Unsaturated Soil Mechanics
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Week 03
Lecture - 08
Concept of Water Retention and Soil Water Characteristics-I

Hello all waves in the concept of vapour pressure lowering which can be well understood using Kelvin’s equation.

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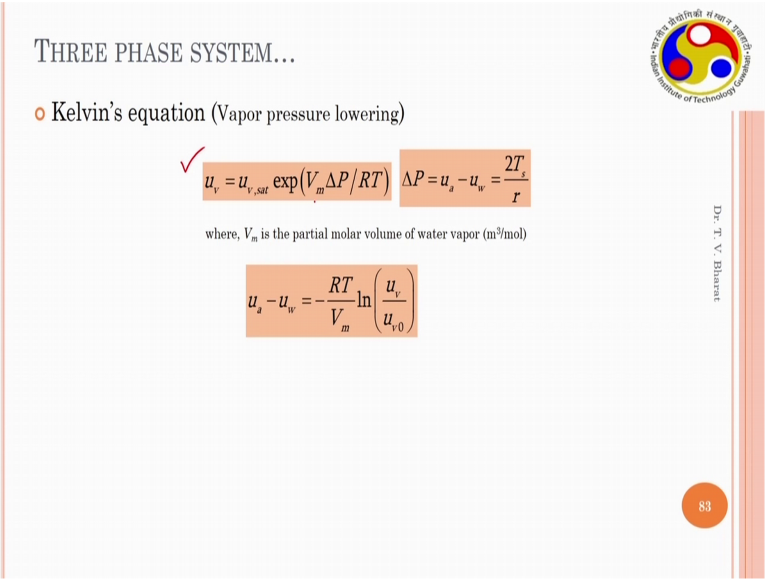

THREE PHASE SYSTEM…

- Kelvin’s equation (Vapor pressure lowering)

$$u_v = u_{v,sat} \exp\left(V_m \Delta P / RT\right) \qquad \Delta P = u_a - u_w = \frac{2T_s}{r}$$

where, V_m is the partial molar volume of water vapor (m³/mol)

$$u_a - u_w = -\frac{RT}{V_m}\ln\left(\frac{u_v}{u_{v0}}\right)$$

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So, Kelvin’s equation a which states that the vapour pressure on a curved surface is equals to the saturated vapor pressure times exponential of partial molar volume of water times change in the pressure across the interface divide by RT.

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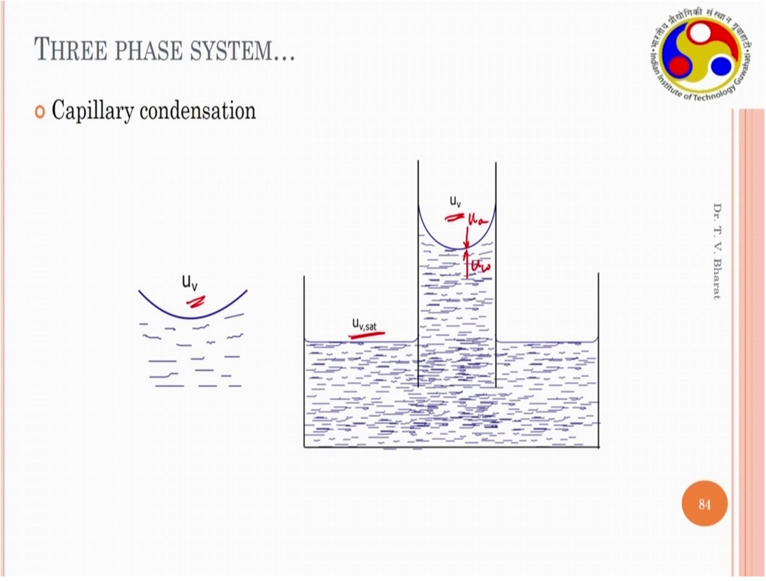

THREE PHASE SYSTEM…

- Capillary condensation

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So, the implication of Kelvin’s equations is that above a curved surface the vapor pressure is fluid. So if you consider a capillary tube immersed in a beaker of water, water rises in order to balance the chemical potential and it assumes a meniscus or curved surface like this depending on the interaction between the capillary tube and the fluid. So, this is a typical example of water in a glass beaker or glass capillary so you have a meniscus like this.

