A Mini Project report on

COMPREHENSIVE ANALYSIS OF SOIL COMPACTION: METHODS, EFFECTS, AND APPLICATIONS

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Submitted by:

NIKUMANI KALITA

M.TECH 3rd Semester

Roll No: PG/C/23/10

ASTU Registration No: 368104119

Under the guidance of:

DR. (MRS.) BINU SHARMA

Professor, Department of Civil Engineering

Assam Engineering College

ASSAM ENGINEERING COLLEGE

JALUKBARI, GUWAHATI-13, ASSAM

CERTIFICATE OF SUPERVISION

This is to certify that the work presented in this report entitled — "**COMPREHENSIVE ANALYSIS OF SOIL COMPACTION: METHODS, EFFECTS, AND APPLICATIONS"** is carried out by Nikumani Kalita, Roll No: PG/C/23/10, a student of M.Tech 3rd semester, Department of Civil Engineering, Assam Engineering College, under my guidance and supervision and submitted in the partial fulfillment of the requirement for the award of the Degree of Master of Technology in Civil Engineering with specialization in Geotechnical Engineering under Assam Science and Technology University.

Date:

Place:

DR. (MRS.) BINU SHARMA

B.E. (Gau), M.E. (U.O.R), Ph.D. (Gau)

Professor, Department of Civil Engineering,

Assam Engineering College,

Jalukbari, Guwahati-781013

CERTIFICATE FROM THE HEAD OF THE DEPARTMENT

This is to certify that the following student of M.Tech 3rd semester of Civil Engineering Department (Geotechnical Engineering), Assam Engineering College, has submitted her project on — "**COMPREHENSIVE ANALYSIS OF SOIL COMPACTION: METHODS, EFFECTS, AND APPLICATIONS"** in partial fulfillment of the requirement for the award of the Degree of Master of Technology in Civil Engineering with specialization in Geotechnical Engineering under Assam Science and Technology University.

Name: NIKUMANI KALITA

College Roll No: PG/C/23/10

ASTU Roll No: 230620062008

ASTU Registration No: 368104119

Date:

Place:

DR. JAYANTA PATHAK

Professor & Head of the Department

Department of Civil Engineering

Assam Engineering College

Jalukbari, Guwahati- 781013

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Date:

Place:

Nikumani Kalita

M.Tech, 3rd Semester

Geotechnical Engineering

Department of Civil Engineering

Assam Engineering College

Jalukbari, Guwahati-13

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CHAPTER 1

1. BACKGROUND

1.1 Introduction to soil compaction

Compaction of soil refers to the process of increasing the density of soil by reducing the volume of air within its pores (See, Fig.1.1). The process of compaction involves mechanically rearranging and packing the soil particles into a closer state of contact in order to reduce the porosity (or void ratio) of soil and therefore increase its dry density. Compaction is the term used to describe a relatively rapid decrease in the air voids under a loading of short duration. This is typically achieved through the application of mechanical energy, such as rolling, tamping, or vibrating to the soil. In engineering, soil refers to a natural material composed of a mixture of mineral particles, organic matter, air, and water. It is the fundamental material used in construction and geotechnical engineering due to its role as a foundation for structures. Engineers study the properties of soil to understand how it behaves under different conditions and design foundations that are stable, safe, and efficient. Compaction is the most common and important method of soil improvement. The densification of soil by the application of mechanical energy is known as compaction. It is a process by which the soil grains get rearranged more closely, the volume of air voids get reduced, and the density of soil increased.

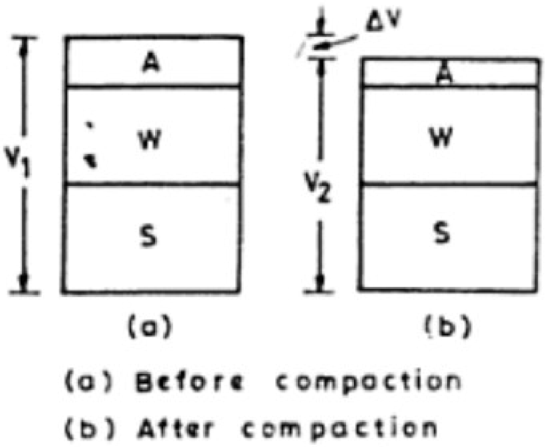

Fig 1.1: Soil Compaction (**Source:** *Basic and Applied Soil Mechaanics,* Vol. Fourth edition)

1.2 Desirable Effects of Compaction on soil

- **Improved Soil Stability**: In some cases, compaction can increase the stability of the soil, which is particularly important for construction purposes. Compacted soil forms a denser base, reducing the likelihood of erosion or shifting, which is crucial for building foundations or roads.
- **Prevention of Soil Erosion**: When the soil is compacted, it can create a more solid surface, which may reduce the movement of soil particles during heavy rainfall or wind. This can help prevent erosion in some circumstances, particularly in areas prone to intense rainfall.
- **Better Water Retention in Some Soil Types**: In soils with a very loose structure, compaction can reduce water infiltration, causing rainwater to stay on the surface. In arid areas with sandy soils, this can help conserve moisture for a short period, reducing water evaporation. However, this effect can be temporary, and over-compaction leads to negative consequences.
- **Improved Load-Bearing Capacity**: In construction, compaction of soil can increase its load-bearing capacity. This is important for ensuring the long-term stability of roads, pavements, and other structures built on soil.
- **Increased Surface Smoothness for Agricultural Equipment**: For fields where machinery is used, compacted soil may create a smoother surface, reducing the likelihood of equipment getting stuck or causing damage to crops. This is especially true for soils that are naturally loose or sandy.

1.3 Purpose of Soil Compaction

Soil compaction is necessary to increase the bearing capacity and stiffness of in-situ (natural state) or chemically modified soils. Compaction increases the shear strength of soils by adding friction from the interlocking of particles. Future settlement of soils is reduced by increasing the stiffness and eliminating voids creating a densified soil. The removal of voids reduces the chance of the soil settling or shrinking or expanding and it decreases water seepage that would lead to deleterious shrinking and swelling soil properties. Shrinking or swelling properties compromise the pavement structure thereby leading to premature failure of the pavement structure.

1.4 Advantages of Soil Compaction

a) Settlements can be reduced or prevented: Compaction reduces the void spaces in the soil, which decreases the potential for future settlement under applied loads. When soil is compacted to its maximum density, it becomes less likely to compress further under heavy structures or traffic loads. This ensures stability and reduces the risk of uneven settlement that can cause cracks or structural failure.

b) Soil strength increases and stability can be improved: Compaction enhances the contact between soil particles, increasing frictional resistance and cohesion. This results in higher shear strength and improved soil stability, allowing the soil to better withstand applied stresses. Improved strength is critical for supporting foundations, roads, and embankments.

c) Load carrying capacity of pavement/subgrades can be improved: Compact soil is more resistant to deformation under repeated loads, making it suitable for supporting pavements and road subgrades. When properly compacted, the soil resists rutting, subsidence, and fatigue, extending the lifespan of roads and reducing maintenance costs.

d) Undesirable volume changes (by frost action, swelling, shrinkage) may be controlled: Compaction minimizes voids, which reduces the amount of water that can enter the soil. This helps control issues like frost heave in cold climates and shrinkage or swelling in clay-rich soils during moisture changes. Controlling these volume changes ensures durability and prevents damage to structures or pavements.

CHAPTER 2

2. TYPES OF SOIL COMPACTION

Soil compaction can be categorized based on the method or equipment used to achieve it, as well as the specific goals and conditions of the soil. The main types of soil compaction include:

- **Dynamic Compaction:** It is a technique applied to increase the density of the soil by means of an impact or vibration. This usually happens in a repeated, cyclic manner where particles can rearrange and compress themselves. Dynamic compaction is used to improve soil stability and load-bearing capacity in construction projects where quick and effective compaction is needed.
- **Vibratory Compaction:** This is one type of dynamic compaction where direct application of vibratory action on the ground through special rollers such as vibratory rollers or a plate compactor creates an action in which it shakes the particles to some extent, resulting in their effective compaction. It is used in granular soils, such as sands and gravels, that are amenable to vibration. Impact or hammer compaction is widely applied in road construction, earthworks, and foundation preparation.
- **Impact or Hammer Compaction:** This technique uses a hammer or weight to repeatedly pound blows into the soil. Every blow compresses the soil, thereby reducing its volume. Impact compaction is very efficient for granular soils and is normally used when compacting layers of soil for deep foundations or major construction works.
- **Kneading Compaction:** This happens when a kneading motion is applied on the soil, usually done through rolling equipment or machinery, applying pressure and shear forces. The action works to push and pull the soil into a denser form. It is applied for cohesive soils like clay, as the kneading action helps to break down soil clumps and densify the material.
- **Static Compaction:** This type of compaction occurs when a steady load is applied to the soil, gradually compressing it. The pressure from the applied weight is uniform and continuous, and the soil is compacted without any additional vibrations or impacts. Static compaction is typically used in construction for leveling and stabilizing soil under buildings, roads, and other structures.

Each type of compaction is suited for particular soil types and construction needs, and the right kind must be chosen to yield the desired soil properties without damaging the soil structure.

2.1 Compaction of Cohesion-less Soil

Compaction of cohesionless soils (such as sands and gravels) is an important process to increase their density and improve their engineering properties, especially in construction and foundation work. Since cohesionless soils do not have the internal strength provided by cohesive forces, compaction in these soils requires specific techniques to improve their load-bearing capacity, stability, and drainage characteristics.

Dynamic or vibratory compaction is suitable for most cohesionless soils, providing the required energy to move the particles to a denser arrangement. Compaction is preferably done by vibratory rollers or plate compactors in cohesionless soils. Vibration causes the soil particles to rearrange themselves in a denser formation, reducing the spaces between them. It does very well for granular soils like sand and gravels, which are found to respond well to such vibrations.

- **Vibratory Rollers:** Used in building roads or for heavy work in earthworks, the large rollers come with a vibrator mechanism. The force vibration helps to compact the soil layer strongly and make it more solid.
- **Plate Compactors:** For smaller fields or finer granulation required, plate compactors provide localized vibration for achieving superficial compaction.

