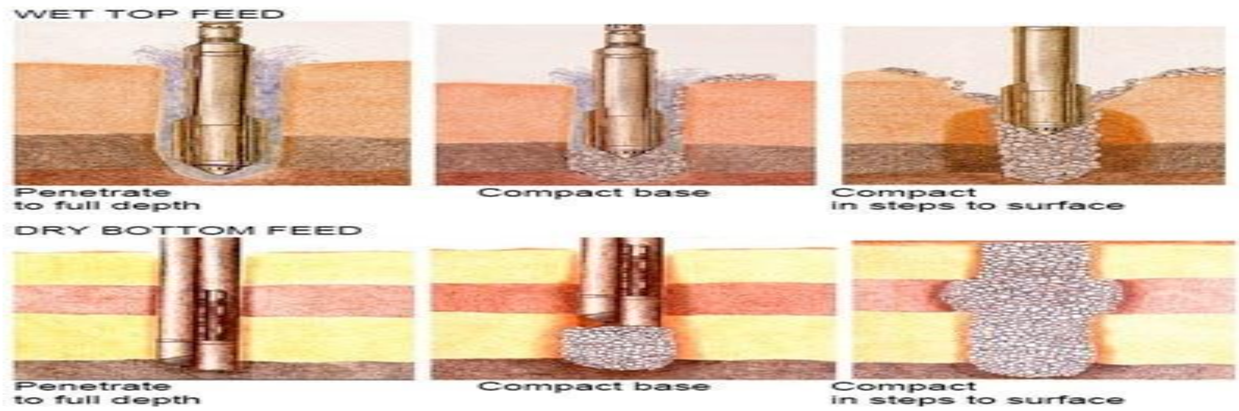
Stone Columns: In contrast with vibro-compaction, which is undertaken solely to compact granular soils, stone columns may be installed in granular or cohesive soils. Vibrated stone columns are relatively stiff with respect to the surrounding ground.

Stone columns may be provided in areas where subsoil consists of more than about 5 m thick soft cohesive soil and where stability and stringent considerations cannot be satisfied with conventional removal / replacement of soft material. Stone columns enable the embankment to be constructed to its full height continuously without requiring stage construction.

6.2 The Technique

A cylindrical vertical hole is made and gravel backfill is placed into the hole in increments and compacted by a suitable device which simultaneously displaces the the material radially.

The vibroflot is allowed to sink into the ground due to its own weight, assisted by water or air as a flushing medium, upto the required depth. The soil surrounding the vibroflot is disturbed or remoulded and the softened material can be removed by jetting fluid. By this process a borehole of larger diameter is formed once the vibroflot is withdrawn. The borehole is backfilled with gravel of 12 to 75 mm.



Boreholes are also made using dry processes-

- Closed end pipe method

A closed end pipe is driven to desired depth and gravel is allowed to fill. The rammer is used to compact the gravel as the pipe is withdrawn.

- Rammed Stone column

Auger boring equipment is used to make a bore whole and cast iron hammer is used to compact the fill.

6.3 Typical values and design guidelines

- **Diameter**

  Diameter installed by vibroflot (0.3 to 0.5m) varies between 0.6 m (stiff clays) and 1.1m (very soft clays).

- **Spacing**

  Determined based on the settlement tolerances for the loads to be applied and degree of improvement required. Generally spaced from 1.2 to 3 m.

- **Length**

  The length of stone columns is sufficient either to extend below the depth of significance stress increase caused by the foundation or should extend through the soft clay to firm strata to control settlements.

6.4 Application of method

- Reduce foundation settlements
  - Stone columns may be arranged to support isolated footings, strip footings or mat foundations.
  - As bearing capacity of stone columns is generally high, settlement is the important criteria. (in the range of 5- 10 mm for single test column)

- Prevent soil liquefaction during earthquakes
- Increase shear strength to improve slope stability
- Increase water permeability to accelerate drainage

BLASTING

7.1 Introduction

It is often necessary to densify loose granular soils to achieve acceptable foundation performance of structures, particularly in areas of seismic activity where it is necessary to reduce soil liquefaction and seismic deformation potential. Compaction in granular soils is achieved by vibration, typically either by insertion of a large vibrating poker into the ground (vibro-compaction) or by frequent drops of a large mass from a great height (deep dynamic compaction). Increases in building code design accelerations for structures in potential seismic areas and the resulting increase in the requirement for densification has led to investigation of the potential for use of explosive compaction (EC) as an economic alternative to the more traditional techniques.