So, the vapour pressure above a curved surface is u v which will be less than the saturated vapour pressure which will be above the flat surface, so this is the implication of Kelvin’s equation. More than that the vapour pressure even though this is less than the saturated vapour pressure water vapour condenses into water and it a accumulates in a capillary tube which we will understand. As there is a pressure drop across the interface, so this is u a atmospheric pressure and this is water pressure. So, there is a pressure drop across the interface because of which there is a change in the vapour pressure.

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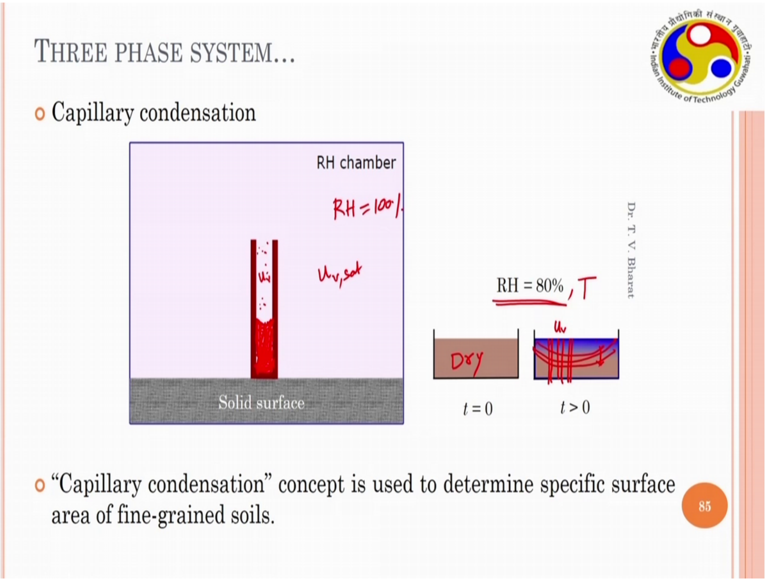

THREE PHASE SYSTEM…

- Capillary condensation

- "Capillary condensation" concept is used to determine specific surface area of fine-grained soils.

Similarly, when there is a capillary tube which causes a lowering of the vapour pressure. So, you have say for example, here you are maintaining RH is equals to 100 percent. So, then you have u v sat here in the ambience, so here the vapour pressure is lower than the saturated vapour pressure u v inside the capillary tube. Even though the vapour pressure inside a capillary tube is lower than saturated vapour pressure, you see that the water accumulates into the capillary tube with time and you see that there is a filling of water in within the tube. So, which fills because number of water molecules that get trapped in this small cavity, so slowly the water level increases within the capillary tube in order to which is nothing but condensation. So, condensation takes place at a vapour pressure which is less than saturated vapour pressure that is implication of Kelvin's equation, this has a very important application are important correspondence to our soil mechanics.

Because, when you take a soil sample which is kept outside this is initially dry which is the oven dried, initially at oven dried state you take a clay powder say a any clay powder or even soil at oven dry state if you take and then place it in the cup and in a atmosphere when you leave it the relative humidity of the atmosphere maybe 80 percent or it could be anything, it may vary usually between 60 to 90 are closed to 100 percentage depending on the location. So, when you have some particular RH and temperature of the ambience, then you would see that there is a accumulation of water at the surface of the soil due to condensation. Because, if you consider force of soil grains has individual capillaries you have number of capillaries attached here which lowers the vapour pressure above this and eventually there is a condensation that takes place at lower vapour pressure which causes accumulation of water at the surface, because of the potential difference from the top surface and the bottom surface there is a diffusion that takes place and water slowly penetrates into the deeper layer of the soil.

So, this happens in any type of soil but clays generally the pore size is very small, so therefore easily the condensation takes place and more water will get accumulate. So, the vapour pressure lowering depends on the capillary size, so here in this particular case Kelvin's equation a simple capillary tube is assumed. Therefore, the pressure drop across the a water interface is 2 T s by r surface tension times 2 by radius of the capillary tube. So, capillary tube diameter or the radius is very important in controlling the vapour pressure and condensation so this is called capillary condensation.

This is a very important concept in soil mechanics because this concept is also utilized in the estimation of specific surface area of fine grained soil such as Carnuts and other clays not expensive clays like Bentonite etcetera. Because, Bentonite generally they have dual porosity system and you have a smaller pore fractions that exist this generally used for only for Carnot clays using adsorption isotherms. So, you take a soil sample and you expose the soil sample to particular temperature and then relative humidity and absorption of. So you would expect that there is a absorption of water molecules around the clay surface and the exchangeable Cations because of the hydration there is a water that accumulates. So, you would see that the adsorption increases with time for a given RH and also it increases the adsorption amount of adsorption also increases with increase in the RH, so using this concept the specific surface area is estimated.

