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NPTEL ONLINE CERTIFICATION COURSES

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SOIL MECHANICS/GEOTECHNICAL ENGINEERING I

PERMEABILITY AND SEEPAGE

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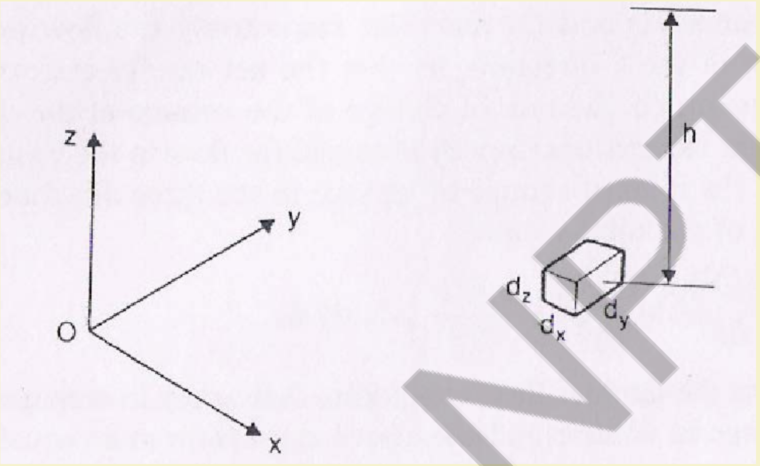
Permeability and Seepage

Equation of Flow through soil:



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The Component of the hydraulic gradient, i_x at the center of the element will be,

$$i_x = -\frac{\partial h}{\partial x}$$ (It is of negative sign as there is a head loss in the direction of flow)

The rate of change of hydraulic gradient, i_x along the length of the element in the x direction will be, $\frac{\partial i_x}{\partial x} = -\frac{\partial^2 h}{\partial x^2}$

Hence gradient at the face of the element nearest to the origin

$$= -\frac{\partial h}{\partial x} + \left(\frac{\partial i_x}{\partial x}\right)\left(-\frac{dx}{2}\right) = -\frac{\partial h}{\partial x} + \frac{\partial^2 h}{\partial x^2}\frac{dx}{2}$$

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From the Darcy's law: $Q = AKi = k_x\left(-\frac{\partial h}{\partial x}+\frac{\partial^2 h}{\partial x^2}\frac{dx}{2}\right)dy\,dz$ (1)

The gradient at the face furthest from the origin is:

$$-\frac{\partial h}{\partial x}+\left(\frac{\partial i_x}{\partial x}\right)\frac{dx}{2} = -\frac{\partial h}{\partial x}-\frac{\partial^2 h}{\partial x^2}\frac{dx}{2}$$

Therefore, Flow = $k_x\left(-\frac{\partial h}{\partial x}-\frac{\partial^2 h}{\partial x^2}\frac{dx}{2}\right)dy\,dz$ (2)

Permeability and Seepage

Expressions 1 and 2 represents respectively the flow into and out of the element in x direction, so net rate of increase of water within the element, i.e., net rate of change of the volume of the element is (1) – (2).

$$= k_x \frac{\partial^2 h}{\partial x^2} dxdydz$$

Similar expression may be obtained for y and z directions. The sum of the rates of change of volume in three directions gives the rate of change of total volume:

$$\left(k_x \frac{\partial^2 h}{\partial x^2} + k_y \frac{\partial^2 h}{\partial y^2} + k_z \frac{\partial^2 h}{\partial z^2} \right) dx\, dy\, dz$$

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Under laminar flow conditions that apply in seepage problem there is no change in volume and the above equation must equal to zero:

$$\left(k_x \frac{\partial^2 h}{\partial x^2} + k_y \frac{\partial^2 h}{\partial y^2} + k_z \frac{\partial^2 h}{\partial z^2}\right) = 0 \qquad (3)$$

Equation 3 is the general expression for the three-dimensional flow.

If the soil is isotropic, $k_x = k_y = k_z = k$

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Permeability and Seepage

The three-dimensional flow equation reduces to

$$\left(\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2}\right) = 0$$

In many seepage problems the analysis can be carried out in two dimensions, the y term usually being taken as zero so that the expressions become:

$$\left(k_x \frac{\partial^2 h}{\partial x^2} + k_z \frac{\partial^2 h}{\partial z^2}\right) = 0 \quad \Rightarrow \quad \left(\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial z^2}\right) = 0$$

An isotropic soil is a soil whose material properties are the same in all direction

Permeability and Seepage

The Laplacian equation just derived can be expressed in terms of the two conjugate functions , ϕ and ψ

If we put

$$\frac{\partial \emptyset}{\partial x} = v_x = k i_x = -k\frac{\partial h}{\partial x} \quad and \quad \frac{\partial \emptyset}{\partial z} = v_z = -k\frac{\partial h}{\partial z}$$

Then,

$$\frac{\partial^2 \emptyset}{\partial x^2} = -k\frac{\partial^2 h}{\partial x^2} \quad and \quad \frac{\partial^2 \emptyset}{\partial z^2} = -k\frac{\partial^2 h}{\partial z^2} \Rightarrow \frac{\partial^2 \emptyset}{\partial x^2} + \frac{\partial^2 \emptyset}{\partial z^2} = 0$$

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Permeability and Seepage

Also if we put $\frac{\partial \Psi}{\partial z} = v_x = -k\frac{\partial h}{\partial x}$ and $-\frac{\partial \Psi}{\partial x} = v_z = -k\frac{\partial h}{\partial z}$

Then, $\frac{\partial \phi}{\partial x} = \frac{\partial \Psi}{\partial z}$ *and* $\frac{\partial \phi}{\partial z} = -\frac{\partial \Psi}{\partial x}$

$$\frac{\partial^2 \Psi}{\partial x^2} = \frac{\partial^2 \phi}{\partial x \partial z} \quad and \quad \frac{\partial^2 \Psi}{\partial z^2} = -\frac{\partial^2 \phi}{\partial x \partial z}$$

Hence, $\frac{\partial^2 \Psi}{\partial x^2} + \frac{\partial^2 \Psi}{\partial z^2} = 0$