Impact (Dynamic) Compaction technique applies impact or repeated blows to compact the soil. This compaction can be achieved using machines such as drop hammers or pile drivers, which deliver a series of impacts to compact loose, granular soils

- **Heavy Impact Hammers:** These are particularly effective for deeper compaction in cohesionless soils, driving the particles to compact more efficiently.

For sites where cohesionless soil has significant depth, deep compaction methods such as Dynamic Replacement or Compaction Grouting may be applied. These methods apply dynamic energy or grout injection to densify deeper soil layers and improve their stability.

2.2 Compaction of Cohesive Soil

Compaction of cohesive soils like clay and silty soils aims at densifying the soil to enhance its strength, stability, and load-bearing capacity. Unlike cohesionless soils that are granular with very low cohesion between the particles, cohesive soils have intermolecular forces or cohesion holding the particles together, which gives them unique properties requiring specific compaction methods.

Methods of Compaction for Cohesive Soils:

- **Static Compaction:** With static compaction, a heavy static load or pressure is used to compress the soil. The latter is usually achieved using rollers, large and massive to place an imprint on the soil surface in order to enhance density. Static compaction is often used in combination with kneading compaction for cohesive soils, particularly when precise control over compaction is required.
- **Dynamic or Impact Compaction**: In some conditions, dynamic or impact compaction may be used as a means of compacting cohesive soils. This involves placing a series of impacts or blows (often using a heavy weight) on the soil. It can be used in the massive earthworks or wherever deep compaction is required.

CHAPTER 3

3. MEASUREMENT OF COMPACTION PARAMETERS

In the laboratory, compaction of soils is determined by specific tests to obtain key parameters that define the compaction characteristics of the soil. Both Static and Dynamic Compaction is done in the laboratory. These tests provide valuable data such as the optimum moisture content (OMC) and maximum dry density (MDD), important for understanding how a soil is going to behave under compaction and during construction.

3.1 Dynamic Compaction:

In the laboratory, tests are designed to simulate this process to evaluate the effect of dynamic loads on soil compaction, stiffness, and strength. Laboratory-based dynamic tests are often used to replicate and study the effects of dynamic compaction. Some of the most commonly used tests to measure compaction parameters include the Proctor Test (Standard and Modified).

3.1.1 Proctor's Theory and Methods

R.R. Proctor, while building dams in the USA in the early thirties, developed the principles of compaction in a series of articles in Engineering News Record (Proctor, 1933). As a tribute to Proctor, the standard laboratory compaction test, which he devised, is called the Standard Proctor Test.

- **Proctor Compaction Test:** The Proctor compaction test is used to find out the optimum moisture content and the maximum dry density of a soil. This test includes compacting a sample of soil in a mold under controlled conditions and measures the density at different moisture levels.
- **Standard Proctor Test (ASTM D698):** This determines the maximum dry density and the corresponding optimum moisture content of a soil.

Procedure:

a) Dry a sample of soil and measure the initial moisture content.
b) Thoroughly mixed the soil at a specified moisture content.
c) Compact the soil in three layers in a mold with a specified volume, 1000 cm^3.
d) A 5.5-kg rammer is used to compact the soil with 25 blows per layer.
e) The total number of blows is fixed to create a uniform degree of compaction.
f) After compaction, the soil sample is weighed, and its moisture content is calculated.

g) The Dry Density is determined as the ratio of the weight of the compacted soil to the volume of the mold.

h) The test is repeated at various moisture contents, typically in 3-5 steps, to construct a compaction curve.

i) Then after draw a graph between Moisture Content & Dry Density amd the graph is as shown in Figure 3.1.

j) From this graph we can get Maximum Dry Density and Optimum Moisture Content.

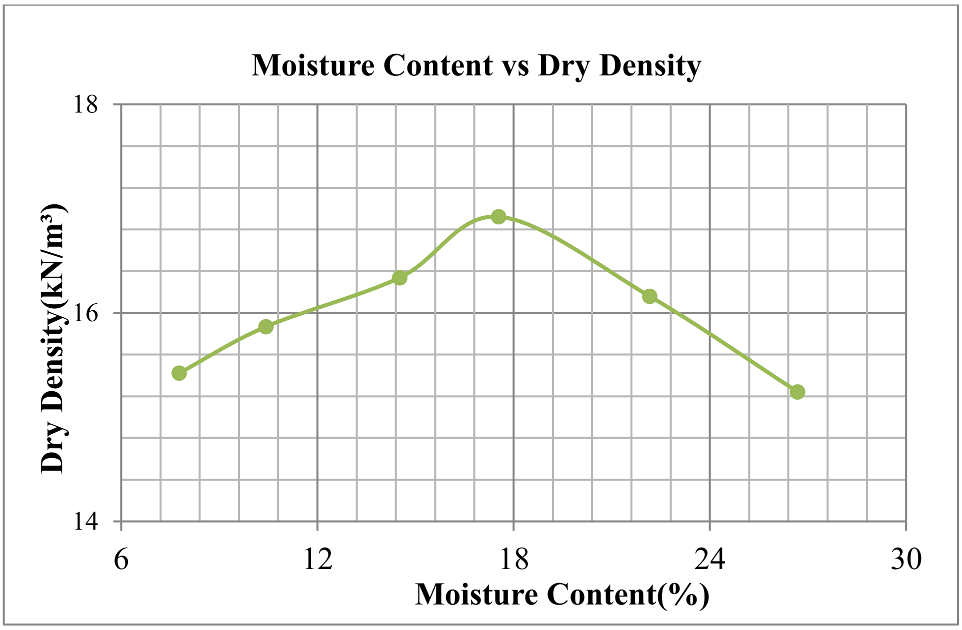

Fig.3.1: Moisture Content vs Dry Density

Maximum Dry Density (MDD): The highest density achieved at a particular moisture content.

Optimum Moisture Content (OMC): The moisture content at which the maximum dry density is obtained.

Typical values of maximum dry unit weights range from 16 to 20 kN/m^3 with the widest range being 13 to 24 kN/m^3. Typical optimum moisture content values range from 10 to 20 per cent with a maximum range of 5 to 30 per cent.

Modified Proctor Test (ASTM D1557): As the Standard Proctor Test but with higher compaction effort to replicate conditions on-site for a construction site for instance like road works. The procedure is just the same with the Standard Proctor Test but-The soil is compacted with a 4.95kg rammer (double the weight of the Standard Proctor Test). Number of layers is five, 25 blows per layer are applied, but the compaction effort is doubled (compaction energy is higher).

Also, the **Reduced Standard Proctor test** and **Reduced Modified Proctor test** are same as Standard Proctor test and Modified Proctor test respectively which is done in laboratory. But the number of blows per layer is 15 in both the test.
Maximum Dry Density (MDD) and Optimum Moisture Content (OMC), but the values tend to be higher than those from the Standard Proctor Test due to the increased compaction effort.

3.1.2 Compaction Energy

Compaction is an aim to increase the density of a material by reducing air voids between particles, which makes the material denser, stronger, and more stable for construction. Compaction energy is the energy required to bring down the volume of the material, such as soil or aggregate, through some form of pressure or mechanical effort. It is mostly applied in construction, engineering, and geotechnical works to enhance the denseness and strength of the material. This includes sub-grade preparation for roads or foundations.

Compaction Energy Measurement: This is often expressed in terms of force per unit area (pressure) or in terms of mechanical work (energy). Typical units are joules (J) or kilojoules (kJ). The energy input for compaction usually depends on the compaction equipment being used, which may range from rollers and compactors, and even the number of compactions passes.

Mathematically $E = (m \times g \times h \times N)/V$

where,

E= Energy of the compacted soil

m= Weight of the hammer

g= Acceleration due to gravity (9.81)

h= Height of fall in meter

N= Number of blows (multiply with layer)

V= Volume of the mould in meter

- For Standard Proctor Test: Energy (E)= 592.5 KJ/m^3
- For Reduced Standard Proctor Test: Energy (E)= 355.5 KJ/m^3
- For Modified Proctor Test: Energy (E)= 2858.43 KJ/m^3
- For Reduced Modified Proctor Test: Energy (E)= 1714.5 KJ/m^3

Factors that Affect Compaction Energy:

- Type of Material: Materials require different amounts of energy for achieving the same degree of compaction. For instance, clayey soils require more energy compared to sandy soils.
- Moisture Content: Moisture content affects the material's ability to be compacted. Optimal moisture content is required for achieving maximum compactness.
- Compaction Technique: Several techniques (for example static versus dynamic compaction) need different energy levels.

3.2 Kneading Compaction

Kneading compaction is one method used to compact soils using repeated kneading or forces applied in the directions of pressing and lifting through either mechanical or manual approaches. This is an efficient method, especially for finer soils like clays. Compaction of such finer soils, like clays, may require a much less forceful and rather a gradual process than some conventional compaction methods used statically or dynamically.

Methodology: Kneading compaction involves the application of pressure to the soil using a kneading action, which may be provided by a machine with specific equipment (such as a kneading compactor) or manually. The pressure applied to the soil helps to reduce air voids and compress the soil particles together.

Applicability: Kneading compaction is applied for fine-grained soils such as clays and silts, which may be hard to compact by other methods like vibration or static pressure. It is most effective when the soil is at or near its optimum moisture content, so that the soil particles are properly lubricated for compaction without becoming too wet.

Process: Mechanical Kneading: Machines fitted with kneading plates or rollers apply alternate forces, causing both vertical and horizontal stresses. The forces facilitate interlocking between the soil particles.

Hand Kneading: For some purposes, hand tools or small mechanical devices may be used to knead soil in small projects or laboratory experiments.

Kneading Compaction in Practice: The energy could be determined by how strong the applied force was and over which distance this had been spread and then quantified using a number of the strokes by compaction.

The Compaction Energy (E) can be expressed mathematically as:

$$\mathbf{E = F \times d \times N}$$

where,

E is the compaction energy in Joules (J).

F is the force applied (in Newton, N).

d is the distance over which the force is applied (in meters, m).

N is the number of kneading strokes or cycles applied.

Different Compaction Devices: The values for force, distance, and strokes may depend on the different types of kneading compaction devices used in the laboratory. For instance, if the motorized kneading machine is used, then the device specifications will usually provide for the force and stroke length.