7.2 The Technique

- A certain amount of explosive charge is buried at a certain depth of a cohesionless soil required to be compacted and is then detonated.
- A pipe of 7.5 to 10 cm is driven to the required depth in a soil stratum. The sticks of dynamite and an electric detonator are wrapped in the water proof bundles and lowered through the casing.
- The casing is withdrawn and a wad of paper of wood is placed against the charge of explosives to protect it from misfire.
- The whole is backfilled with sand in order to obtain the full force of the blast.
- The elctrical circuit is closed to fire the charge. A series of holes are thus made ready.
- Each hole is detonated in succesion and the resulting large diameter holes formed by lateral displacement are backfilled.
- The surface settlements are measured by taking levels or from screw plates embedded at a certain depth below the ground surface.

Once an area of ground has been treated and pore pressures have largely dissipated, repeated applications ("passes") of shaking caused by controlled blast sequences causes additional settlement depending on soil density and stiffness. The first pass destroys any bonds existing between cohesionless soil particles due to aging and other geologic processes, and causes the majority of settlement within the soil mass. Subsequent passes cause additional settlement by cyclic straining. As a result, surface settlement and increased soil resistance to cyclic loading will be caused by the blasting.

7.3 Some guidelines and typical values

- Usually the explosives are arranged in the form of a horizontal grid. The spacing of the charges are decided by the depth of strata to be densified, the size of the charge and the overlapping of the charges. A spacing of 3 to 8 m is typical and a spacing less than 3 m should be avoided.
- Compaction is carried out in a single tier only if the depth of stratum to be densified is less than 10 m or less.
- In such a case the depth of explosive charge should be below half the depth of the mass or stratum to be densified (appox. At 2/3 point)
- More than one tier should be planned if the depth of stratum to be densified is more than 10m. Generally h_e depth of charge should be greater than the radius of Influence (R).
- Successive blasts of small charges at appropriate spacings are likely to be more effective than a single large blast.
- Charges should be timed to explode such that the bottom of the layer being densified upwards in a uniform manner.
- The uppermost portion of the stratum may be less densified which may be compacted by the vibratory rollers
- The amount of charge should be optimal. The surface heave should not be more than 0.15 m.
- Charge masses of less than 2 kg to more than 30 kg have been used.

7.4 Advantages

- Blasting technique involves less time, labour and expense.
- This technique needs no special equipment and could be successfully used for densifying soil at a great depth.
- This could be used to compact a large volume to a substantial depth upto 20m and in small areas where the other methods would be impractical.
- In remote areas where vibrations are favourable, the technique may prove most cost effective.

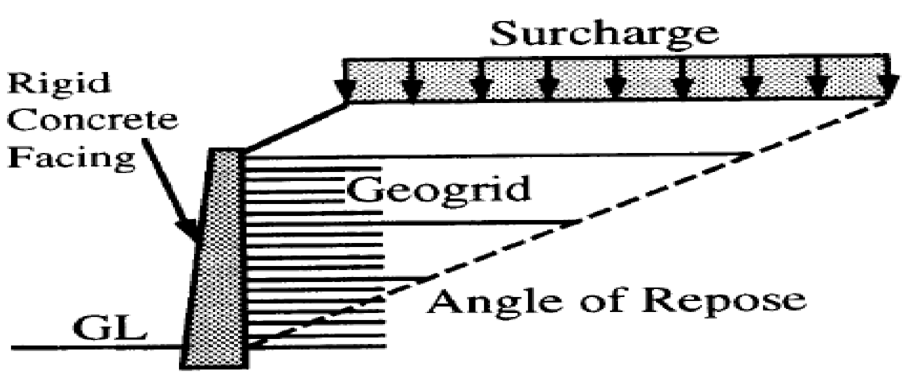
7.5 Limitations

- Non uniformity, potential adversse effects on adjacent structures and the danger associated with the use of explosives in populated areas.
- Very fine grained soils with cohesive forces cannot be compacted by this methos.
- Maximum compaction is obtained only when the soil is completely dry or fully saturated.
- The blasting work is executed only by an experienced contractor under special supervision.