Permeability and Seepage

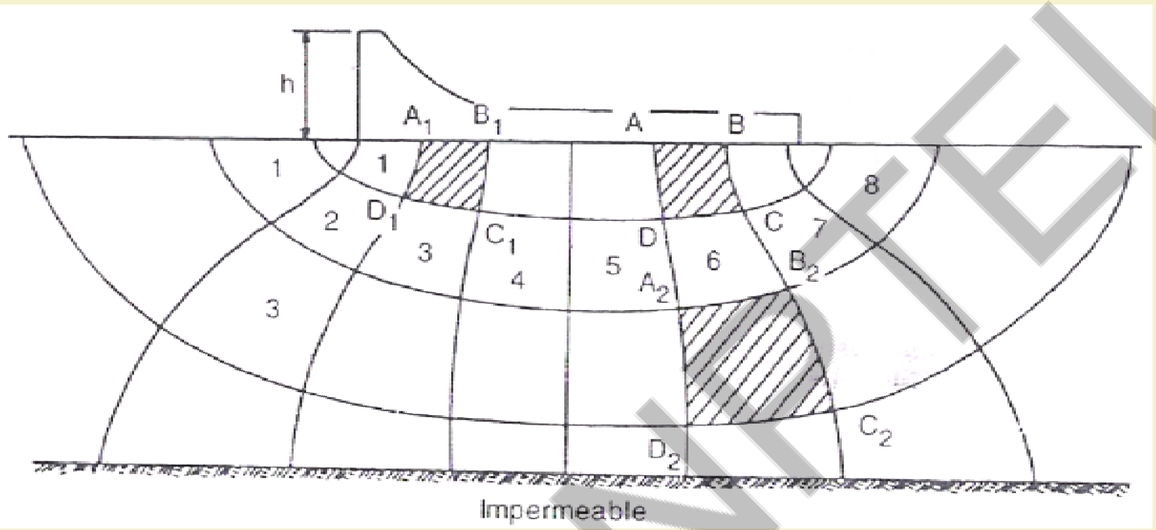
Flow line: The path which water particles follow in the course of seepage are known as flow lines. Water flows from points of high to low head, and makes smooth curves when changing direction. Hence one can draw a series of smooth curves representing the paths followed by moving water particles.

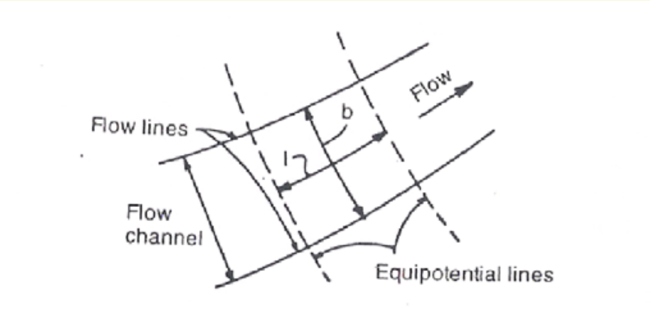
Equipotential lines: As the water moves along the flow line it experiences a continuous loss of head. If we can obtain the head causing flow at points along a flow line, then by joining up points of equal potential one can obtain a second set of lines known as equipotential lines.

Permeability and Seepage

Flow Nets: The flow of water through soil can be represented graphically by a flow net, a form of curvilinear net made up of flow lines intersected by a set of equipotential lines

Permeability and Seepage





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Permeability and Seepage

Figure shows a typical flow net representing seepage through a soil beneath a dam. The flow is assumed to be two-dimensional.

From Darcy's law q = Aki, so if we consider unit width of soil and if Δq = the unit flow through a flow channel, then $\Delta q = k \times b \times 1 \times i = k \times b \times i$ where b is the distance between the two flow lines

In Fig ABCD is bounded by the same flow lines as $A_1B_1C_1D_1$ and by the same equipotentials as in $A_2B_2C_2D_2$. For any figure in the net $\Delta q = k\Delta h\frac{b}{l}$, where Δh = head loss between the two equipotentials and l is the distance between the equipotentials

Permeability and Seepage

Flow through $A_1B_1C_1D_1 = \Delta q_1 = k\Delta h_1 \frac{b_1}{l_1}$

Flow through $A_2B_2C_2D_2 = \Delta q_2 = k\Delta h_2 \frac{b_2}{l_2}$

Flow through $ABCD = \Delta q = k\Delta h \frac{b}{l}$

If it is possible to draw flow net so that $l_1 = b_1, l_2 = b_2 \; and \; l = b$. when we have this arrangement figures are termed as squares and the flow net is a square flow net. With this condition, $\frac{b_1}{l_1} = \frac{b_2}{l_2} = \frac{b}{l} = 1.0$

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Permeability and Seepage

Since square ABCD has the same flow lines as $A_1B_1C_1D_1$

$$\Delta q = \Delta q_1$$

Since square ABCD has the same equipotentials as $A_2B_2C_2D_2$

$$\Delta h = \Delta h_2 \quad \Rightarrow \quad \Delta q_2 = k\Delta h_2 = k\Delta h = \Delta q = \Delta q_1$$

$$\Delta q = \Delta q_1 = \Delta q_2 \quad and \quad \Delta h = \Delta h_1 = \Delta h_2$$

Permeability and Seepage

Assume h = total head los and q = total quantity of unit flow

$$\Delta h = \frac{h}{N_d} \ and \ \Delta q = \frac{q}{N_f}$$

Where $N_f \ and \ N_d$ number flow lines and potential drops, respectively

$$\Delta q = h\Delta h \frac{b}{l} = k\Delta h$$

(b=l for square flow net

$$k\frac{h}{N_d} = \frac{q}{N_f} \Rightarrow q = kh\frac{N_f}{N_d}$$

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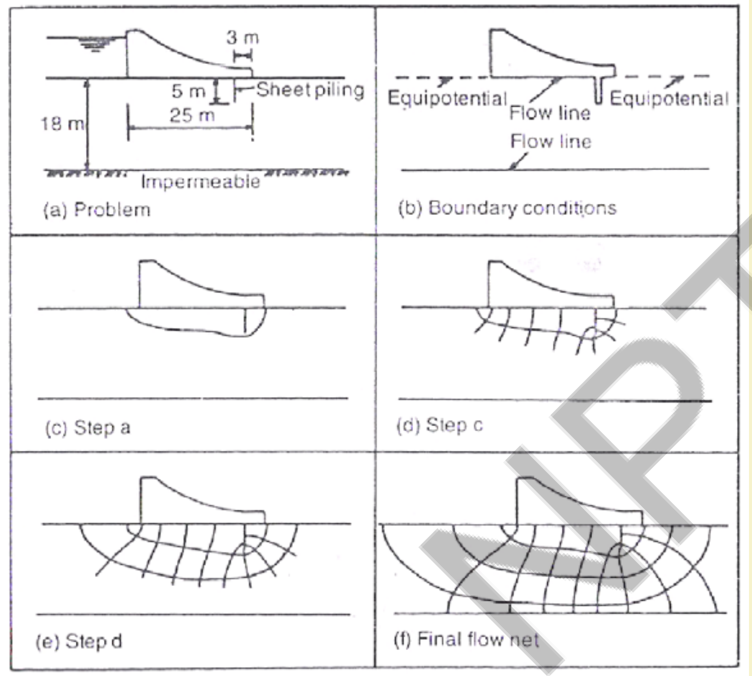
Permeability and Seepage



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PERMEABILITY AND SEEPAGE

Most loose deposits are probably isotropic, i.e., the value of permeability in the horizontal is the same in the vertical direction. Practice of constructing earth embankments and dams is spreading of the soil in loose layers and then compacted. This construction technique results in a greater value of permeability in the horizontal direction than that in the vertical direction. The value in the vertical direction is usually 1/5 to 1/10 of the value in horizontal direction