3.3 Static Compaction

Static compaction is the compaction process where a constant pressure is applied over the material for a long period of time, without using any dynamic or vibratory forces. This is generally applied for dense cohesive soils (clays), and the primary reasons are to enhance the strength and stability of soil, particularly for foundation work, embankments, and pavement base courses.

Laboratory Static Compaction: Static compaction is normally carried out in a lab by applying a pressure or static load over a sample of soil placed into a cylindrical mold. Under known weight or pressure, the sample is compacted, and then its dry density is determined.

The test can include the following procedures:

- Mixed the soil with known water content and keep it for 24 hours.
- Next day Place the soil in a mold.
- Apply a known static load (weight) or pressure to the soil.
- Measuring the compressed height till it gives constant value.

In static compaction, the compaction energy is related to the pressure (force per unit area) and the displacement (distance) that the soil undergoes under a static load. The general formula for work (or energy) applied during static compaction is:

$$E = P \times A \times d$$

where,

E is the compaction energy

P is the applied pressure

A is the contact area over which the pressure is applied

d is the displacement or the distance the soil sample is compressed.

CHAPTER 4

4. COMPARISON OF DIFFERENT SOIL COMPACTION TESTS

4.1. Standard Proctor Test (SP) vs. Modified Proctor Test (MP)

These two tests determine the optimum moisture content (OMC) and maximum dry density (MDD) of a soil sample. These are fundamental to determining how a soil is expected to act in its state of compaction. The Standard Proctor test is generally used for soils that are expected to experience relatively moderate compaction, such as subgrade soils for road construction and foundations. Results obtained in Standard Proctor test are employed in those projects which require standard compaction techniques, such as general earthworks or in some road construction projects. The Modified Proctor test is suited for soils that are likely to be compacted with heavier equipment or in more intensive conditions. It better suits higher-density soils used on highways, dams, or airport runways.

Table 4.1: Standard Proctor vs Modified Proctor Test

Property	Standard Proctor Test	Modified Proctor Test
Compaction Energy	Lower compaction energy	Higher compaction energy
Rammer Weight	2.6 kg	4.5 kg
Drop Height	310 mm	457 mm
Layers	3 layers	5 layers
Blows per Layer	25 blows per layer	25 blows per layer
Purpose	General compaction in moderate conditions	High-density compaction for heavy infrastructure
Application	Subgrade for roads, foundations, embankments	Pavement base layers, airports, embankments
Typical Maximum Dry Density (MDD)	Lower MDD due to lower energy	Higher MDD due to higher compaction energy

4.2. Dynamic Compaction vs. Kneading Compaction vs. Static Compaction

These three compaction processes are applied in construction and engineering to increase the density of soil, but they apply forces differently with respect to certain types of soils.

Dynamic Compaction: Dynamic compaction is the application of high-energy impacts or vibrations to compact soil. A heavy weight or impact device is dropped on the soil surface repeatedly, or a vibrating machine is employed, transferring energy to the soil. This method is primarily applied for the improvement of loose, granular soils, such as sand and gravel.

Kneading Compaction: Kneading compaction is the application of a kneading action to the soil which is often through mechanical means or manually. This process is very effective for cohesive soils such as clays and silts that deform easily under pressure but resist deformation much more strongly under vibratory conditions.

Static Compaction: Static compaction employs steady, non-vibratory pressure applied to the soil over time. This method applies a heavy, constant load (often from a roller or press) to the soil, thereby causing the soil particles to compress gradually and uniformly.

Table 4.2: Dynamic Compaction vs. Kneading Compaction vs. Static Compaction

Property	Dynamic Compaction	Kneading Compaction	Static Compaction
Compaction Mechanism	High-energy impact or vibration	Kneading (compressive & shear forces)	Steady, uniform pressure
Forces Involved	High-frequency, dynamic impacts	Gradual, controlled pressure	Constant compressive pressure
Ideal Soil Types	Granular soils (sand, gravel)	Cohesive soils (clay, silts, organic soils)	Cohesive soils (clays, silts)
Compaction Energy	High energy, rapid impacts/vibrations	Moderate energy, gradual kneading	Moderate energy, steady pressure
Applications	Roads, embankments, deep foundations	Soil testing, foundation compaction	Foundations, subgrades, pavements

Advantages	Effective for deep compaction, fast process	Controlled compaction, no soil disturbance	Uniform, gentle compaction
Disadvantages	Not suitable for cohesive soils, potential soil segregation	Slower process, not ideal for granular soils	Slower, less effective for granular soils

4.3 Effects of Moisture Content and Soil Type on Test Results

Moisture content and soil type are two of the most important factors influencing the compaction test results, including those from the Standard Proctor, Modified Proctor, and other compaction methods. These factors influence the optimum moisture content (OMC), maximum dry density (MDD), and the overall compaction behavior of the soil.

Moisture Content Impact on Compaction Test Results: Moisture content is the volume of water in the soil as a percentage of the dry weight. In compaction tests, moisture content impacts how particles in the soil will compact and therefore impacts the optimum moisture content and maximum dry density.

At Low Moisture Content: When the soil moisture content is very low, the particles cannot provide enough lubrication to slide past each other easily. This makes it difficult for the particles to pack closely together, thereby resulting in a lower maximum dry density (MDD). Increased resistance to compaction: Dry soils require more energy for compaction. The soil tends to be crumbly or stiff, making it difficult to achieve a uniform compaction.

At Optimum Moisture Content (OMC): The optimum moisture content (OMC) is the moisture content at which a soil reaches its maximum dry density (MDD) during compaction. There is enough moisture at this point that helps soil particles slide by one another, reducing friction, but not enough water to create a slurry. The soil displays a balance between cohesion and lubrication, meaning that the particles pack the most tightly and reach the maximum density.

When Moisture Content is Very High: When moisture content is above the optimum, the soil becomes too wet, and the excess water fills the pores between particles, reducing the volume of air that can be expelled during compaction. The soil becomes saturated, and water acts as a lubricant rather than helping in compaction. This leads to a lower dry density since the excess water prevents soil particles from closely packing together.

Excessive Water: Leading to poor compaction due to too soft soil particles being left without reaching maximum density.

Soil Type Effect on Test Results: The soil type is a major factor when determining the behavior of soil during compaction. As discussed earlier, different soils have different properties that play a significant role in their characteristics. Some of the main characteristics affected by the soil type are particle size, plasticity, cohesion, and permeability.

Granular Soils (Sands, Gravels):

- Low Cohesion: Granular soils, like sands and gravels, have very little to no cohesion between the particles. The particles are more easily rearranged under compaction, allowing for higher compaction energy to be transferred.
- Less Sensitive to Moisture: Granular soils generally respond well to dynamic compaction or mechanical methods and are less sensitive to changes in moisture content.
- High Permeability: These soils have high drainability, with moisture draining well and leaving the soil less affected by excess moisture as compared to fine-grained soils.
- High Optimum Moisture Content (OMC): Typically, granular soils require less moisture to achieve compaction, and they usually have a lower OMC compared to fine-grained soils.

Cohesive Soils (Clays, Silts):

- High Cohesion: Such cohesive soils include clay and silt, which have strong inter-particle forces due to water and electrostatic interactions, and often make compaction difficult at dry or wet conditions.
- High Moisture Sensitivity: Such soils are much more sensitive to changes in moisture content. Too little moisture makes it dry and brittle, while too much moisture results in a slushy, saturated mixture.
- Low Permeability: Fine-grained soils such as clays have low permeability; hence, they hold moisture for longer periods, and any excess water can deteriorate the compaction. They also take a longer time to drain and are more vulnerable to compaction disturbance in case of over-compaction or under-compaction.
- Low Optimum Moisture Content (OMC): Clay soils have a higher OMC compared to granular soils, meaning they require more moisture to achieve maximum density. However, excessive moisture content beyond the optimum moisture content renders the soil too saturated and loses its dry density.

Organic Soils:

- Low compaction efficiency: Organic soils, such as peat or muck, have high organic matter content, which can reduce compaction efficiency. The high organic content of the soil can absorb plenty of water and perhaps not compact well even when at optimum moisture content.
- Low Strength and Stability: Organic soils generally have a low strength and are more compressible under load, making them difficult to compact to a high density.

Effect of Compaction Results:

- Granular soils generally have a greater MDD because of their ability to adjust quickly to the applied compaction energy.
- Cohesive soils have a lower MDD since the high cohesion between particles gives it a stronger resistance to rearrangement in the compaction process.
- Organic soils, with high organic content, are difficult to bring to the same level of compactness due to the lack of structural integrity.

4.4. Test Limitations and Suitability for Different Soil Types

Dynamic Compaction: Dynamic compaction (DC) is a ground improvement technique involving the repeated dropping of a heavy weight onto the ground surface to densify soils. While effective in many cases, its performance and applicability vary depending on soil type, project requirements, and site conditions. Below is an analysis of its limitations and suitability for granular soils, cohesive soils, and organic soils.

Granular Soils:

- **Suitability**: Granular soils, such as sands and gravels, are highly suitable for dynamic compaction. The method is particularly effective in these soils due to their ability to rearrange particles into a denser configuration under impact energy. The vibrations generated during DC help overcome interparticle friction, facilitating compaction.
- **Limitations**: While DC works well for loose to medium-dense granular soils, very dense granular soils or soils with a significant amount of fines (silt or clay) may exhibit diminished compaction efficiency.

Cohesive Soils:

- **Suitability:** Cohesive soils, like clays and silty clays, are less suitable for dynamic compaction because of their low permeability and cohesive nature, which restricts particle movement during impact. However, under certain conditions, such as partially saturated states, limited improvement can be achieved.
- **Limitations:** Excess pore water pressure may develop, leading to a slow consolidation process and requiring extended periods for dissipation. High moisture content can cause instability or deformation instead of compaction. The method is generally less effective compared to other techniques like preloading or wick drains.

Organic Soils:

- **Suitability:** Dynamic compaction is generally unsuitable for organic soils, such as peat or soils with a high organic content. These soils have low stiffness, high compressibility, and a tendency to rebound after impact, making them resistant to permanent densification.
- **Limitations:** The organic matter content causes high energy absorption with minimal density improvement. Potential for excessive settlement or displacement due to the lightweight and fibrous nature of the soil. Risk of instability or structural failure due to inadequate bearing capacity.

