MODULE – 6

Soil Improvement Techniques
RECAP

- LIQUEFACTION MITIGATION TECHNIQUES:
  - Avoiding Liquefaction Susceptible Soils
    - susceptibility of the soil judged by historical, geological, compositional and state criteria of the soil
  - Building Liquefaction-Resistant Structures
    - Designing foundation elements to resist effects of liquefaction
  - Mitigation methods include vibro–compaction, dynamic compaction and vibro–stone columns.

- Vibro – Replacement Stone Column Method
  - Wet top feed process:
    - Steps involved: penetration, compaction and completion
    - Areas of Application
  - Down bottom feed process:
    - Steps involved: penetration, installation and completion
    - Areas of Application
  - The V – Rex and Vibro Stitcher
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- Vibro - Compaction:
  - Steps involved:
    - penetration, compaction and completion
  - Effects and Test Pattern
  - Offshore and Land-based

- Soil Improvement Methods:
  - Densification Techniques (dynamic compaction, blasting)
  - Reinforcement Techniques
  - Grouting and Mixing Techniques
  - Drainage Techniques

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Soil Improvement Methods

Ground Reinforcement:

- Stone Columns
- Deep Soil Nailing
- Jet Grouting
- Geosynthetics
- Lime Columns
- Mechanically Stabilized Earth

- Soil Nails
- Micropiles (Mini-piles)
- Ground Anchors
- Fiber Reinforcement
- Vibro-Concrete Column
- Biotechnical
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Soil Improvement Methods

Ground Improvement:  Ground Treatment:
- Deep Dynamic Compaction  - Soil Cement
- Drainage/Surcharge  - Lime Admixtures
- Electro-osmosis  - Flyash
- Compaction grouting  - Dewatering
- Blasting  - Heating/Freezing
- Surface Compaction  - Vitrification

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DYNAMIC COMPAC TION
✓ Many types of earth construction, such as dams, retaining walls, highways, and airport, require man-placed soil, or fill. To compact a soil, that 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. This process must not be confused with consolidation, in which water is squeezed out under the action of a continuous static load.

Objectives:
(1) Decrease future settlements
(2) Increase shear strength
(3) Decrease permeability

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Sequence of Dynamic Compaction:

- Technique
- Energy transfer mechanism
- Stages of compaction
- Application – which soils are compacted?
- Types
- Ground Vibrations
- Design Considerations

Technique:

- Technique involves repeatedly dropping large weight from crane
- 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.

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Done systematically in a rectangular or triangular pattern in phases.
Each phase can have no of passes; primary, secondary, tertiary, etc.
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- 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

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- Deep craters are formed by tamping
- Craters may be filled with sand after each pass
- Heave around craters is generally small
Energy Transfer Mechanism:

- Energy transferred by propagation of Rayleigh (surface) waves and body (shear and compression) waves
  - Rayleigh: 67%
  - Shear: 26%
  - Compression: 7%

Densification Process:

- Compressibility of saturated soil due to presence of micro bubbles
- Gradual transition to liquefaction under repeated impacts
- Rapid dissipation of pore pressures due to high permeability after soil fissuring
- Thixotropic recovery
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Application:

- Applicable to wide variety of soils
- Grouping of soils on the basis of grain sizes
- 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
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- 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.

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- 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.
Types of Dynamic Compaction:

- Dynamic compaction
- Dynamic consolidation
- Dynamic replacement
- Rotational dynamic compaction
- Rapid impact dynamic compaction

Dynamic Compaction:

- It is the compaction of unsaturated or highly permeable saturated granular materials by heavy tamping.
- The response to tamping is immediate.
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Rotational Dynamic Compaction:

- A new dynamic compaction technique which makes use of the free fall energy as well as rotational energy of the tamper called Rotational Dynamic Compaction (RDC)
- The technique increases depth of improvement in granular soils
- Comparative study showed that the cone penetration resistance was generally larger than conventional dynamic compaction and the tamper penetration in rotational dynamic compaction was twice as large as that of conventional dynamic compaction
Rapid Impact Dynamic Compaction:

Dynamic Consolidation:

- The improvement by heavy tamping of saturated cohesive materials in which the response to tamping is largely time dependent
- Excess pore water pressures are generated as a result of tamping and dissipate over several hours or days after tamping.
Dynamic Replacement:

➢ The formation by heavy tamping of large pillars of imported granular soil within the body of soft saturated soil to be improved

➢ The original soil is highly compressed and consolidated between the pillars and the excess pore pressure generated requires several hours to dissipate

➢ The pillars are used both for soil reinforcement and drainage
**Evaluation of Improvement:**

- 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.