REINFORCED EARTH STRUCTURES

8.1 Introduction

The concept of soil enforcement is based on the existence of strong soil-reinforcement interaction like roots, due to their tensile strength and frictional or adhesion properties reinforce the soil. Many hypotheses have been postulated, in the past 25 years, about the load transfer between the soil and reinforcement and their interaction. Reinforced earth is a composite material formed by the friction between the earth and the reinforcement. By means of friction the soil transfers to the reinforcement the forces built up in the earth mass. The reinforcement thus develops tension and the earth behaves as if it has cohesion. Mechanically Stabilized Earth Walls (MSEW) and Reinforced Soil Slopes (RSS) are usually considered as cost-effective soil-retaining structures. By inclusion of tensile reinforcing elements in the soil, the strength of the soil can be improved significantly such that the vertical face of the soil/reinforcement system is essentially self supporting. Based on limited data, reinforcement accounts for 45 to 65 percent of total cost.



(c) Geosynthetic reinforced soil-rigid wall (GRS-RW) system (*Tatsuoka*, 1994)

8.2 Types of reinforcing material

Extensible Reinforcement

Tensile strain in the reinforcement is greater or equal to the horizontal extension required to develop an active plastic state in the soil.

Inextensible Reinforcement

Tensile strain in the reinforcement is significantly less than the horizontal extension required to develop an active plastic state in the soil.

Thus an extensible reinforcement makes the structure brittle while the other type makes it flexible

Example:

Inextensible

Steel, Galvanised steel, Polyster coated fiberglass.

Extensible

Major geosynthetic materials such as geogrid sheet, woven and non woven geotextile sheet, coated fibre strips, rigid plastic strips, composites and three dimensional honey comb type products.

8.3 Applications of Reinforced Soil

More common applications of reinforced soil are in the form of RETAINING WALLS. Reinforced soil structures can be grouped into three classes:

- Embankment and Retaining walls
- Foundations and Subsoil reinforcements
- Insitu Reinforcements (soil-nailing), existing slopes and excavations.

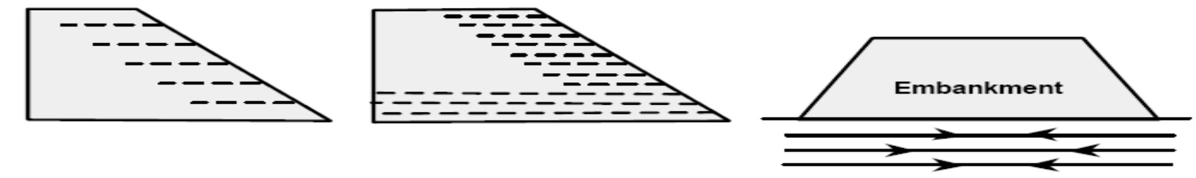
Embankment and Retaining walls

A primary role of reinforcement in an embankment or a retaining wall is to support the outward earth pressure (lateral thrust) in the fill while maintaining the full bearing capacity in the foundation. The purpose of these reinforcement is to per form as

(a) Superficial slope reinforcement and edge stiffening.

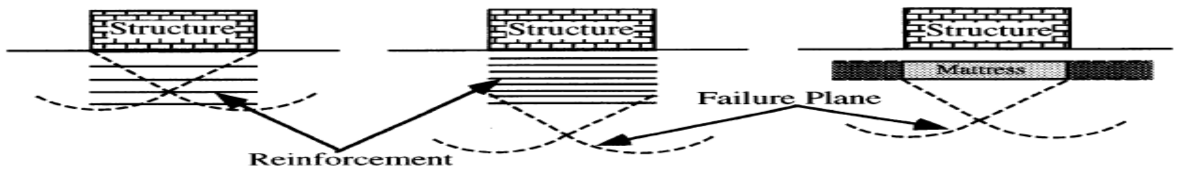
(b) Main body reinforcement

(c) Reinforcement at the base of retaining wall.



(a) Superficial reinforcement (b) Body reinforcement (c) Foundation reinforcement

- Foundations and Subsoil reinforcements



(i) Sparcely layered system (ii) Densly layered system (iii) Mattress Foundation

Reinforced Earth Walls

Mechanically Stabilized Earth Walls (MSEW) and Reinforced Soil Slopes (RSS) are usually considered as cost-effective soil-retaining structures. By inclusion of tensile reinforcing elements in the soil, the strength of the soil can be improved significantly such that the vertical face of the soil/reinforcement system is essentially self supporting.