Kneading Compaction: Kneading compaction involves applying repetitive kneading or shearing forces to soil using equipment like tamping rollers, padfoot rollers, or pneumatic rollers. This method works by breaking down soil aggregates and rearranging particles to achieve densification. Its effectiveness and limitations vary with different soil types, as outlined below.

Granular Soils:

- **Suitability:** Kneading compaction is moderately effective for granular soils like sands and gravels, particularly those with a significant fraction of fines. The shearing action helps rearrange particles to achieve a denser structure, though the compaction effect is generally less pronounced than with vibratory techniques.
- **Limitations:** Purely granular soils, especially those with minimal fines, are less effectively compacted by kneading due to the lack of cohesion and the inability to retain the shape imparted by kneading forces. High energy input is often required to achieve noticeable densification in clean sands or gravels.

Cohesive Soils:

- **Suitability:** Kneading compaction is particularly suitable for cohesive soils, such as clays and silty clays, due to their plasticity and ability to respond well to kneading forces. The shearing motion breaks down larger clods and helps distribute moisture uniformly, which is crucial for achieving optimum compaction.
- **Limitations:** Excess moisture content can lead to smearing or instability during kneading, reducing the effectiveness of compaction. Multiple passes may be needed to achieve uniform compaction, increasing the time and cost of the operation. Fine-grained soils may exhibit slow drainage, which could hinder compaction in water-saturated conditions.

Organic Soils:

- **Suitability:** Kneading compaction is generally ineffective for organic soils, such as peat or soils with high organic content. These soils lack the structural integrity and compressibility needed to achieve meaningful densification through kneading.
- **Limitations:** Organic soils tend to rebound after compaction due to their fibrous and lightweight nature. High compressibility and low shear strength make them prone to deformation rather than densification. Even with repeated kneading, the long-term settlement of organic soils undermines compaction efforts.

Static Compaction: Static compaction involves the application of steady, continuous pressure to soil using heavy rollers, plates, or loads. It densifies soil by compressing particles without significant dynamic or vibratory forces. While effective for certain applications, its performance varies with soil types, as outlined below.

Granular Soils:

- **Suitability:** Static compaction is moderately effective for granular soils, particularly when the soil has some fines or is partially saturated. The steady pressure helps rearrange particles, but the lack of vibration limits its ability to overcome interparticle friction in clean, dry sands and gravels.
- **Limitations:** Static compaction is less effective for purely granular soils like clean sands and gravels, where vibratory or dynamic methods achieve better results. It is generally unsuitable for achieving deep compaction in granular soils, as the effect of static pressure diminishes with depth.

Cohesive Soils:

- **Suitability:** Static compaction is highly effective for cohesive soils such as clays and silts. The steady pressure consolidates the soil mass and helps eliminate air voids. It is particularly effective when cohesive soils are at or near their optimum moisture content, as it enhances plastic deformation and densification.
- **Limitations:** Cohesive soils with high moisture content may experience squeezing or extrusion under static loads, reducing the effectiveness of compaction. The process is relatively slow compared to dynamic or kneading compaction methods and may require multiple passes to achieve uniform density.

Organic Soils:

- **Suitability:** Static compaction is generally unsuitable for organic soils, such as peat or highly organic clays. These soils tend to absorb the applied pressure without significant densification due to their high compressibility and fibrous structure.
- **Limitations:** Organic soils may exhibit significant rebound or settlement after the load is removed, negating the effects of compaction. The low shear strength and highwater content in organic soils further reduce the effectiveness of static pressure.

CHAPTER 5

5. FIELD COMPACTION TECHNIQUES

Field compaction refers to compacting soil or other materials at the construction site to get the desired density and strength for foundations, embankments, roadbeds, or other civil engineering structures. The primary goal is the reduction of air voids, increase in soil density, and stability. Several field compaction techniques exist depending on the type of soil, the compaction requirements, and the equipment available. Below are the primary types of field compaction techniques:

Static Compaction: Static compaction employs the weight of equipment or other means to compact soil without vibration or impact. It is generally suitable for finer soils, such as clays and silts, where vibration may cause problems like excessive settlement or instability.

Methods of Static Compaction:

- **Rolling (Static Rollers)**: Static rollers are those rollers that compress the soil by their own weight. These are used for fine-grained soils such as silts and clays, where a smooth, even compaction is desired.
- **Heavy Equipment (Graders, Loaders, Dump Trucks)**: In some applications, large vehicles such as dump trucks or graders are used for static compaction by driving over the soil repeatedly to compress it. It is often used in big earthworks for coarse-grained soils such as sand.

Vibratory Compaction: Vibratory compaction uses the dynamic energy of vibrating rollers or other equipment in order to reduce air voids in the soil. This method is quite suitable for granular soils, such as sand and gravel, which can be very easily compacted by the vibration.

Methods of Vibratory Compaction:

- **Vibratory Rollers**: It is equipped with a vibrating drum that creates dynamic forces; it helps in rearranging soil particles and improving the compaction process. This is highly effective for granular soils such as sands and gravels. These are normally used in road construction, embankment building, and so on, requiring high-density compaction.
- **Vibratory Plate Compactors**: They are used in such confined places like trenches. This smaller machine vibrates soil to compact in places which cannot be accessed because of either the space present there or the presence of obstacles surrounding that area.

Impact Compaction (Pneumatic and Dynamic Compaction): It impacts repeatedly and gives compaction to the soil, relying upon the blows and impacts, which make soil compact.

This method works very efficiently for loose and low-density granular soils, while it is applied sometimes in some other cohesive soils if proper conditions are found.

Method of Impact Compaction

- **Pneumatic Rollers**: Pneumatic rollers make use of a series of rubber-tired rollers that are used to apply pressure and impact the soil. Rolling and impact forces are then used to densify the soil to stabilize it for construction purposes. Pneumatic rollers work effectively on cohesive soils, such as clays, as well as in high-moisture-content soils.
- **Dynamic Compaction (Drop Hammers)**: This method consists of dropping a heavy weight, often termed a "drop hammer," from some height onto the ground with an impact load. Dynamic compaction is applied when compaction is required up to great depths and is very suitable for loose granular soils and soil that cannot be compacted by vibratory methods.

5.1. Rollers and Their Applications

Rollers are multiform machines or tools adapted for a certain application; they are widely used, primarily to compress, flatten, or even mold surfaces for use in many construction processes, manufacturing sectors, in agriculture, and many others. So, in soil compaction, depending on the nature of the soil and the requirement of the compaction process, different types of rollers are used. Here are the primary types of rollers used for soil compaction:

a) **Smooth Drum Rollers (Static Rollers):** Rollers featuring a single, large, smooth steel drum with uniform pressure application to compact the soil. These have no vibrating mechanism. (See, Fig.5.1)

Fig. 5.1: Smooth Drum Roller (**Source**: https://www.bigrentz.com/equipment-rentals/compaction-equipment/single-drum-roller/54-inch-single-drum-smooth-ride-on-roller)

b) **Vibratory Rollers**: Vibratory rollers have a vibrating drum that gives extra compaction force. The vibration ensures that deeper compaction is achieved, especially in granular soils. (See, Fig.5.2)

Fig. 5.2: Vibratory Rollers (**Source:** https://5.imimg.com/data5/ZG/BG/JG/SELLER-3151341/152222835520180328.jpg)

c) **Padfoot Rollers (Sheepsfoot Rollers)**: These rollers have a drum fitted with protruding "feet" or pads that knead the soil during compaction. The feet help break up the soil, and there is better compaction of cohesive soils. (See, Fig.5.3)

Fig. 5.3: Padfoot Roller(**Source:** https://www.solutionplanthire.com.au/wp-content/uploads/2018/03/padfoot_2-515.png)

d) Tandem Rollers: Tandem rollers have two smooth steel drums, at the front and rear respectively. Both drums apply equal pressure to the soil at the same time. (See, Fig.5.4)

Fig. 5.4: Tandem Roller

(**Source:** https://5.imimg.com/data5/SELLER/Default/2022/12/JG/ME/QT/164154601/hamm-hd99i-vv-tandem-roller.jpg)

e) Pneumatic Rollers (Rubber-Tired Rollers): Pneumatic rollers have multiple rubber tires applying kneading pressure to the soil. The tires inflate to a certain pressure to accomplish the required compaction. (See, Fig.5.5)

Fig. 5.5: Pneumatic Rollers

(**Source:** https://www.bomag.com/fileadmin/_processed_/5/c/csm_BW_11_RH-5_S_087d1f24c3.png)

f) **Grid Rollers**: Grid rollers have a drum with a series of grid-like metal bars or grids that create a deeper compaction effect, particularly for cohesive soils. (See, Fig.5.6)

Fig. 5.6: Grid Roller

(**Source:** https://gms.gumtree.co.za/api/v1/za-ads/images/73/737d964d-7800-4b74-877a-8b6e687114b0?rule=s-I35.auto)

g) **Tri-axle Rollers**: The description of a tri-axle roller is of one with three axles in it, typically having the availability of both smooth and pneumatic tires. They apply compacting forces well spread in nature. (See, Fig.5.7)

Fig. 5.7: Tri-axle Rollers

(**Source:** https://image.made-in-china.com/2f0j00KJZtPdVgrnuU/Tri-Axle-Loading-Road Roller-Lowboy-Trailer.webp)

Table 5.1: Rollers and Their Applications

Roller Type	Description	Primary Uses
Smooth Drum Rollers (Static Rollers)	Large smooth steel drum that applies static pressure on the soil.	- Compaction of granular soils (sand, gravel). - Surface compaction (roads, parking lots). - Base and sub-base compaction in road construction.
Vibratory Rollers	Rollers with vibrating drums that enhance compaction with additional force.	- Compacting granular soils (sand, gravel). - Asphalt compaction (roads, highways). - Subgrade compaction in road construction.
Padfoot Rollers (Sheepsfoot Rollers)	Drum with protruding "feet" that knead and compact cohesive soils.	- Compaction of cohesive soils (clay, silt). - Heavy-duty compaction in embankments, dams, and subgrade layers. - Deep compaction in road construction.
Tandem Rollers	Two smooth steel drums, one at the front and one at the rear, for uniform compaction.	- Final compaction of asphalt (roads, parking lots). - Light to medium compaction of granular soils.
Pneumatic Rollers (Rubber-Tired Rollers)	Rollers with multiple rubber tires that apply kneading pressure.	- Compaction of fine-grained soils (clay, silt). - Final compaction for smooth finishes (asphalt paving). - Road and airport construction.
Grid Rollers	Drum with metal bars or grids that apply deep compaction pressure.	- Compaction of cohesive soils (clay). - Soft or marshy soils. - Heavy-duty compaction (embankments, dams).
Tri-axle Rollers	Rollers with three axles, often combining smooth and pneumatic tires.	- Medium to light compaction of granular soils. - Road construction, including moderate compaction of asphalt and base layers.