![Image of compaction process](image.png)

\[ D_{\text{max}} = n \sqrt{W \times H} \]

Where,

- \( D_{\text{max}} \) = Max depth of improvement, m
- \( n \) = Coefficient that caters for soil and equipment variability
- \( W \) = Weight of tamper, tons
- \( H \) = Height of fall of tamper, m

- The effectiveness of dynamic compaction can also be assessed readily by the crater depth and requirement of backfill.
## SOIL DYNAMICS

<table>
<thead>
<tr>
<th>Reference</th>
<th>n-Values</th>
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<tbody>
<tr>
<td>Menard and Broise (1975)</td>
<td>1.0</td>
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<td>Leonard et al. (1980)</td>
<td>0.5</td>
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<tr>
<td>Bjolgerud and Han (1963)</td>
<td>1.0 (rockfill)</td>
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<tr>
<td>Smoltcyk (1983)</td>
<td>0.5 (soil with unstable structure)</td>
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<td>0.67 (silts and sands)</td>
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<td>1.0 (purely frictional sand)</td>
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<td>Lukas (1980)</td>
<td>0.65 - 0.8</td>
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<tr>
<td>Mayne et al. (1984)</td>
<td>0.3 - 0.8</td>
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<tr>
<td>Gambin (1984)</td>
<td>0.5 - 1.0</td>
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<td>Qian (1985)</td>
<td>0.65 (fine sand)</td>
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<td>0.68 (soft clay)</td>
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<td>0.55 (loess)</td>
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<td>Van Impe (1989)</td>
<td>0.65 (silty sand)</td>
</tr>
<tr>
<td></td>
<td>0.5 (clayey sand)</td>
</tr>
</tbody>
</table>

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## SOIL DYNAMICS

**Ground Vibrations:**

- Dynamic compaction generates surface waves with a dominant frequency of 3 to 12 Hz.
- These vibrations generate compression, shear and Rayleigh waves.
- The Raleigh waves contain about 67 percent of the total vibration energy and become predominant over other wave types at comparatively small distances from the source.
- Raleigh waves have the largest practical interest for the design engineers because building foundations are placed near the ground surface.
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- 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 such as portable seismograph, accelerometers, velocity transducers, linear variable displacement transducers (LVDT), etc.

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- The frequency of the Raleigh waves decreases with increasing distance from the point of impact.
- Relationship between PPV and inverse scaled distance is shown graphically (the inverse scaled distance is the square root of the compaction energy, divided by the distance, d from the impact point).
### Soil Dynamics

#### Effect on Humans:

- **0.1 mm/sec** not noticeable
- **0.15 mm/sec** nearly not noticeable
- **0.35 mm/sec** seldom noticeable
- **1.00 mm/sec** always noticeable
- **2.00 mm/sec** clearly noticeable
- **6.00 mm/sec** strongly noticeable
- **14.00 mm/sec** very strongly noticeable
- **17.8 mm/sec** severe noticeable

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#### Monitoring and Control:

![Diagram](image)

- **Van with Receiving and Processing Unit**
- **FM Receiver**
- **FM Discriminator**
- **Signal Conditioner**
- **Data Acquisition System**
- **Digital Oscilloscope**
- **Printer**
- **Tamper with Accelerometer and FM Transmitter**
- **Total Station to Measure Tamper Position After Impact**

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Design and Analysis Consideration:

- Depth of improvement, d
- Impact energy, E
- Influence of cable drag
- Equipment limitations
- Influence of tamper size
- Grid spacing, S
- Time delay between passes
- Soil conditions

Depth of Improvement (d):

Primary concern

- Depends on:
  - Soil conditions
  - Energy per drop
  - Contact pressure of tamper
  - Grid spacing
  - Number of passes
  - Time lag between passes
Impact Energy (E):

- Weight of tamper times the height of drop
- Main parameter in determining the depth of improvement
- Can be calculated from the equation

\[ D_{\text{max}} = n\sqrt{W \times H} \]

(Free falling of weights)

Influence of Cable Drag:

- Cable attached to the tamper causes friction and reduces velocity of tamper.
- Free fall of tamper is more efficient.
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Equipment Limitations:

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

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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
Time Delay between Passes:

- Allow pore pressures to dissipate.
- Piezometers can be installed to monitor dissipation of pore pressures following each pass.