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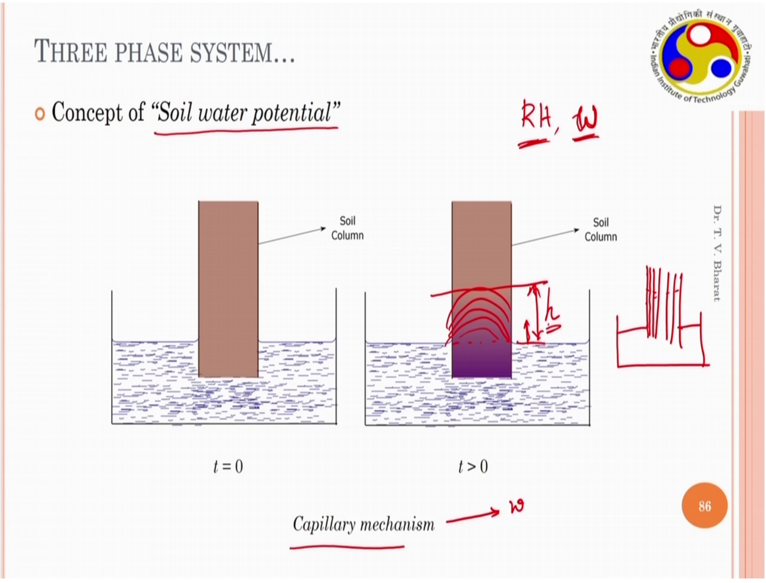

THREE PHASE SYSTEM…

- Concept of *"Soil water potential"*

RH, w

Capillary mechanism → w

As we have seen that there are important state variables such as a relative humidity, when relative humidity is maintained you would see that there is a accumulation of water so the water content of the soil changes. So, these 2 are important state variables relative humidity and water content and also they are dependent on each other, you one can establish a constitutive relationship between these 2 state variables also. However, simply the RH is not alone the controlling factor for the water accumulation or water retention in soil mass, there are other factors that would influence the water retention in soils. So therefore, it is not the RH versus w there are something called soil water potential which is used as a important state variable to relate with the water content.

So for example, if you consider if you immerse a soil column in a water reservoir at time t equal to 0 just immersed in a water reservoir after time t equal to 0, you would expect that the lower portion of the soil mass get saturated and the water content increases within the soil mass even above thus this free surface free water surface. So, above this level also there is a water diffusion that takes place and then the water content increases above this level due to the capillary mechanism. Which is similar to inserting one capillary tube or multiple capillary tubes into soil mass into a water reservoir, therefore there is a rise of water within these capillary tubes which is similar to this.

So therefore, due to the capillary mechanism there is a rise of water into the soil column. So therefore, due to the capillary mechanism there is the rise in water the water content is now related to the capillary mechanism if you have a thin capillary. So, raise is higher if you have larger capillary the raise is smaller. So, the water content depends on here capillary mechanism plays a role on water content of soil mass, the water content also varies with the height of the soil samples from the free water surface. Similarly the soil water potential also gets influenced to due to electro Osmotic mechanism.

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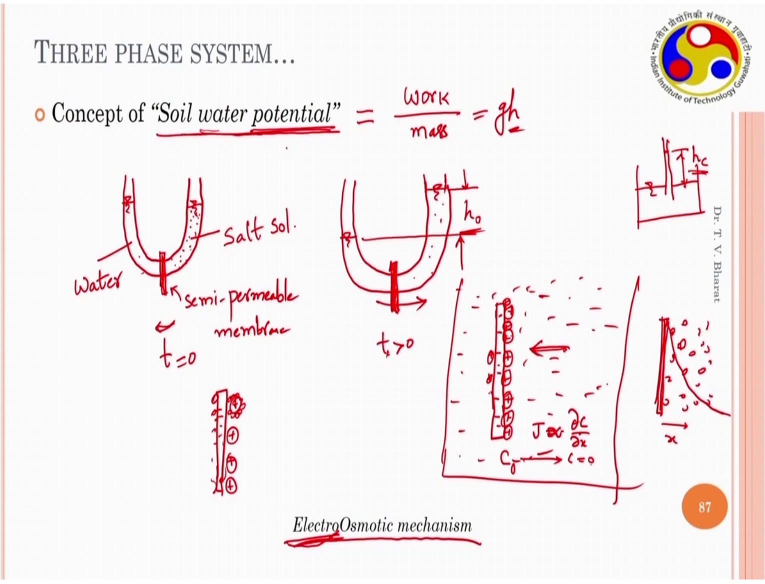