5.2. Selection of Equipment Based on Soil Type

Table5.2: Selection of Equipment Based on Soil Type

Equipment	**Most Suitable Soils**	**Typical Application**	**Least Suitable Soils**
Smooth wheeled rollers, static or vibrating	Well graded sand, gravel, crushed rock, asphalt	Running surface, base courses, subgrades	Uniform sands
Rubber tired rollers	Coarse grained soils with some fines	Pavement subgrade	Coarse uniform soils and rocks
Grid rollers	Weathered rock, well graded coarse soils	Subgrade, subbase	Clays, silty clays, uniform materials
Sheepsfoot rollers, static	Fine grained soils with > 20% fines	Dams, embankments, subgrades	Coarse soils, soils with cobbles, stones
Sheepsfoot rollers, vibratory	As above, but also sand-gravel mixes	Subgrade layers	
Vibratory plates	Coarse soils, 4 to 8% fines	Small patches	Clays and silts
Tampers, rammers	All types	Difficult access areas	
Impact rollers	Most saturated and moist soils		Dry, sands and gravels

5.3. Field Control of Compaction

Depending on the type of compaction equipment used, the optimum water content for a given soil may vary between the laboratory and field. The water content used in the field compaction is called the placement water content which may be equal to, lower than or higher than the optimum water content determined in the laboratory. The compaction of soil in the field must be such as to obtain the desired unit weight at the optimum moisture content. The procedure of checking involves:

- Measurement of the dry unit weight, and
- Measurement of the moisture content.
- There are many methods for determining the dry unit weight and/or moisture content of the soil
- in-situ. The important methods are:
- Sand cone method
- Rubber balloon method,
- Nuclear method, and
- Proctor needle method.

Sand Cone Method (ASTM Designation D-1556)

The sand for the sand cone method consists of a sand pouring. The jar contains uniformly graded clean and dry sand. A hole about 10 cm in diameter is made in the soil to be tested up to the depth required. The weight of soil removed from the hole is Sand-cone apparatus

determined and its water content is also determined. Sand is run into the hole from the jar by opening the valve above the 3785 cm (1-gal) cone until the hole and the cone below the valve is completely filled. The valve is closed. (See, Fig.5.8)

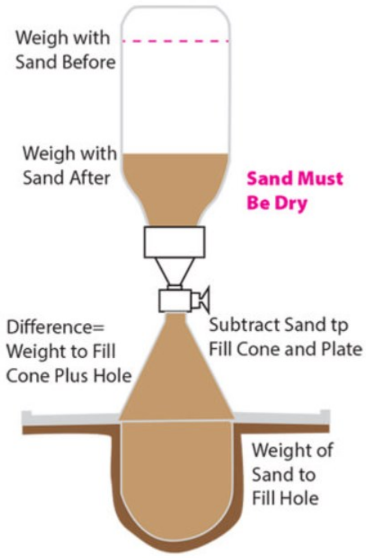

Fig.5.8: Sand Cone Density Method for Compaction

(**Source:https://www.globalgilson.com/Content/Images/uploaded/blog/2019/december/sand.jpg**)

Rubber Balloon Method (ASTM Designation: D 2167)

The volume of an excavated hole in a given soil is determined using a liquid-filled calibrated cylinder for filling a thin rubber membrane. This membrane is displaced to fill the hole. The in-place unit weight is determined by dividing the wet mass of the soil removed by the volume of the hole. The water (moisture) content and the in-place unit weight are used to calculate the in-place dry unit weight. The volume is read directly on the graduated cylinder. The instrument may be used either in drilled holes or on the surface of the ground. The main advantage of this equipment is that a single operator can obtain an immediate and accurate determination of the in-situ dry density and moisture content. (See, Fig.5.9)

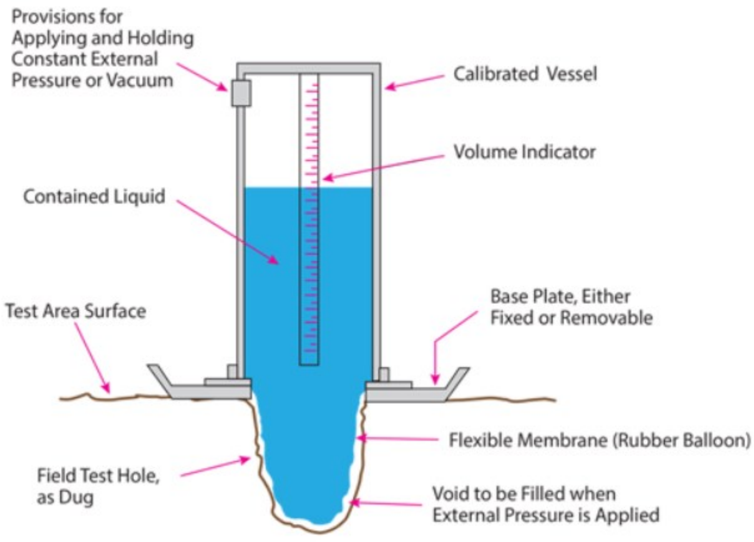

Fig. 5.9: Rubber Balloon Method

(Source: https://www.globalgilson.com/Content/Images/uploaded/blog/2019/december/balloon-2.jpg)

Nuclear Moisture-Density Method

Surface type nuclear moisture-density method is used nowadays as it can produce results quickly. The primary components of this kind of apparatus consist of a nuclear source that releases gamma rays, a detector that detects gamma rays or photons travelling through the soil under test, and a sealar or counter that measures how quickly the gamma rays reach the detector. Radium-beryllium and cesium-americium-beryllium combinations are the nuclear sources.

Some of the gamma rays that are released into the soil during equipment operations are absorbed, but some are transmitted directly to the detector or hit by soil mineral electrons. By recording the nuclear count rate at the detector, one can determine the inverse relationship between the amount of gamma radiation that reaches it and the density of the soil. The equipment manufacturer provides a calibration curve, from which the observed count rate is obtained to determine the density. (See, Fig.5.10)

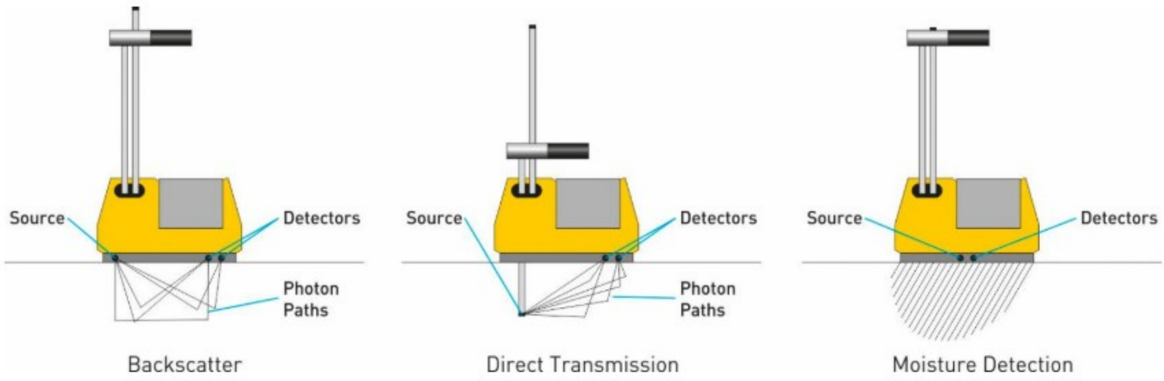

Fig. 5.10: Nuclear Moisture-Density Method

(**Source:** https://www.utest.com.tr/upload/Node/23174/pics/ekle_1050.jpg)

Proctor Needle Test

The Proctor needle is made up of a spring-loaded plunger attached to a graduated needle shank that has a needle point attached to it. There are needle points with different cross- sectional areas available, allowing for the measurement of a broad range of penetration resistance. A loaded gauge that is fixed over the handle is used to read the penetration force. In order to utilize the needle in the field, a calibration curve is drawn in the lab with the water content as the abscissa and the penetration resistance as the ordinate. By sticking the Proctor needle into the compacted soil inside the Proctor mould, the laboratory penetration resistance is determined. At the end of each Proctor compaction, the penetration resistance corresponding to different water contents is thus noted, and a calibration curve is plotted. The placement water content may be ascertained using this curve. The penetration resistance of the compacted soil in the field is determined with the Proctor's needle, and its water content is read off from the calibration curve. (See, Fig.5.11)

Fig.5.11: Proctor Needle Apparatus
(**Source:** https://www.utest.com.tr/upload/Node/23156/xpics/UTS-0665-0666_Proctor_Penetrometer_and_Needle_Set_2.jpg)

Table 5.3: Field Test for Quality Assurance of Compaction

Test Method	Measurement
Sand Cone	Density
Rubber Balloon	Density
Nuclear Gauge	Moisture content and density
Dynamic cone penetrometer	Penetration index
Soil stiffness gauge	Stiffness
Falling weight deflectometer	Stiffness
Light weight deflectometer	Stiffness
Electrical density gauge	Density
Time domain reflectometry	Moisture Content

Chapter 6

6. Factors Affecting Compaction

Soil compaction is an important process in geotechnical engineering to increase the strength, stability, and durability of the ground under foundations. The efficiency of soil compaction depends on several factors; therefore, it is worth considering them to achieve optimal results. The following are the main factors that affect soil compaction:

- **Soil Type**: Type of soil determines how readily it can be compacted. Granular soils, such as sands and gravels, are relatively easy to compact since their particles are more angular and can easily rearrange under pressure. Cohesive soils, like clay and silts, tend to be more difficult to compact.
- **Moisture Content**: The moisture content of the soil determines its behavior when compacted.All soils have an optimum moisture content at which they can be compacted to a maximum dry density. If the soil is too dry, it becomes resistant to compaction due to a lack of lubrication between particles. If the soil is too wet, it becomes softer and may lose its load-bearing capacity due to water filling the voids between particles.
- **Compaction Energy**: The amount of energy applied during the compaction process directly influences the level of soil density achieved. The energy usually comes from compaction equipment, like rollers or rammers. More energy of compaction, say, from a heavier roller or from more impacts of the rammer yields better compaction, mainly for deeper layers or denser soils. For cohesive soils, there is often a greater energy needed in order to break the cohesion among the particles, which then will settle in a denser configuration.
- **Layer Thickness** : The compaction efficiency varies with the thickness of the soil layers being compacted. Soil can be compacted more effectively in thin layers, usually 4–6 inches thick. Compacting thick layers can lead to insufficient compaction at the bottom layer as the force of compaction is not deep enough. Proper layering means that every layer is properly compacted to the density required before the next layer is placed, thus providing a stable, well-compacted foundation.
- **Type of Compaction Equipment**: Compaction equipment will also affect the compaction process. The type of equipment will depend on the soil, layer thickness, and required compaction effort.
- **Soil Density** : The initial density of soil before compaction determines how much compaction is to be used. Soils having a low initial density like loose sands or silts are relatively easy to compact, and thus, less energy is expended to get the desired compaction in such soils. However, higher natural density soils, such as dense gravels or clays, require more energy and efforts to compact

suitably.