The general differential equation for flow in three dimensional case was derived earlier is:

$$\left(k_x\frac{\partial^2 h}{\partial x^2}+k_y\frac{\partial^2 h}{\partial y^2}+k_z\frac{\partial^2 h}{\partial z^2}\right)=0$$

For two-dimensional case: $$\left(k_x\frac{\partial^2 h}{\partial x^2}+k_z\frac{\partial^2 h}{\partial z^2}\right)=0$$

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Unless kx is equal to kz the equation is not a true Laplacian and cannot therefore be solved by a flow net described before. To utilise the method itmust be modified for an equivalent homogeneous system. Steps:

$$\frac{k_x}{k_z}\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial z^2}=0 \quad \Rightarrow \quad \frac{\partial^2 h}{\partial {x_t}^2}+\frac{\partial^2 h}{\partial z^2}=0$$

Where $\frac{1}{{x_t}^2}=\frac{k_x}{k_z}\frac{1}{x} \quad or\, x_t = x\sqrt{\frac{k_z}{k_x}}$

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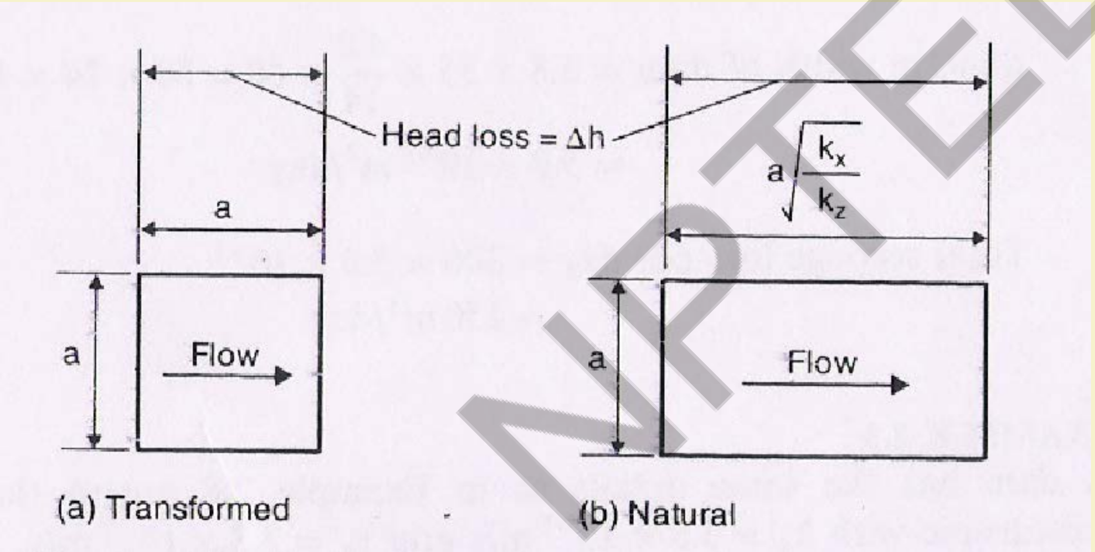
The equation modified is now a Laplacian and involves the two coordinates variables xt and z. It can be solved by a flow net provided that the net is drawn to a vertical scale of z and a horizontal scale of

$$x_t = x\sqrt{\frac{k_z}{k_x}}$$

PERMEABILITY AND SEEPAGE

Seepage quantity in an anisotropic soil



This is exactly as before:

$$q = kh\frac{N_f}{N_d}$$

The only problem is what value to use for k

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PERMEABILITY AND SEEPAGE

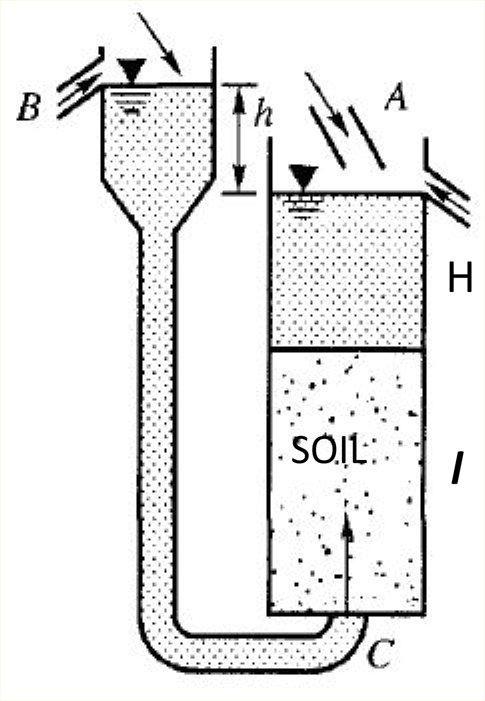
Using the transformed scale a square flow net is drawn and Nf and Nd are obtained. If we consider a square in the transformed flow net it will be as shown in Fig a. The same figure drawn to natural scales (i.e., scale x= scale z), will appear as shown in Fig b. Let ke be the effective permeability for the anisotropic condition.

From Fig a: $$q = a k_e \frac{\Delta h}{a} = k_e \Delta h$$

From Fig b: $$q = a k_x \frac{\Delta h}{a\sqrt{\frac{k_x}{k_z}}} = \sqrt{k_x k_z}\,\Delta h$$

$$\Rightarrow \quad k_e = \sqrt{k_x k_z}$$

PERMEABILITY AND SEEPAGE



Critical Hydraulic Gradient: The total head of water above the base = h+H+l, and the head of water in the sample above the base = H+l, therefore the excess hydrostatic pressure acting on the base of the sample = $\gamma_w h$

PERMEABILITY AND SEEPAGE

If any friction between the soil and the side of the container is ignored, then the soil is on the point of being washed out when the downward forces equals the upward forces:

Downward forces = Buoyant unit weight x volume= $\gamma_w \dfrac{G_s - 1}{1+e} Al$

Upward forces = $h\gamma_w A$

$$h\gamma_w A = \gamma_w \frac{G_s - 1}{1+e} Al \quad \Rightarrow \quad \frac{h}{l} = \frac{G_s - 1}{1+e}$$

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7. A large sized excavation is made in stiff clay whose saturated unit weight is 17.27 kN/m^3. When the depth of excavation reaches 7.5m, cracks appear and water begins to flow upward to bring up sand to the surface. Subsequent boring indicate that the clay is underlain by sand at a depth of 11m below the original ground surface. What is the depth to the water table outside the excavation below the original ground level?

PERMEABILITY AND SEEPAGE

6. If excavation is carried out in a soil with a porosity of 0.40 and the specific gravity of solids of 2.65, determine the critical gradient. A 1.50m layer of the soil is subjected to an upward seepage head of 1.95m. What depth of coarse sand would be required above the soil to provide a factor of safety of 2.5? Assume that sand has the same porosity and specific gravity of solids as the soil.