Structural Applications

Reinforced Earth is used in urban, rural and mountainous terrain for

- Retaining Walls
- Seawalls
- Bridge Abutments
- Submerged walls
- Railway Structures
- Truck dumps
- Dams
- Bulk storage facilities

8.4 Advantages

- *Flexibility* - Reinforced Earth structures distribute loads over compressible soils and unstable slopes, reducing the need for deep foundations

- *High load-carrying capability, both static and dynamic* - applied structural loads are distributed through the compacted granular fill and earth pressure loads are resisted by the gravity mass
- *Ease and speed of installation* - prefabricated materials and granular soil simplify construction and minimize the impact of bad weather
- *Pleasing appearance* - panels may be given a variety of architectural treatments
- *Economy* - 15-50% savings over cast-in-place concrete walls, depending on wall height and loading conditions.

8.5 Description of a Reinforced Earth Wall

Reinforced Earth Wall consists of three components - precast concrete **facing panels**, **metallic (steel) soil reinforcements** and **granular backfill**. Its strength and stability are derived from the frictional interaction between the granular backfill and the reinforcements, resulting in a permanent and predictable bond that creates a unique composite construction material.

Facing Panels

Concrete Facing Panels

- Panels are manufactured in factory conditions using high-quality steel moulds.
- Concrete facing panels are delivered to the construction site in stacks of five panels. Timber spacers are placed between the panels to facilitate unloading and handling. All facing panels are clearly marked with the appropriate type. This allows each facing panel to be installed in the correct location.
- The use of discrete facing panels makes Reinforced Earth structures particularly tolerant to differential settlement.
- Concrete facing panels are available in a variety of textured and patterned finishes. Different colours can be achieved with the use of pigmented concrete.
- Concrete facing panels are durable and have proven to be especially resilient to fire damage.
- Tried and tested repair methods allow individual panels damaged by, for example, vehicle collision, to be replaced without compromising the integrity of the structure.

Steel Facing Panels

- Galvanized steel facing panel is a lightweight steel mesh facing that is suitable for both permanent and temporary applications.

- These facing panels can be constructed to form vertical, stepped or sloping structures.
- It is easy to handle and cut on site making it ideal for structures with complex geometry or curved alignments. It can be clad with brick or stone and is often used to form spandrel walls to our precast concrete arches.
- Large sized stone can be placed behind the facing to give an attractive natural appearance. It is also possible to establish vegetation behind the facing to form a green slope.

Soil Reinforcement

- Both steel and synthetic soil reinforcement are available to suit the particular requirements of the project.
- Most Reinforced Earth structures are constructed using galvanized steel high adherence reinforcing strips. These provide a low-strain, robust and durable solution suitable for most land based applications.
- In corrosive environments, such as marine applications, galvanized steel is unsuitable for permanent structures. For these applications, the GeoStrap® synthetic soil reinforcement provides a suitable alternative to steel. The GeoStrap is connected to concrete facing panels through fully synthetic GeoMega® sleeve, thus providing a durable non-metallic mechanical connection.
- This fully synthetic solution enables a wider range of fill materials to be used, including recycled aggregates containing potentially corrosive material.

Durability of reinforcement

- The durability of galvanized steel earth reinforcements depends on the electrochemical properties of both the reinforcements and the reinforced backfill.
- We know the rate at which the galvanization is consumed and the rate at which the underlying steel corrodes once the zinc is gone, so it is a simple calculation to determine a structure's expected life. Conversely, given a service life requirement (typically 75 years for permanent structures, 100 years for critical structures), the amount of steel required to achieve that service life can also be calculated. Practically speaking, reinforcing strips are manufactured in a single, standard cross section and design requirements are met by varying the *number* rather than the *size* of the reinforcements.

Back fill characteristics controlling

The backfill characteristics that affect the service life of buried galvanized steel are pH, soil resistivity at 100% saturation, and the levels of dissolved sulfate and chloride ions.