- **Temperature**: Temperature can affect the compaction process, especially when it is involved with cohesive soils such as clays. In cold temperatures, the soil may be stiff and hard to compact, while in very hot conditions, the soil dries out too fast, hence making the compaction less effective. Temperature also affects moisture content, which further affects compaction efficiency.

6.1. Moisture Content

Moisture content is the most critical parameter when dealing with compaction in soils. If the soil has a very low moisture content, it cannot be compacted well as particles will not adhere to one another. In addition, if the moisture content of the soil is high, it may become adhesive and lose its compactive capability.There is a moisture content at which compaction takes place most efficiently, called the optimum moisture content (OMC). (See, Fig.6.1) At that point, the soil particles are nicely lubricated so that they might slide past each other and develop a denser structure.

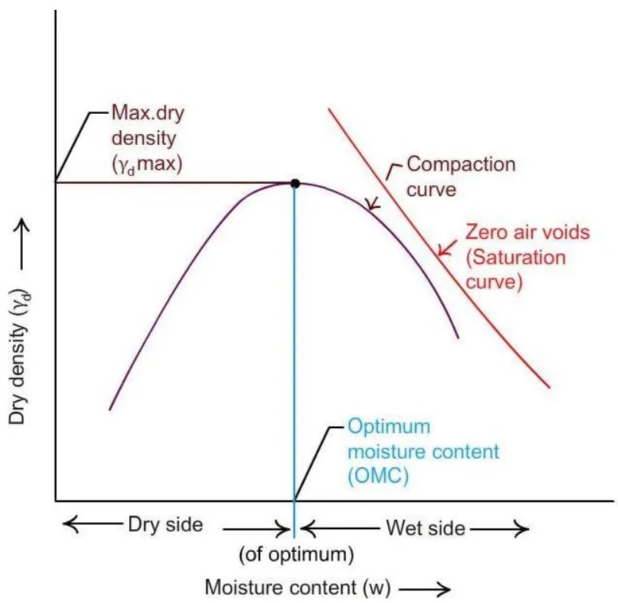

Fig. 6.1: Moisture content vs Dry Density of soil
(**Source:** https://i0.wp.com/civilblog.org/wp-content/uploads/2015/12/Fig-1-Moisture-content-dry-density-relationship.jpg?w=640&ssl=1)

Table 6.1: Comparison of Dry of Optimum with Wet of Optimum Compaction (**Source:** *Basic and Applied Soil Mechaanics,* Vol. Fourth edition)

Property	Dry of Optimum	Wet of Optimum
Structure after Compaction	Flocculated(random)	Dispersed(oriented)
Water Deficiecy	More	Less
Permeability	More, isotropic	Less, anisotropic
Compressibility		
At low stress	Low	Higher
At high stress	High	Lower
Swelling	High	Low
Shrinkage	Low	High
Stress-Strain behaviour	Brittle: High peak Higher elastic modulus	Ductile: no peak, lower elastic modulus
Construction pore water pressures	Low	High
Strength (undrained) as moulded,after saturation	High somewhat higher if swelling prevented	Much lower low

6.2. Soil Type and Gradation

The type of soil determines whether it is compacted easily, or whether it is hard to do so. The higher the percentage of clay and fine particles in a soil, the better it is able to compact since its particles are small enough to easily fill voids. Grading of soil is the amount of particle size in it. Well-graded soils with a mix of the smaller and larger particles in it tend to compact in better conditions than poorly graded soils, which have an equal size of particles; these fill the void more efficiently and give denser compaction. (See, Fig.6.2)

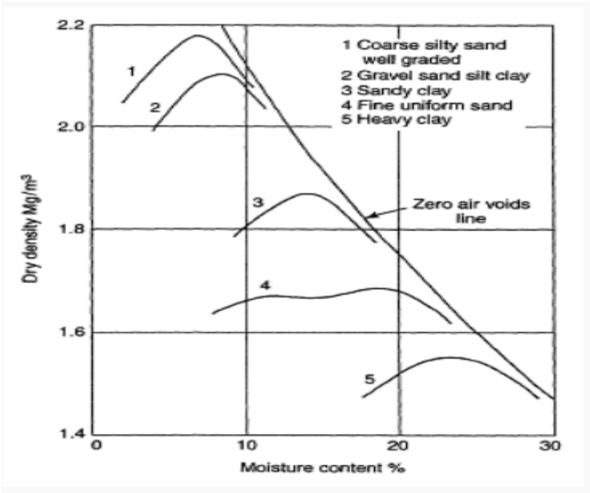

Fig.6.2: Compaction curve for different soil gradation

(**Source:** https://www.flatgeo.com/images/stories/SoilMec/compaction_En.png)

6.3. Compaction Energy and Effort

Compaction energy is the total force or work applied to the soil during the compaction process, usually by mechanical equipment, and depends on factors such as the type, weight, and frequency of the compactor. The compaction effort combines both the energy applied and the duration or number of passes made by the compactor. The efficiency of compaction depends on the achievement of the optimum balance of energy and effort, which varies with soil type, moisture content, and layer thickness. Granular soils generally require less effort with higher frequency compactors, whereas cohesive soils demand more energy and effort for particle rearrangement, often using static or impact rollers for deeper penetration. Together, these factors make a compacted material dense and stable, ensuring the soil strength for construction projects.

(See, Fig.6.3)

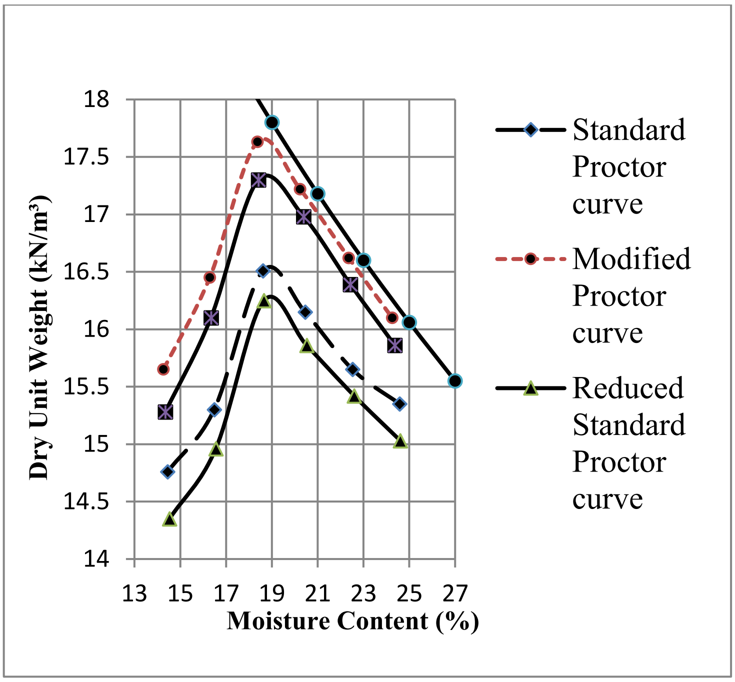

Fig. 6.3: Compaction curve at different Compactive Effort

6.4. Environmental Conditions

Environmental conditions play an important role in soil compaction because of the dependency of the compacting process on temperature, moisture content, and other weather conditions. Optimal moisture content is required to ensure that the compaction process works effectively because more or less water than optimal can cause the soil not to densify. Cold temperatures might also decrease the compactability of the soil since the moisture may freeze, thereby impeding the action of the compaction forces on the particles, and excessively warm weather may cause evaporation of moisture, resulting in dry, compacted soils. Rain or snow could prevent compaction since soils are too wet but temporarily enhance moisture content; in any case, wetting can also result in instability. All of this points to the need for an environmental consideration that decides which time is most suited to compaction to yield the desired soil density and stability. (See, Fig.6.4)