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SOIL MECHANICS/GEOTECHNICAL ENGINEERING I

PERMEABILITY AND SEEPAGE

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Permeability and seepage: Application 1

1. The results of a constant head permeability test in a fine sand are as follows: area of the soil sample, 180 sqcm; length of the specimen, 32 cm; constant head maintained, 46 cm; flow of water through the specimen , 200 ml in 5 minutes. Determine the coefficient of permeability in cm/s.

Ans: 0.00258 cm/s

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Permeability and seepage: Application 2

2. Compute the coefficient of permeability of a soil on which a falling head test has been carried out. Area of sample =80 cm^2, area of stand pipe = 4cm^2 and length of soil sample = 15 cm. Time vs head difference readings are as given below:

Time (minute):	0	27	60
Head difference, h (cm):	107	105	103

Permeability and seepage: Application 3

3. For a field permeability test by pumping out , a well was sunk through a horizontal stratum of sand 15 m thick and underlain by a impervious layer. Two observations wells were sunk at horizontal distances of 15 m and 35 m, respectively from the pumping well. The initial position of the water level was 2m below the ground level and after a steady state pumping at a rate of 925 lit/m., the drawdown in the observation wells were found to be 2.5 m and 1.3 m respectively. Calculate the coefficient of permeability.

Permeability and seepage: Application 4

4. A bed of sand consists of three horizontal layers of equal thickness. The magnitude of the coefficient of permeability of both the upper and lower layers is 4×10^{-4} mm/s and for the middle layer, it is 6×10^{-2} mm/s. What is the ratio of the average permeability of the bed in the horizontal direction to that in the vertical direction?

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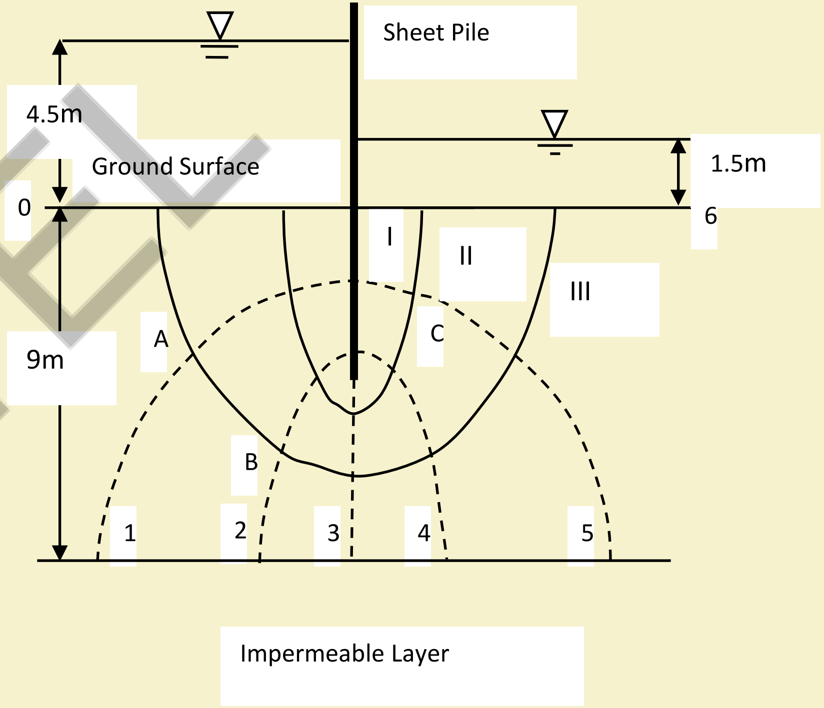
Permeability and seepage: Application 5

5. A flow net for flow around a single row of sheet piles in permeable soil is shown in Figure Given $K_x = K_y = K = 5 \times 10^{-2}$ mm/s, determine:
(a) How high (above the ground surface) will the water rise, if measured by Piezometers placed at points A, B, C and D ?
(b) What will be the rate of seepage through the flow channel II per unit length of the sheet pile?
(c) What is the total rate of seepage through the permeable layer per unit length?



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SOIL MECHANICS/GEOTECHNICAL ENGINEERING I

COMPACTION OF SOIL

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Soil Compaction

Problematic Geomaterial and potential Problems

Type of Geomaterial	Name	Potential Problems
Natural	Soft Clay	Low strength, high compressibility, large creep deformation, low permeability
	Silt	Low strength, high compressibility, high liquefaction potential, low permeability, high erodibility
	Organic Soil	High Compressibility, Large creep deformation
	Loose sand	Low strength, high compressibility, high liquefaction potential, high permeability, high erodibility
	Expansive soil	Large volume Change
	Loess	Large volume change, high collapsible potential

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Soil Compaction

Problematic Geomaterial and potential Problems

Type of Geomaterial	Name	Potential Problems
Fill	Uncontrolled fill	Low strength, high compressibility, nonuniformity, high collapsible potential
	Dredged material	High water content, low strength, high compressibility
	Reclaimed fill	High water content, low strength, high compressibility
	Recycled material	Nonuniformity, high variability of properties
	Solid waste	Low strength, high compressibility, nonuniformity and high degradation potential
	Bio-based by-product	Low strength, high compressibility and high degradation potential

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Soil Compaction:

Compaction means "to press closely together"

In soil mechanics it means press the soil particles tightly together expelling air from the void spaces (reduction in void ratio)

- Consolidation also results in reduction in void ratio but consolidation and compaction are not the same
- Compaction is instantaneous and consolidation is slow
- Saturation is the essential condition for consolidation which is not for compaction

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Soil Compaction

Purpose of Compaction:

Compaction increases soil's density and produces three important effects:

An increase in soils shear strength

A decrease in future settlement of soil

A decrease in its permeability

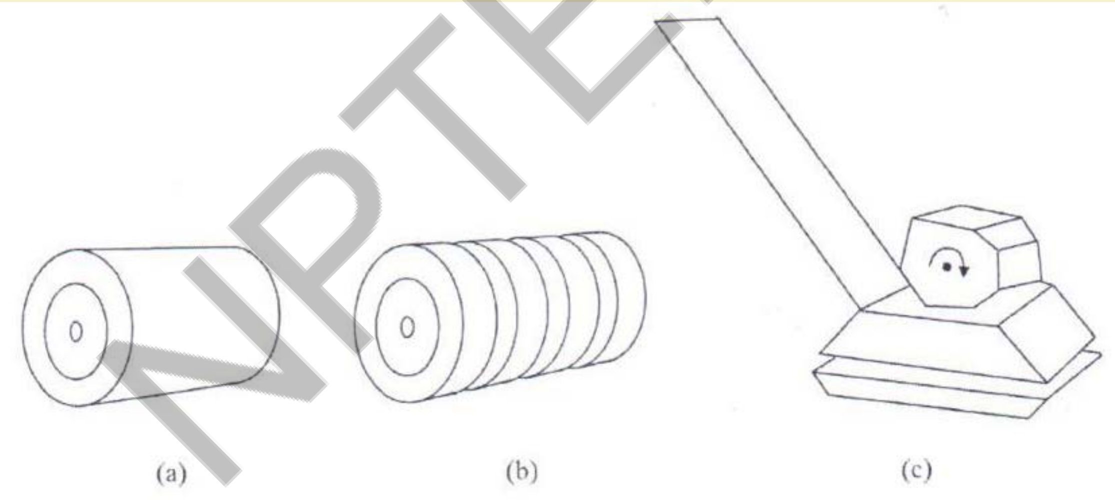
These three effects are beneficial for the construction of various types of earth structures namely, highways, airfield, earthen dam etc