Submergence in fresh or salt water increases the potential for corrosion loss, but submerged behavior is well understood and design adjustments can be made to produce safe and durable structures. For normal dry-land construction, the acceptable ranges for pH, resistivity, chlorides and sulfates are

pH	5 - 10
Resistivity	> 3000 ohm-cm
Chlorides	< 100 ppm
Sulfates	< 200 ppm

Physical characteristics:

- Although the standard specification for Reinforced Earth select backfill requires less than or equal to 15% passing the 0.075 mm (No. 200) sieve, materials with up to 40% passing *may be considered under limited circumstances and after careful testing*. The Owner/ Consultant must weigh the potential cost advantage of using such fine-grained backfill against the possibly significant increase in the number and length of steel reinforcements required, as well as the resulting increase in the Reinforced Earth backfill volume.
- Under no circumstances should a backfill with greater than 15% fines be used in a periodically submerged structure

Chemical characteristics:

- pH 5 - 10
- Resistivity > 3000 ohm-cm
- Chlorides < 100 ppm
- Sulfates < 200 ppm

8.6 Construction

- Reinforced Earth system is straightforward to construct. No specialist plant or labour is required. Construction operations are performed from the backfill side of the structure, making it ideal for structures where disruption to adjacent features needs to be minimised.
- Facing panels, soil reinforcement and ancillary items are delivered to site as required. All facing panels are clearly marked with the appropriate type. This allows each facing panel to be installed in the correct location.
- The first course of facing panels is constructed on a small mass concrete levelling pad.

- Layers of granular backfill are placed and compacted and soil reinforcement is connected to the facing panels at the appropriate levels. Where concrete facing panels are being used a hydraulic excavator is used to lift the panels into place.
- Geotextile strips are placed across the panel joints to prevent the loss of fines from the backfill whilst allowing the structure to drain. Lightweight compaction equipment is used to compact the fill within 2m of the facing panels. Outside of this zone heavier compaction equipment can be used.
- Construction of the TerraTrel system is similar to the concrete faced system. However, the lightweight steel facing panels can be easily handled and can be cut to size on site.

8.7 Stability

Stability of Reinforced Earth structures is dependent upon many factors. The number and length of the reinforcing strips is determined by considering the combined effects of the select and random backfills, the foundation and backslope materials, surcharge loads, service life requirements and, if applicable, submergence conditions and seismic acceleration. Construction methods must also be considered, along with both site and subsoil drainage and scour protection. Ultimately, stability is assured by providing a reinforced granular mass of sufficient dimensions and structural capacity, bearing on adequate foundation material, having a durable facing material, well-chosen drainage systems, and proper embedment of the toe of the wall.

8.8 Stability Evaluation

Reinforced Earth structures are evaluated for ***external stability*** and ***internal stability***.

External stability considers the behavior of the site under the loading imposed by the Reinforced Earth structure, and is primarily influenced by site geotechnical and hydraulic conditions. Internal stability refers to the behavior of and interrelationship among the components of the Reinforced Earth structure itself - the facing, the reinforcing strips and the select backfill. Each type of stability will be discussed separately.

8.9 Economics

Reinforced Earth, when compared with conventional retaining structures, is economical solution. The cost effectiveness depends on the geometry of the structure and the use of backfill soil. Hence, the economic position can only be determined for a specific project.

The cost effectiveness increases when the height of the structure is more, e.g. if for 2m high structure, Reinforced Earth is cheaper by 15%; then for 4m high structure, the cost would be 20% cheaper than conventional retaining structures and so on.

***Some other aspects of Reinforced Earth wall can be referred from the word file MSE 14.**

SHALLOW FOUNDATIONS ON REINFORCED SOIL

Reinforced soil, or mechanically stabilized soil, is a construction technique that consists of soil that has been strengthened by tensile elements such as metal strips, geotextiles, or geogrids.

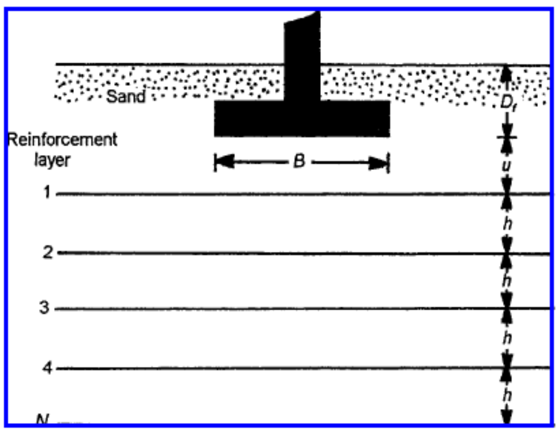


FIGURE 7.2 Foundation on metallic strip reinforced granular soil

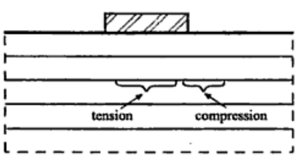


Figure 1.10. Compression and tension in the same reinforcing member in the subsoil beneath footing.