Reinforcement Techniques

(a) Compaction Piles:

- Granular soils are generally improved effectively by compaction piles.
- Usually made of pre-stressed concrete or timber.
- They are driven into a loose sand or gravel deposit in a grid pattern and left there.
- Seismic performance of the soil deposit is improved by three mechanisms:
  - Reinforcement.
  - Densification.
  - Increasing the lateral stresses.
- Improvement can be achieved with reasonable economy to depths of about 60 ft.
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(b) Vibroflotation and Vibro-replacement:

- Vibroflotation involves the use of a vibrating probe (vibroflot) suspended by a crane, that can penetrate granular soil to depths of over 100 feet.
- The vibrations of the probe cause the grain structure to collapse thereby densifying the soil surrounding the probe.
- The vibroflot is raised and lowered in a grid pattern.
- Vibro-replacement is a combination of vibroflotation with a gravel backfill resulting in stone columns (reinforcement and drainage).
- Vibroflotation is most effective in clean granular soils with fines content less than 20% and clay contents below 3%.
- Soil depth up to 35 m has been successfully densified by vibroflotation.

(c) Stone Columns:

- They are dense columns of gravel.
- Usually installed by vibroflotation process.
- Used to treat depths over 100 ft.
- The vibrations of the probe cause the grain structure to collapse, thereby densifying the soil surrounding the probe.
- Increase bearing capacity.
- Decrease total and differential settlement.
- Used to increase shear strength by accelerating consolidation by allowing radial drainage and introducing columns of stronger material.
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**GROUTING AND MIXING TECHNIQUES**

a) Compaction Grouting:
   - A slow-flowing water/sand/cement mix is injected under pressure into a granular soil.
   - The grout forms a bulb that displaces and hence densifies the surrounding soil.
   - A good option if the foundation of an existing building requires improvement.
   - **Merit:** Less expensive process.
   - **Demerits:** - Difficult to analyze the results.
     - Usually ineffective near slopes or for near-surface soils.

b) Jet Grouting:
   - The soil is mixed with cement grout injected horizontally under high pressure in a previously drilled borehole.
   - Jet grouting begins at the bottom of the borehole and proceeds to the top.
   - Leaves behind a relatively uniform column of mixed soil-cement.
   - The diameters of jet-grouted columns are generally greater in coarse-grained soils than in fine-grained soils.
   - Jet grouting can be performed in any type of inorganic soil to depths limited only by the range of drilling equipment.
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GROUTING AND MIXING TECHNIQUES

(c) Soil Mixing
- Jetting or augers are used to physically mix the cementitious matter and soil.
- As the mixing augers are advanced into the soil, grout is pumped through their stems and injected into the soil at their tips.
- After the design depth has been reached, the augers are withdrawn while the mixing process continues.
- The soil mixing process leaves behind a uniform (constant width) column of soil-cement.
- There can be overlapping of treated columns.
- Soil mixing can be used in virtually any type of inorganic soil.
- The strength of the soil-cement mixture depends upon the type of grout, type of soil and the degree of mixing.

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GROUTING AND MIXING TECHNIQUES

(d) Intrusion Grouting
- A fluid grout is injected under pressure to cause controlled fracturing of the soil.
- Relatively viscous and strong cement grouts can be used.
- Primarily, the improvement occurs in the form of the increased stiffness and strength of the soil mass.
- Some densification achieved.
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GROUTING AND MIXING TECHNIQUES

- Jet Grouting
- Intrusion Grouting
- Compaction Grouting

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DRAINAGE TECHNIQUES

- Reduce liquefaction hazards by increasing the drainage ability of the soil.
- As the pore water within the soil can drain freely, the build-up of excess pore water pressure is reduced.
- Include installation of drains of gravel, sand or geo-synthetic materials.
- Synthetic wick drains can be installed at various angles, in contrast to gravel or sand drains that are usually installed vertically.
- Drainage techniques often supplement other types of soil improvement techniques.
DRAINAGE TECHNIQUES

- Rate of pore pressure dissipation depends on the diameter and spacing of stone columns and on the permeability and compressibility of the surrounding soil.