Greater the compaction the greater is the benefits

Compaction is the cheap and effective way for improvement of soils properties

Soil Compaction

Conventional –use of roller or plates to repeatedly apply static pressure, kneading action or vibration on ground surface to densify geo-materials



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Soil Compaction

Compaction is quantified by its dry unit weight, which can be computed in terms of bulk unit weight and moisture content

In most cases dry soil can be best compacted if certain amount of water is added to it. Water acts as a lubricant and soil particles to be packed together. If, however, too much of water is added it results a lesser density. Thus for a given compactive effort there is a particular moisture content at which the dry unit is the greatest and compaction is the best. This moisture content is called 'optimum moisture content' and the associated dry unit weight is known as the maximum dry unit weight

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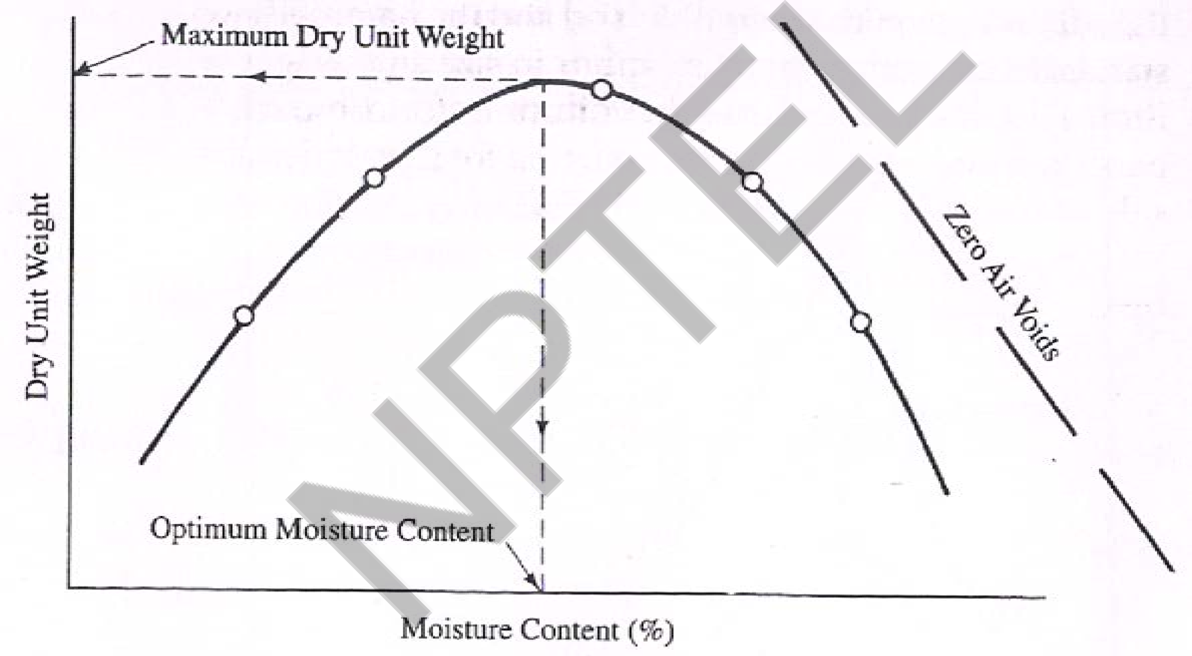
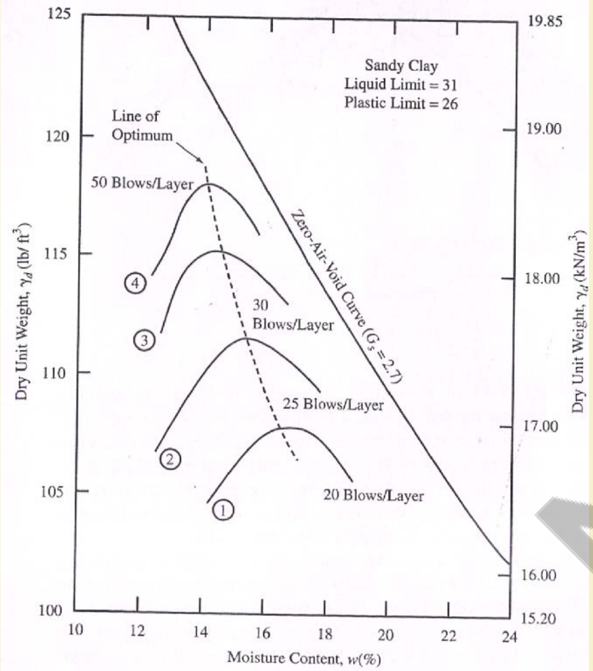
Soil Compaction

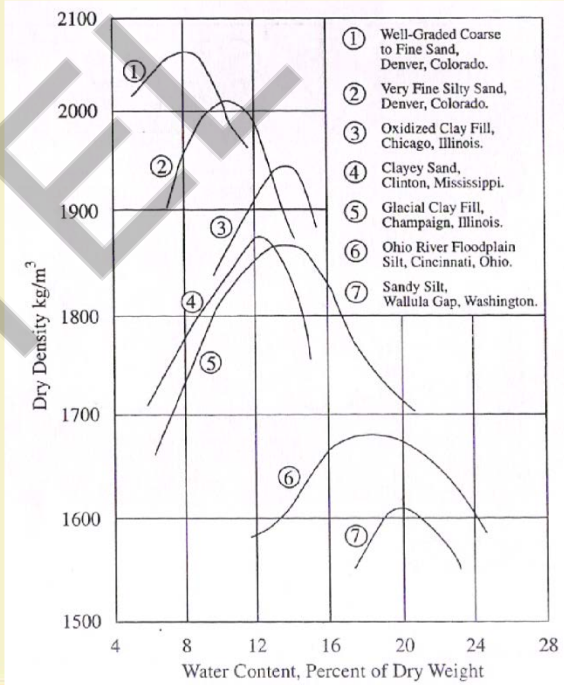


Soil Compaction

Effect compactive effort



Effect of soil type



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Soil Compaction

A smooth wheel roller employs two or three sooth steel rollers, It is useful in compacting base courses and paving mixtures, It is also used to provide smooth finished grade. Smooth wheel roller provides compactive effort through it self weight