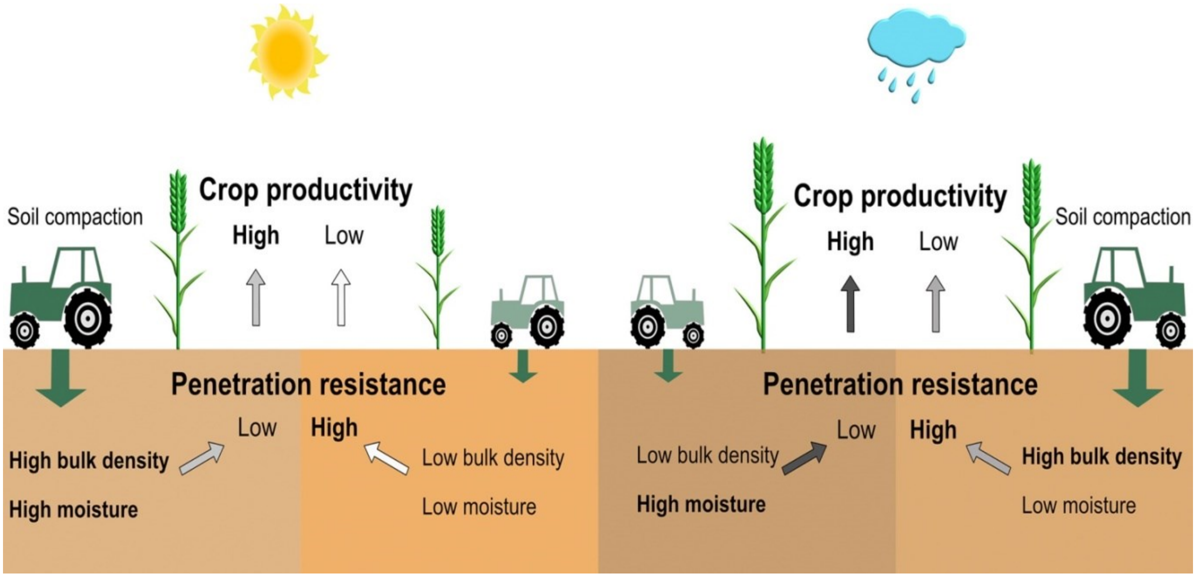

Fig.6.4: Enviromental impact

(**Source:** https://ars.els-cdn.com/content/image/1-s2.0-S0048969721058411-ga1.jpg

CHAPTER 7

7. EFFECTS OF COMPACTION ON SOIL STRUCTURE

Compaction highly influences soil structure, which in turn changes the physical aspects and overall functionality of the soil. The prominent impacts of compaction on soil structure are the following.

Decrease in Porosity: The compaction process reduces pore volume in the soil. Soil porosity is required for the passage of water, air, and nutrients. When the soil is compacted, pore space is decreased between soil particles and hence porosity.

Permeability reduction: Water infiltration decreases in compacted soils. Fewer and smaller pore spaces reduce the draining capacity of water through the soil, resulting in more surface runoff and potential erosion. Poor drainage in agricultural soils or construction sites can be the result.

Bulk density increase: Bulk density increases,edvwhich forces the soil particles closer together. High bulk density usually characterizes a tightly packed soil, making it sometimes hard for plant roots to penetrate into the soil. This is particularly limiting for crops since it keeps root growth restricted with poor plant development.

Reduction in Root Penetration: Roots struggle to penetrate compacted layers, particularly in deeper soil horizons. When soil is compacted, it becomes harder for roots to grow and spread, limiting the uptake of water and nutrients and leading to stunted plant growth.

Soil Structure Breakdown: Compaction breaks down natural soil aggregates. Healthy soils contain aggregates, clumps of particles, that allow for better air and water movement. Compaction disrupts these aggregates and creates a denser, less friable structure, which is harder for plants to thrive in.

7.1. Changes in Soil Properties (Density, Permeability, Strength)

Soil Density (Dry Density & Bulk Density):

Dry Density: Compaction increases the dry density of soil by reducing the volume of air between the soil particles. This is because soil particles are packed more closely together under compaction. The dry density of the soil increases because its particles are more closely spaced. In most cases, the structure is stronger as well, so that it is better able to carry larger loads.

Bulk Density: Bulk density is the ratio of the total mass of the soil to the total volume, including both solids and voids. Compaction usually increases bulk density because the soil particles are packed more tightly, which reduces the pore space. With higher compaction, the soil contains fewer void spaces. It has a higher bulk density, thus making the soil denser and more resistant to compression under load.

Permeability: Permeability is the capacity of a soil to convey water and air through its pores. Effect of Compaction on Permeability. The pore spaces are reduced as soil is compacted. Lower permeability is associated with this. The smaller the void spaces between particles, the harder it is for water and air to flow through. Highly compacted soils, as with heavy clay, are less permeable and may exhibit poor drainage. The sandy soils will have relatively high permeability, but compaction reduces it.

Shear Strength: The ability of the soil to resist failure due to shear force. Compaction usually increases the shear strength of soil because the soil particles are more closely packed, thus reducing the ability of the soil to deform or fail under applied forces. In granular soils (such as sands), the higher compaction significantly increases the bearing capacity and makes the soil stronger. In fine-grained soils (such as clays), though compaction does increase frictional resistance between particles, excessive compaction causes a loss of cohesion especially when the soil is either too dry or too wet during compaction.

7.2. Impact on Pore Structure and Void Ratio

Pore Structure: As compaction increases, soil particles become more closely packed, so the volume of voids decreases. The pore spaces get smaller, so the soil's pore structure becomes more dense and less connected. It decreases the air-void as it compresses the particles of soil inside. Air is reduced; this decrease is the ability of storage by air in the soil. Compaction also reduces the volume available for water to occupy in the soil. The smaller the pores, the harder it is for water to move through the soil, leading to reduced permeability. Compaction can alter the pore distribution. In very compacted soils, pores may become more isolated or less interconnected, leading to more localized areas of higher or lower water retention. In some instances, compression decreases the interconnectivity of the pores. Less water and air will pass through soils because of this effect in the soil. This would be more significant for those fine-grained soils referred to as clays whose properties are very sensitive during compaction.

Void Ratio: Compaction reduces the volume of the voids of air and water in the soil but the volume of solids is held constant. Hence, Since the volume of voids decreases but that of the solids remains the same, the void ratio decreases as compaction increases. With an increase in soil compaction, the density increases and the void ratio decreases. The higher the density of the soil (because of higher compaction), the lower the void ratio.

Void Ratio = Volume of voids/Volume of soil

7.3 Influence on Shrinkage and Swelling Behavior

Shrinkage Behaviour: Shrinkage is the decrease in volume of soil as it dries and loses water, pulling the soil particles closer together. When soil is compacted, the void spaces between particles are reduced, which limits the ability of the soil to shrink further as water is lost. More compacted soils tend to experience less volume change when drying because they are already densely packed. The soil structure after compaction will be denser, and fewer and smaller voids are found. This will result in less shrinkage upon drying because the particles are already tightly packed, and it is difficult for them to contract further. In clayey soils, which have a high shrink-swell potential due to the presence of clay minerals like montmorillonite, compaction can still help reduce shrinkage to some extent by decreasing the volume of voids, but the soil may still shrink significantly under drying conditions due to the plasticity and behavior of the clay minerals. In sandier soils, the shrinkage behavior is not as noticeable, and compaction reduces any remaining noticeable shrinkage because sandy soils do not shrink much under dry conditions.

Swelling Behavior: Swelling happens when soil expands upon hydrating. It can be caused by water molecules being attracted to each other and creating a distance between clay particles. Compaction generally reduces swelling potential as it reduces void volume and pore space overall in soil. When compacted, the water- holding capacity of the soil is diminished because the denser the soil, then the lesser the amount of water entering the soil to result in swelling. Reduced pore volume and compacted structure leave limited space for water to seep into the soil, and the soil is likely to swell less. In fine-grained soils, compaction may decrease the amount of swelling, but it will not eliminate it altogether. Even montmorillonite clay-rich soils will swell in the presence of water, although less than uncompacted soil. High plasticity soils and expansive clays (such as bentonite or kaolinite) are very sensitive to moisture content changes. Although compaction reduces their swelling potential, if the moisture content increases significantly, the soil can swell.

Table 7.1: Effects of Compaction on Soil Property

Soil Property	Effect of Compaction
Density (Bulk & Dry)	Increases
Permeability	Decreases
Void Ratio	Decreases
Shrinkage	Decreases
Swelling	Decreases
Strength	Increases
Compressibility	Decreases
Consolidation	Reduces
Plasticity	Decreases

CHAPTER 8

8. APPLICATIONS OF COMPACTION IN CIVIL ENGINEERING PROJECTS

Compaction is an essential process in civil engineering, which provides assurance to infrastructure projects in terms of stability, durability, and long-lasting service. It is generally applied to improve soil properties in terms of strength, stability, and load-bearing capacity.

8.1. Roads and Highways

Compaction plays a great role in road and highway construction, maintenance, and performance. In general, it helps a road structure stay in a proper form for sufficient loads from vehicles and prevents further excessive settlement or cracking and rutting during road life. Key applications of compaction on road and highways are given as follows.

Subgrade Preparation (Base of the Road): This is the natural ground or soil that forms the basic foundation for the road. Improved compaction of this layer supports the weight of the road and the traffic.

Applications:

- **Load-Bearing Capacity**: Compaction of the subgrade enhances the load-bearing capacity of this layer of subgrade to be able to bear the weight from vehicular loading without excessive deformations.
- **Decreased Settlement**: Correct compaction will minimize the chance of further settlement or un-even subsidence that could cause cracking or potholes.
- **Stable Base**: It offers a stable base course to support other courses of the road structure.

Base and Subbase Layers: The base and subbase are made of layers of material (usually granular materials like crushed stone, gravel, or sand) placed over the subgrade. These layers serve to distribute load from traffic and allow for drainage.

Application:

- **Enhanced Structural Strength**: Compaction enhances the strength and density of the base and subbase that can carry a road surface, along with loads from traffic.
- **Prevention of Rutting**: Well-compacted base and subbase prevent rutting and deformation or failure due to the traffic loads.
- **Water Drainage**: Compaction of these layers helps in water drainage and prevents water from accumulating beneath the road, which may weaken the road structure and cause cracking.

Pavement Surface (Asphalt or Concrete): Pavement layer (can be asphalt or concrete) the final surface on which the vehicles are driven. This pavement mix needs to be compacted in order to be able to attain all the essential properties like smoothness and durability.

Application:

- **Ensures smoothness**: Compaction of the asphalt or concrete ensures that an even, smooth surface is achieved. Therefore, it enhances a ride quality as well as safety.
- **Reduces Air Voids**: In asphalt, compaction reduces air voids, increasing density and enhancing the durability and performance of the pavement.
- **Increases Durability**: A well-compacted pavement resists cracking, potholes, and deformation due to the weight of traffic and environmental factors like freeze-thaw cycles.

Road Shoulders: The shoulders of roads offer space for emergencies and ensure the integrity of the edge of the road.

Application:

- **Prevents Edge Cracking**: The compaction of the shoulder material ensures that water accumulation, traffic loads, and vibrations do not cause the edges of the road to erode or crack.
- **Improves Drainage**: Well-compacted shoulders allow for drainage, thereby preventing water accumulation along the road, which might weaken the pavement and base layers.