VERIFICATION OF GROUND IMPROVEMENT

(a) Laboratory Testing Techniques:
- Allows greater control and more accurate measurement of stress, strain and environmental conditions than field tests.
- Inevitably suffer from the problem of sample disturbance.
- Can only provide verification at discrete points.
(b) Field Testing Techniques:

1. In situ testing techniques
   - Usually, in-situ test are performed to evaluate the liquefaction potential of a soil deposit before the improvement was attempted.
   - Common tests include SPT, CPT, PMT and so on.
   - Interpretation of soil improvement effectiveness must be done carefully.
   - Should be done at least 72 hours after densification has taken place.

2. Geophysical Testing Techniques:
   - Used to test the effectiveness of the soil improvement methods, which cause an increase in the stiffness of the treated soil.
   - Common tests include the Cross bore hole tests and downhole tests, SASW and so on.

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CASE STUDY #1

➢ Using Stone Columns as a Suitable Liquefaction Remediation in Persian Gulf Coast (Moayedi et al. 2010)

- The site was a waste water septic tank project resting on a highly liquefaction susceptible soil layer.
- The excess pore pressure values in the non-drain system model sharply increased to a high amount within just 2 seconds after the earthquake shaking.
- For the model using stone column system, excess pore water pressure was found to increase more slightly and up to 9 seconds did not show any significant liquefaction zone at all.
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CASE STUDY #1

The amount of excess pore pressure in different depths for drained system comes out to be much less than what observed in non-drained system.

![Fig. 1: Excess pore water pressure versus depths in centre-line without drain pile](image1)

![Fig. 2: Excess pore water pressure versus depths in adjust to drain pile system](image2)

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CASE STUDY #2

- **Soil liquefaction prevention by Electro – osmosis (Hocking and Hebner, 2006)**
  - Hocking and Hebner (2006) activated an electro – osmotic gradient away from the foundation of the existing structure.
  - A constant, low direct current (D.C.) was applied between the electrodes inserted in the saturated soil.
  - Gave rise to pore fluid movement in the negatively charged soil from the anode to the cathode and thus, modified the pore-water pressure.
  - Caused the ground water to move away from the foundation of the structure.
CASE STUDY #2

- The structural stability of the foundation was maintained by preventing the liquefaction of the sub base soils during the simulation of the earthquake event.
- Adopted in the existing structures with almost negligible disturbance or disruption to the existing structures.
- Very effective for short term stabilization of certain type of soils, such as fine sands, silty sands and silts.
- Electro-osmosis is not used extensively.

CASE STUDY #3

- Drain Improvement Method for Reduction of Liquefaction Potential (Sesov et al., 2004)
- Laboratory model tests were conducted on a shaking table using a laminar box in 1-g gravity field to test the efficiency of micro-drains.
- Basic ground model consisted of two layers of saturated silica sand, having relative density 80% and 40% at the bottom and top respectively.
- Six Prefabricated drains were installed in the upper layer with only 5 cm of their height being placed in the bottom layer. Spacing between the drains was kept as 10 cm.
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CASE STUDY #3

- The generation and dissipation of excess pore pressure in saturated sandy layers were compared between micro drains and gravel drains, during and after the termination of shaking.
- Decrease of the level of maximum pore pressure was observed.
- Drains significantly elongated the time (cycles) required for liquefaction occurrence and shortened the time period for complete dissipation by accelerating the dissipation process.

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➢ Conclusions from the Case Studies:

- Adequate soil improvement techniques should be adopted if it is inevitable to construct in the liquefaction prone areas.
- If the soil improvement is conducted properly, the treated ground can be expected to perform much better than the untreated one.
- It is difficult to predict the effectiveness of the methods in advance for a particular site.
- The efficiency of the soil improvement technique will be dependent upon several factors such as the equipment employed, method used, the skill of the contractor and so on.
- A proper knowledge along with proper quality control at the site is required to assure satisfactory improvement.