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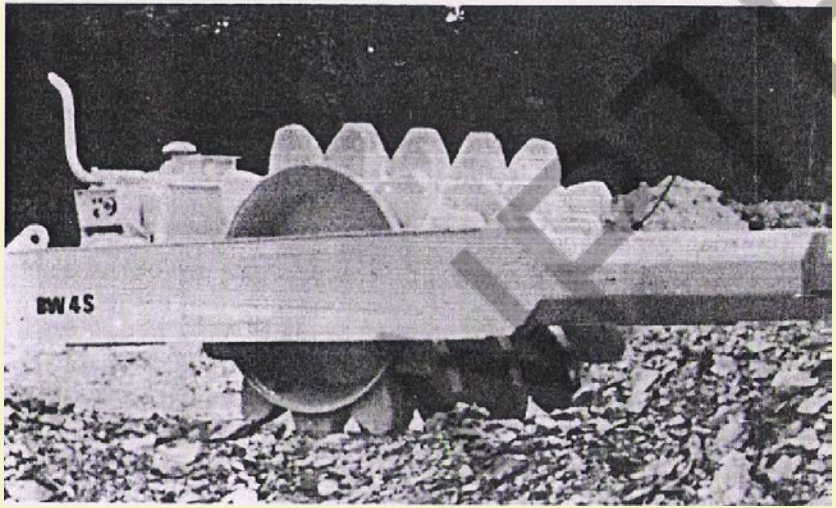
Soil Compaction

A sheep foot roller consists of drum and attached projecting feet
Area of contact between the soil and roller is less causing greater compacting pressure.
It also provides kneading action and is effective for compacting fine grained soil



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Soil Compaction

A pneumatic roller consists of a number of rubber tyres highly inflated, Vary from a small rollers to a very large and heavy. Most heavy pneumatic roller s are towed , some smaller ones self propelled , Clayey soils and silty soil can be compacted effectively by this type of rollers. Also suitable for granular soil containing small amount of fines

Soil Compaction

A vibratory roller contains some kind of vibrating unit that imparts an up and down vibration to the roller as it is pulled over the soil. Vibrating units can supply frequencies of vibration at 1500 to 2000 cycles per minute, depending on compacting requirements. They are effective in compacting granular materials – particularly clean sans and gravel

Recommended Type of Compaction Equipment

Geo-material Type	First Choice	Second Choice	Comments
Rock Fill	Vibratory Roller	Rubber Tire Roller	
Plastic Soil, CH, MH	Sheep foot roller	Rubber tire roller	Thin lifts desired
Law plasticity soil-CL, ML	Sheep Foot Roller	Rubber tire vibratory roller	Moisture control is critical
Plastic sands and gravels-GC, SC	Vibratory, Pneumatic roller	Pad food roller	
Silty sands and gravels-SM GM	Vibratory roller	Rubber tire, pad foot roller	Moisture control critical
Clean sand-SW, SP	Vibratory roller	Impact, rubber tire roller	
Clean gravels-GW, GP	Vibratory roller	Rubber tire, impact, grid roller	Grid useful for over sized particles

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Lift Thickness and Number of passes for different compaction equipment

Equipment	Applicability	Compacted lift thickness	Number of Passes
Sheep foot roller	For fine grained fills or coarse grained fills with more than 20% fines	150 mm	4-6 for fine grained fills 6-8 for coarse grained fills
Rubber tire roller	For clean coarse grained fills with 4 - 8% fines	250 mm	3-5
	For fine grained fills or well graded coarse grained fills with more than 8% fines	150-200	4-6
Smooth wheel roller	Appropriate for sub-grade or base course compaction of well graded sand gravel mixtures	200-300	4
	May be used for fine grained fills other than earth dams	150-200	6

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COMPACTION OF SOIL

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Typical Compaction Requirements

Compaction fill for	% of Modified Maximum dry unit	Moisture range about optimum moisture content
Roads D = 0 – 0.5 m	90-105	-2 to +2
Roads D>0.5 m	90 – 95	-2 to +2
Small Earth Dam	90 - 95	-1 to + 3
Large Dam	95	-1 to +2
Embankment	95	-2 to +2
Foundation	95	-2 to +2
wall	90	-2 to +2
Trench	90	-2 to +2
Clay liner	90	0 to +4

COMPACTION OF SOIL

Lift Thickness and Number of passes for different compaction equipment

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Sheep foot roller	For fine grained fills or coarse grained fills with more than 20% fines	150 mm	4-6 for fine grained fills 6-8 for coarse grained fills
Rubber tire roller	For clean coarse grained fills with 4 - 8% fines	250 mm	3-5
	For fine grained fills or well graded coarse grained fills with more than 8% fines	150-200	4-6
Smooth wheel roller	Appropriate for sub-grade or base course compaction of well graded sand gravel mixtures	200-300	4
	May be used for fine grained fills other than earth dams	150-200	6

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COMPACTION OF SOIL

Equipment type	Applicability	Compacted lift thickness	Number passes
Vibrating smooth drum rollers	For coarse grained fills and sand gravel mixtures-rock fill	200-300 mm for soil 900 for rock	4-6
Vibrating plate compactors	For coarse grained fills with less than 4-8% fines, placed thoroughly wet	200-250	3-4
Crawler tractor	Best suited for coarse grained fills with less than 4-8% fines placed thoroughly wet	150-250	3-4
Power tamper or rammer	For difficult access, trench backfill, suitable for all inorganic fills	100-150 for silt or clay, 150 for coarse grained fills	2

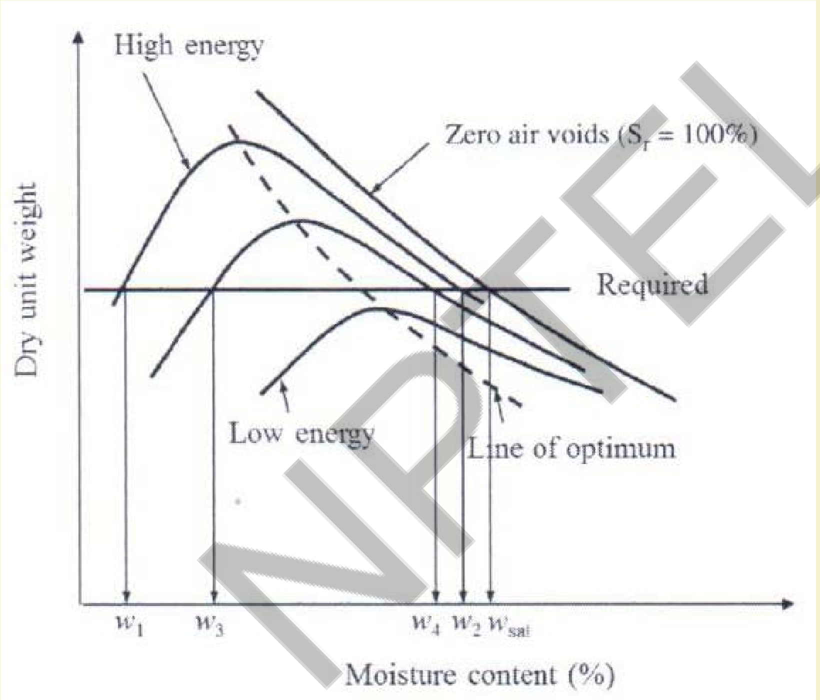
COMPACTION OF SOIL

Application: conventional compaction has been used for earthworks, such as roads, embankments, dams, slopes, and parking lots and sport field