The metallic strips that are used for reinforced soils are usually galvanized steel strips. However, the galvanized steel strips are subject to corrosion at the rate of about 0.025 to 0.05 mm/year. Hence, depending on the project service life of the given structure, allowances must be made for the rate of corrosion.

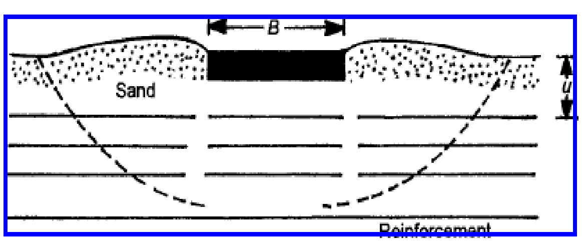


FIGURE 7.3 Failure in reinforced earth by tie break ($u/B < 2/3$ and $N > 4$)

Geotextiles and geogrids are non biodegradable materials. They are made from petroleum products such as polyster, polythelene, and polypropylene. Geotextiles perform four major functions: (a) allow drainage from the soil; (b) keep the soil layer separated; (c) provide reinforcement to the soil; and (d) allow free seepage from one layer of the soil to the other.

In shallow foundations the first reinforcement layer is placed at a distance u measured from the bottom of the foundation. The distance between each layer of reinforcement is ‘h’. It was experimentally shown that the most beneficial effect of reinforced earth is obtained when u/B is less than 2/3 of B and the number of layers of reinforcement (N) is greater than 4 but no more than 6 to 7. If the length of the ties (i.e. reinforcement strips) is sufficiently long, failure occurs when the upper ties break.

The figure below shows an idealized condition for the development of a failure surface in reinforced earth which consists of two zones. Zone I is immediately below the foundation which settles with the foundation which settles with the foundation during the application of load. In zone II the soil is pushed outward and upward. Points , A_1, A_2, A_3,… and B_1, B_2, B_3,..., which define the limits of zone I and II, are points at which maximum shear stress, τ_{max}, occurs in the *xz* plane. The distance $x = x'$ of the point measured from the centerline of the foundation where maximum shear stress occurs is a function of *z/B*

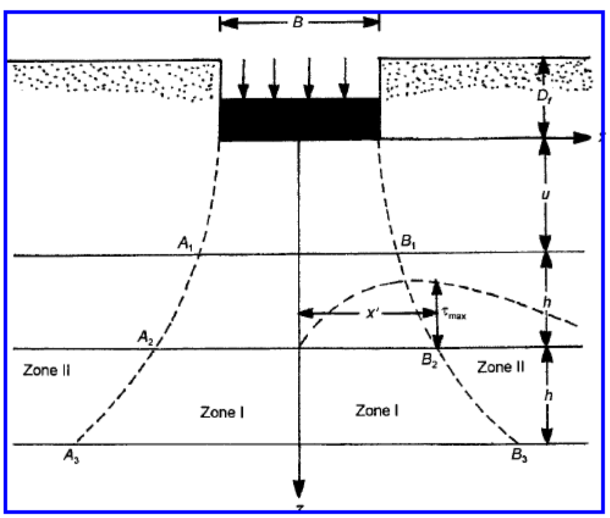


FIGURE 7.4 Failure surface in reinforced earth at ultimate load

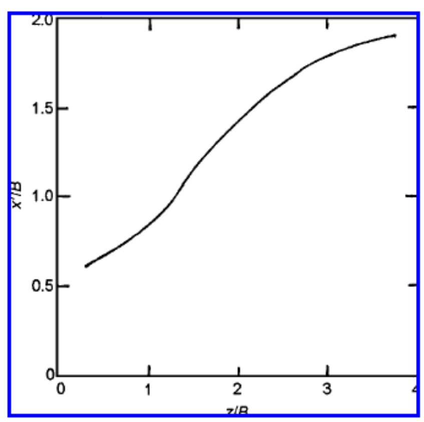


FIGURE 7.5 Variation of x'/B with z/B

---

*Soil stabilization (Mechanical (mixing), Chemical (lime), Cementation (Cement, bitumen)) can be referred from the regular books (Transportation books or GIT by P Purushothama Raj).

*‘Grouting and Geotextiles’ from GIT by P Purushothama Raj.