THREE PHASE SYSTEM…

- Concept of "Soil water potential" $= \frac{\text{work}}{\text{mass}} = gh$

ElectroOsmotic mechanism

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87

What is this electro Osmotic mechanism let us understand we have seen that if you have a U shaped tube. So, you take a U shaped glass tube so where you have a semi permeable membrane, a semi permeable membrane which separates a water and a salt solution this is water and this is salt solution. So, you have number of a solute which is added to the solvent, so in this particular case we expect that at equilibrium at this is this is at time t equal to 0. Now at time t equal to t greater than 0 the same system if you brought now so you would see that there is a initial height.

Now, water from this reservoir would move on to the other side to decrease the concentration of the salt in the right hand column. So, there is a head that develops to bring the chemical potential equilibrium which is called a which is the Osmotic head. This is similar to a capillary head we have seen earlier where when a small capillary or thin capillary is immersed in a water reservoir, there is a rise of water in the capillary which is the capillary head similar to the capillary height are raised. You would see a Osmotic head that is developed in when the solute is present in this column and there is a semi permeable membrane which filters the solute to move from right hand side to the left hand side.

So, in this case water moves from left to right to equilibrate the chemical potential, if the semi permeable membrane was not present diffusion of the solute takes place from right to left in order to balance the chemical potential. So, this is a relevant to our clay system where we have a clay particle which is negatively charged, there is a negative charge in the clay surface because of isomorphous substitution the it attracts positive ions on the surface and so there are so many exchange you will cations that are present which are attracted in from the environment and kept it on the surface of course on the this side also.

So, now when this clay particle is exposed to the water you would see that then when the water is available or if this clay particle is taken and put it in a beaker of water, we expect that these ions should diffuse from this clay particle surface to the bulk solution because, concentration of these ions is very high here the concentration is c not and here the concentration is 0. So therefore there is a concentration gradient exist a from the surface to the bulk solution, therefore there should be a flux diffusion flux that should take place to equilibrate the concentration of these ions throughout this beaker of water.

However clay particles are negatively charged and they would not allow this ions to go away from the surface and this clay particle negative charge acts as a semi permeable membrane in this particular case. So therefore, there is a Osmotic flow of water takes place from the bulk solution towards the clay surface, so which causes which causes a diffusion of ions distributed in this particular manner. Here the concentration decreases from the particle surface towards the bulk solution in this particular manner.

So, you have you have a denser densely packed exchangeable ion close to the surface and the concentration decreases depletes with increase in the distance from the clay surface. So, this mechanism is just similar to the osmosis that takes place due to the semi permeable membrane. So therefore, Osmotic mechanism also takes place in clays especially expansive clays, where you have a (Refer Time: 14:47) more led mineral where one more led mineral has a it has a very high surface area and very high cation exchange capacity therefore it exhibits the Osmotic mechanism very well. In case of

(Refer Time: 15:00) at the specific surface area is low and cation exchange capacity is very low the Osmotic mechanism is not that dominate.

So, because of the Osmotic mechanism also there is a potential decrease, there is a potential decrease because of the presence of these cations exchangeable cations around the clay surface and because of that there is a change in the potential this Osmotic head or cosmetic potential is also included in soil water potential. Clay particle is just now I said that the clay particle is negatively charged and it has positive ions around the surface, when the water molecules are available such as keeping a clay sample oven dried clay sample in atmosphere. So, then it attracts the positive ions at the surface it attracts the water molecules on to the surface, so there is a hydration of exchangeable cations and hydration of clay surface that takes place.

So, because of this is a Osmotic electro this is a electrostatic forces that available around the clay particle surface, therefore there is a additional potential due to adsorption of water molecules around the clay surface and water molecules, so therefore combination of these 2 is called a electro Osmotic mechanism. So, initially this is the capillary mechanism and electro Osmotic mechanism all these mechanisms are included in soil water potential, soil water potential is nothing but it is the potential can be defined as the amount of work done or potential energy stored per unit mass in bringing same mass m from reference to the point in question.

So, potential is work done per unit mass. So, this is a this is simply gh or simply presented with h. So, in the in case of a capillary raise, there is a capillary rise of head h this is a soil water potential it is called and in this particular case this is the h c, so soil water potential includes all of them and which is synonym to total suction soil water potential is synonym to total suction.