Advantage: construction equipment is readily available. It is a well established ground improvement method that has long history and extensive knowledge in the industry

Limitations: the depth improvement is limited, mainly used for fill and not for insitu natural geo-materials, geo-material should be within the moisture content close to the optimum moisture content to be more effective, it is challenging to achieve uniform compaction of geo-materials in a large area

COMPACTION OF SOIL



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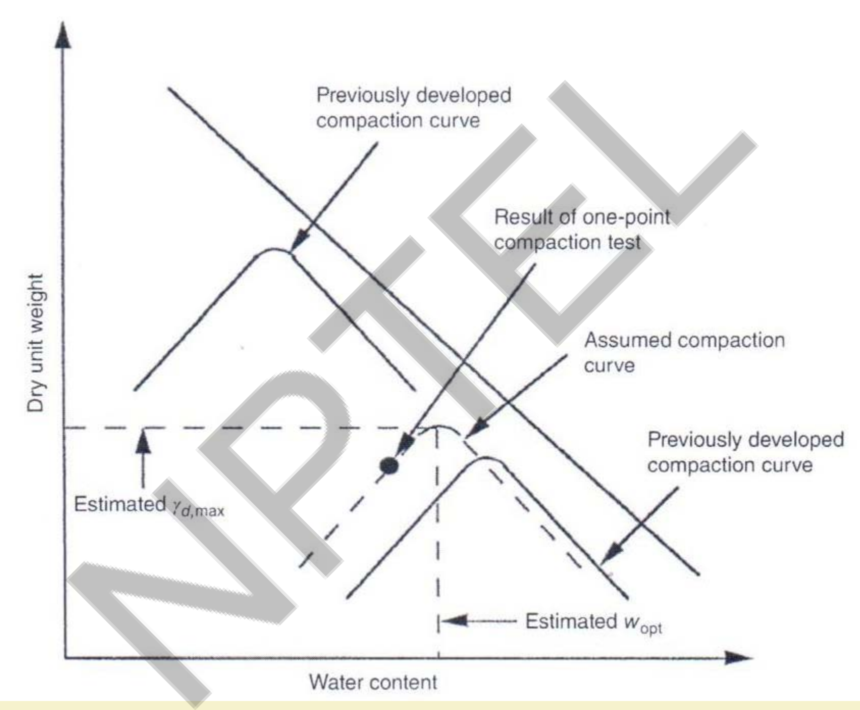
COMPACTION OF SOIL



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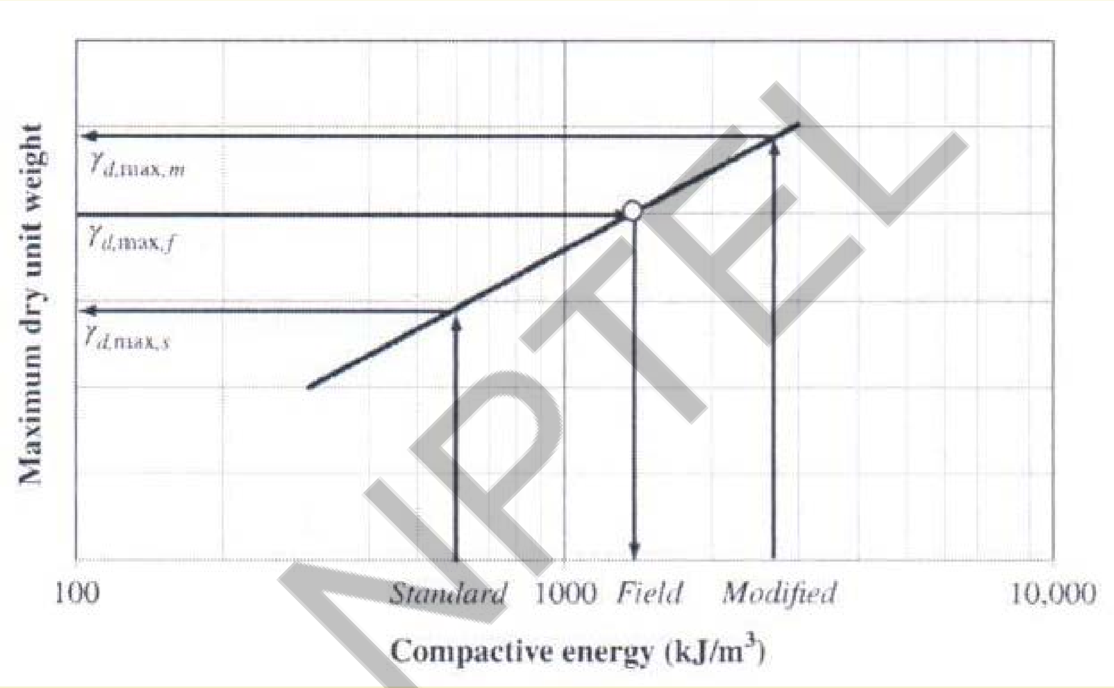

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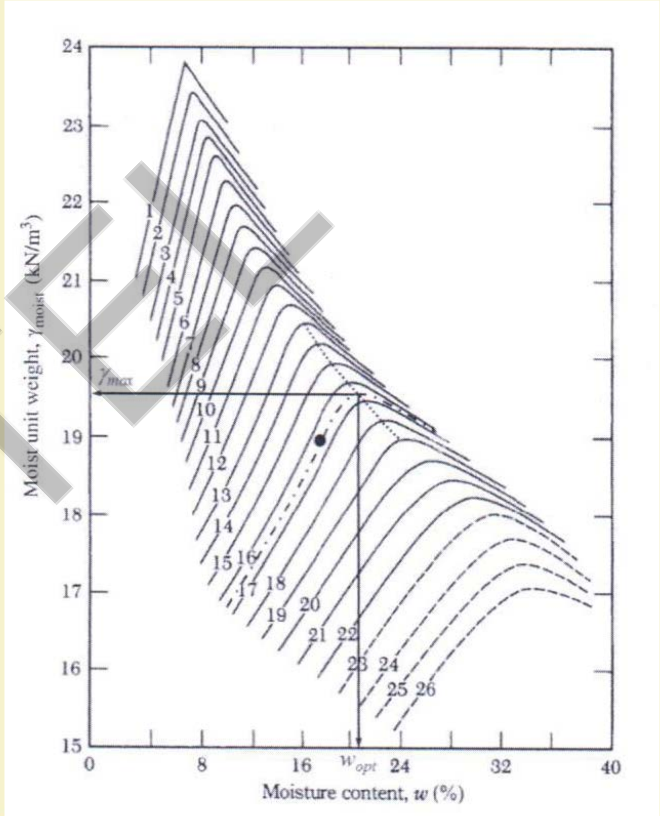