Road Rehabilitation and Resurfacing: Rehabilitation and resurfacing aims to rehabilitate damaged roads to put them in proper working condition. In these two projects, an existing pavement is milled sometimes, and compaction of bases or sub-bases is a requirement.

Application:

- **Re-Compaction of Subgrade/Base Layers**: Following milling or excavation, the base and subgrade layers are compacted to recover their load-bearing capacity and avoid future settlement.
- **Resurfacing**: Once asphalt or concrete is replaced, proper compaction ensures that the new surface will bond well with the base layers, reducing the chance of future cracking or rutting.
- **Correction of Rutting or Cracking**: Compaction can also be used to correct existing rutting, cracks, or other deformations in the pavement by re-compacting the underlying layers and re-stabilizing them.

Road Construction in Difficult Sites : In difficult sites, such as soft soils, floodplains, or wetlands, special techniques are needed to stabilize and compact soil.

Application:

- **Stabilization of Poor or Marshy Soils**: In soft or marshy soils, deep compaction techniques such as vibro-compaction, dynamic compaction, or the use of geotextiles can stabilize the ground and increase its load-carrying capacity.
- **Differential Settlement**: Compaction prevents differential settlement of soft soils that may cause cracks, misalignment, or displacement of road sections.
- **Filling and Compaction**: In wetlands or floodplains, compacted fill material is used to raise the road level and create a stable foundation for construction.

Heavy Traffic Roads and Highways: Highways that are designed to carry heavy traffic loads require particularly well-compacted layers to endure the repeated and high loads over time.

Application:

- **Improved Load Distribution**: Compaction improves the load distribution of heavy vehicles, thereby reducing wear and tear on the road surface and preventing early damage.
- **Extended Life**: A well-compacted base and pavement layer increases the service life of highways through reduced deformation, cracking, and pothole formation.

Compaction for Road Safety and Performance: All road layers undergo proper compaction, thus guaranteeing the roads can carry the traffic loads and perform for a considerable length of time across various weather conditions.

Application:

- **Prevents structural failures**: Structural failure is the inability of roads to support uneven settling, cracking of the pavement, and rutting caused by heavy loads and environmental factors.
- **Better Ride Quality**: Proper compaction enhances rideability by providing a smooth and stable surface that ensures comfort and safety for the driver.

8.2. Embankments and Dams

The application of compaction in constructing embankments and dams is essential to ensure its stability, safety, and longevity. Compaction refers to the process of minimizing the volume of air voids in soil or any other construction material to increase its density, strength, and impermeability. This section will give a comprehensive description of how compaction is applied in embankments and dams:

Strength and Stability of the Structure: Soil compaction, in embankment and dam construction, is vital because it assures that the soils are strong enough to resist forces like the structural weight, pressure of water, and other influences like seismic waves or water head fluctuations.

Application:

- Systematic layers of soil are placed and compacted together to form a solid, stable base.
- This compaction decreases the air voids in the soil, and therefore, it increases the density of the soil, making a stronger and stiffer embankment or dam. The compacted material increases its shear strength as well, hence reducing the failure tendency of such material under stress or deformation.

Water Seepage Control: One of the primary purposes of embankments and dams is to stop the flow of water, either to prevent flooding or to hold back water in reservoirs. Compaction reduces the permeability of the soil so that water cannot seep through the embankment.

Application:

- Compaction techniques decrease the size of voids between soil particles. As a result, the permeability of soil is reduced.
- This is critical in the core of embankment dams. Low permeability is essential for preventing seepage and lowering the potential of internal erosion or piping failure.I
- Impervious zones, typically made with clay or other low-permeability materials, are compacted to create an effective barrier against water flow.

Settlement and Deformation Reduction: Embankments and dams settle under the weight of the structure and the water behind it. Differential settlement causes cracking, misalignment, and failure. Proper compaction reduces the potential for differential settlement.

Application: Soil layers are compacted to a uniform density so that the settlement is not uneven. Settlement tests, like observing the behavior of the embankment under load, are performed to ensure that the compaction is effective and stable in the long run.

Increased Strength and Longevity: A well-compacted soil will result in the long-term stability of embankments and dams. Compaction increases the soil's resistance to erosion, weathering, and other environmental effects.

Application:

- Compaction increases the cohesion of the soil, hence its resistance to erosion by water and wind.
- This prevents the loss of materials and degradation of the structure in embankments and dams due to heavy rainfall or fluctuating water levels.

Core Compaction in the Dam: In an embankment dam, the core is the most vital area where compaction must be undertaken to stop leakage of water and assure stability of the dam.

Application:

- The central part of the dam usually is built using low permeability materials such as clay or fine aggregate mixture.
- The core of the dam is then compacted to high density to form an impervious barrier that resists seepage.
- The core should be compacted particularly strictly and some special methods of compaction can be used to provide the required low permeability and strength.

8.3. Foundations and Sub-grades

Compaction is the key element in foundation and sub-grade construction. It makes sure that structures are stable, have enough load-bearing capacity, and last longer by enhancing the physical properties of the soil or other materials making up the layers of foundation and sub-grade. Compaction of foundations and sub-grades prevents settlement, reduces permeability, and generally enhances the overall performance of the construction. Below is a comprehensive overview of how compaction is applied to foundations and sub-grades:

Increasing Load-Carrying Capacity: One of the primary objectives of compaction is to increase the density of the soil, thus increasing the load-carrying capacity of the foundation and sub-grade.

Application:

Compacted soil has reduced air voids, leading to a denser and stronger material. This is essential for foundations that will support heavy loads from buildings, bridges, or other structures.

- In areas with loose or weak soils, proper compaction can improve the bearing capacity, ensuring that the structure does not experience excessive settlement or deformation.

Reducing Settlement and Uneven Movement: One of the main concerns with foundations and sub-grades is settlement over time, which can lead to uneven movement and damage to the structure.

Application:

- Compaction compacts soil particles, thus reducing the possibility of excessive settlement. Properly compacted sub-grades prevent differential settlement, where some areas of the foundation sink more than others.
- Uniform compaction reduces the risk of long-term deformation, which could result in structural issues such as cracks in walls, floors, or foundations.
- In areas with poor or expansive soils, compaction stabilizes the soil and reduces the likelihood of swelling or shrinking, which are frequent causes of foundation movement.

Soil Strength and Stiffness Improvement: Soil strength and stiffness are essential to ensure that the foundation can support loads imposed by the superstructure without excessive movement or failure.

Application:

- Compaction increases the density and reduces void ratio in soils, thus imparting higher strength and stiffness by shear. For foundations that bear heavy loads, this is considered important.
- Cohesive soils will have more shear strength due to compaction and the soil will not slump or slide easily. For granular soils, greater stability is achieved by less likelihood of loss through internal friction upon load.

Reduction of Permeability: The foundation and sub-grade shall be capable of resisting water infiltration and protecting the structure against damage due to moisture such as erosion or weakening of the foundation.

Application:

- Compaction reduces the soil's permeability by reducing the void spaces between the particles, thus limiting the amount of water that can pass through the soil.
- Where foundations are likely to be exposed to water (for instance, near water tables or in flood-prone areas), compacted sub-grades prevent the ingress of water into the foundations, thus eliminating the possibility of erosion or frost heave.

Uniformity and Consistency: A foundation or sub-grade is required to be uniform to support the even dissemination of loads uniformly over the top surface so there is no occurrence of uneven stressing that might further lead to cracking or failure at the structural integrity.

Application:

- Applied in layers in 6 inches to 12 inches thick units, and before the addition of each layer; the applied load is compacted to a designated density.
- This layered approach ensures that the soil or material is compacted uniformly across the entire area of the foundation or sub-grade.
- Engineers use tools such as nuclear densometers or sand cone tests to verify the consistency and uniformity of compaction throughout the construction process.

Preventing Erosion and Surface Disturbance: Proper compaction helps protect the foundation and sub-grade from erosion or surface disturbance, particularly in areas with loose or silty soils that are prone to wind or water erosion.

Application:

- This also means that, due to soil or subgrade material compaction, the surface becomes more resilient to external forces like wind or water, otherwise leading to erosion and degradation of the foundation.
- In case of this dense, compacted material, it will not face surface scouring or instability conditions that may destabilize the foundation.

CHAPTER 9

9. CONCLUSION

Soil compaction is a crucial process in construction and civil engineering, significantly impacting the strength, stability, and durability of structures such as embankments, dams, foundations, and sub-grades. Through the densification and cohesion improvement of soils, compaction enhances their load-bearing capacity, minimizes settlement, and reduces permeability. Different methods, including rolling, kneading, and impact compaction, are used to tailor the compaction process to specific soil types and project requirements, ensuring optimal performance and sustainability.

Proper compaction extends its effects beyond structural stability by preventing water leakage, controlling settlement, and reducing erosion. For embankments and dams, achieving a dense and stable soil layer is critical to withstand environmental forces such as earthquakes and fluctuating water levels. Similarly, in foundations and sub-grade construction, stable and strong soil layers minimize the risk of long-term movement or structural failure, ensuring lasting integrity.

However, achieving effective soil compaction demands careful management of factors such as moisture content, equipment selection, and on-site testing. Quality control and monitoring are essential throughout the compaction process, as inadequate or uneven compaction can result in serious issues, including structural failures, water leakage, or the long-term deterioration of infrastructure. Tests like the sand cone test, nuclear density gauge, and moisture-density analysis play a vital role in verifying compaction efficiency.

Importance in Modern Engineering

In modern engineering, soil compaction is indispensable for improving the performance and longevity of infrastructure. By increasing soil density, it enhances load-bearing capacity, minimizes excessive movement, and ensures uniformity—key factors in preventing foundation problems, cracking, and differential settlement. Additionally, reduced water permeability and erosion resistance make compaction essential for structures such as dams, roads, and embankments, especially in seismic zones, where compacted soil helps mitigate the risk of liquefaction.

Overall, the optimization of soil properties through compaction plays a pivotal role in the cost-efficiency, sustainability, and long-term performance of civil engineering projects. It ensures infrastructure remains resilient to environmental stresses while delivering reliable and durable solutions.

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