COMPACTION OF SOIL

Recommended Number of Tests

Earth Structure	Volume of Fill per test (m3)
Embankment	500-2000
Impermeable liner	200-1000
Subgrade	500-1500
Base Coarse	500-1000
Backfill in trench or around structure	100-200

COMPACTION OF SOIL

Quality Control and Assurance

Quality control and assurance are important pats of conventional compaction because it often involves large area construction . Quality control typically includes the following:

- Quality of fill material, such as type, gradation, and Atterberg limits
- Type and weight of Equipment
- Lift Thickness
- Moisture content at compaction
- Number of Passes

Quality assurance is achieved through field tests after each lift compaction and/or completion of the overall compaction

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 reflectrometry	Moisture content

Non-destructive method

- Apparatus is placed on the ground or compacted fill and emits gamma rays through the soil
- Some of the gamma rays will be absorbed others will reach to a detector
- Soil unit weight is inversely proportional to the amount of radiation that reaches the detector
- Nuclear apparatus also determines moisture content by emitting alpha particles that bombard a beryllium target, causing the Beryllium to emit fast neutrons
- Fast neutrons that strike hydrogen atoms in water molecules lose velocity, the resulting low velocity neutrons are thermal neutrons. Based on thermal neutron counts and proper correlation soil moisture can be determined

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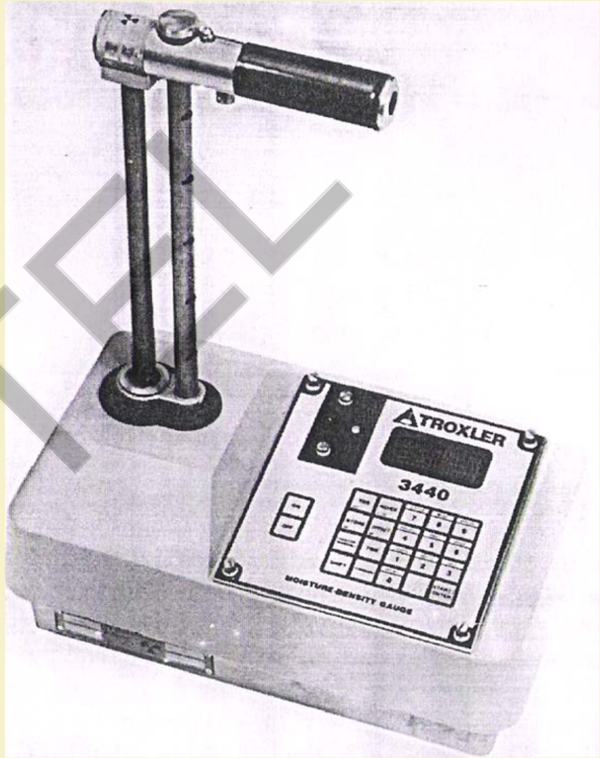
COMPACTION OF SOIL

Nuclear moisture density meter



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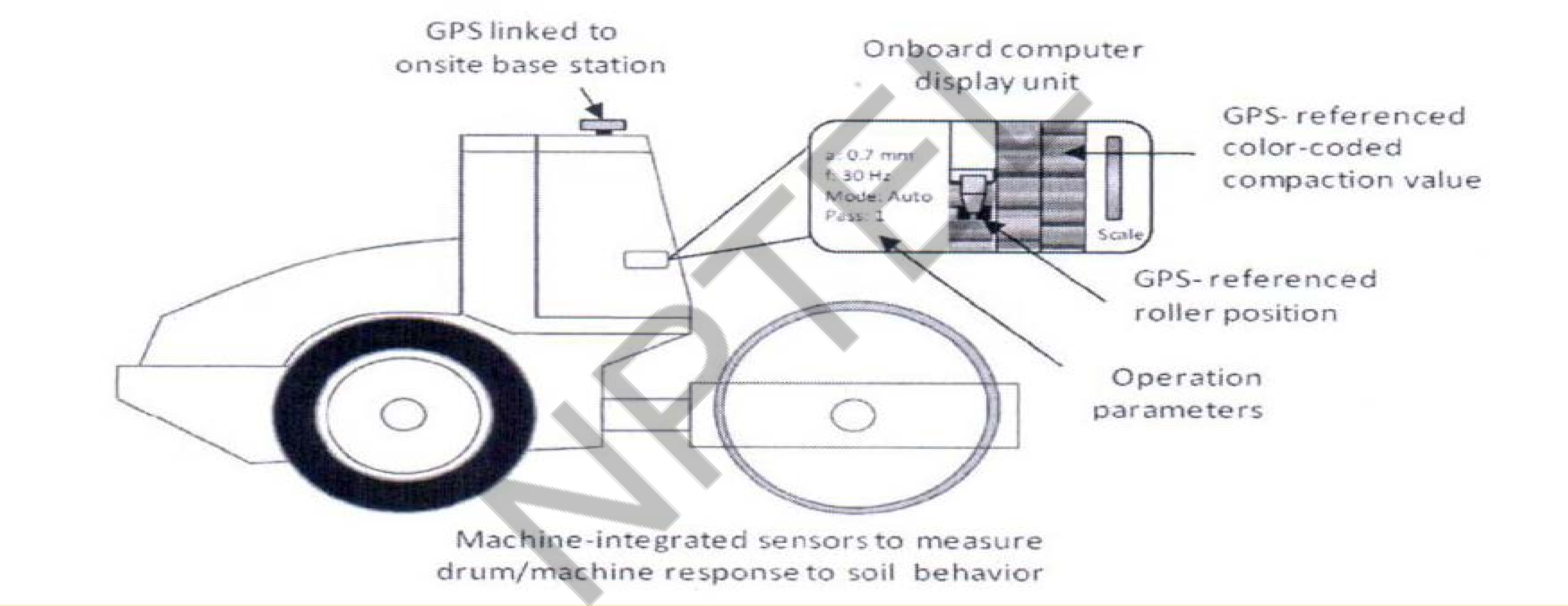
Intelligent Compaction



Basic Concept of Intelligent compaction: Intelligent compaction is a continuous construction technique with quality assurance and control processes incorporated in the construction. This technique includes automatic measurements of geomaterial properties through preinstalled sensors on the machine and adjustment and optimisation of the vibration amplitude, frequency, and/or speed using a feedback control system by the machine operator to achieve uniform compaction and desired target values.

Suitability and application: Same as conventional compaction roller

Advantages and limitations: The IC method has the measurement and feedback system, which helps the operator identify weak spots for further compaction or treatment and QC/QA, avoid over compaction, and reduce the number of passes. The IC method can serve as full coverage of QC/QA and minimize the need for field inspection. Therefore, it can result in more efficient and uniform compaction

Currently the equipment is more expensive than conventional compaction equipment. It requires managing and analyzing a significant amount of data. The method often requires test strips for calibration of target compaction values prior to production compaction

Thank You!!