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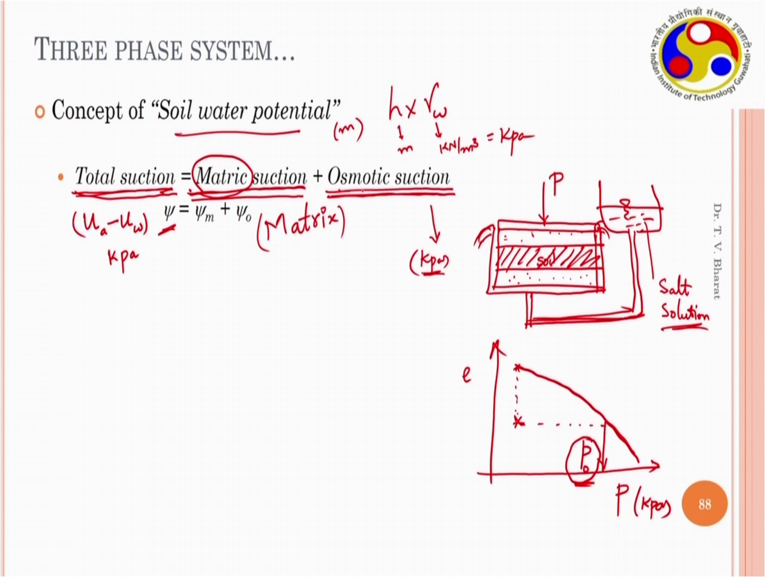

THREE PHASE SYSTEM…

- Concept of "*Soil water potential*"
  - *Total suction* = *Matric suction* + *Osmotic suction*

$\psi = \psi_m + \psi_o$

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The total suction is nothing but a so u a minus u w, so this is the pressure drop nothing but total suction which has units of kilopascal. So, the potential has units of joule per mass kg, but the total suction has units of kilo Pascal soil water potential has units of meter because which is a header.

So, soil water potential can be converted to total suction by multiplying with gamma w so this is a meter and this is the kilo Newton per meter cube that gives kilo Newton per meter square or kilopascal. So, the total suction includes matric suction, the matric suction is consists of the capillary mechanism and os electro Osmotic mechanism. So, the matric suction component includes all of them, matric comes from the matrix due to the soil matrix there is a potential drop or potential change that is indicated with matric suction and Osmotic suction is due to the presence of salts in pour water.

So, this Osmotic suction need to be clearly distinguished from Osmotic mechanism that is consisted in matric suction. So, generally the clay particles the exchangeable ions the exchangeble cations that are present that causes that provides Osmotic mechanism, that provides some suction which is included in the matric suction. But additional salts if you add salt solution to the pore water then that is a contribution to the Osmotic suction. So, this contribution is can be explained if you consider a orometer, where you have soil sample soil and you have a porous stone above and bottom you have a reservoir where the whole sample can be merged in which can be connected to a water reservoir or a burette stand.

So, such a head is maintained there will be a flow of water flow takes place and you apply some load on this. So, when you consolidate the soil sample by increasing the pressure, so this is a initial void ratio and you would see that it consolidate in this manner. If this is a normally consolidated soil sample are initially the sample is in a virgin when it follows a virgin compression line. So, this is how the soil consolidates if you take a duplicate sample prepared now this is a initial void ratio. Now if I change the solution this water with some salt solution, now I put salt solution instead of water under the same pressure you would see that the void ratio drops so this is the new void ratio.

So, this void ratio you can obtain by consolidation when you have water by applying a pressure of this much. So, this is a pressure so therefore the same void ratio can be achieved by passing through salt solution that is equivalent to this pressure. So, addition of salt solution is equivalent to this much of application of this much pressure on a soil, where the pore system consists of a only water so this is called Osmotic pressure or similar to the your Osmotic suction. Because, there is a there is a change in the potential because of that there is a pressure here matric suction is kilo Pascal and this is also kilopascal.

So, this is Osmotic suction kilo Pascal this should be distinguished clearly from the Osmotic mechanism that is existing in matric suction. So, the total suction a Osmotic suction is important not only in a unsaturated soils, which is significantly influencing the soil behavior in saturated condition as well. But matric suction exists only in unsaturated state Osmotic section exist in both the conditions whether the soil is saturated or unsaturated, but matric suction exists only when the soil is unsaturated. So, this total suction versus the water content is a important constitutive relationship which is called soil water characteristic curve or also called water retention curve.

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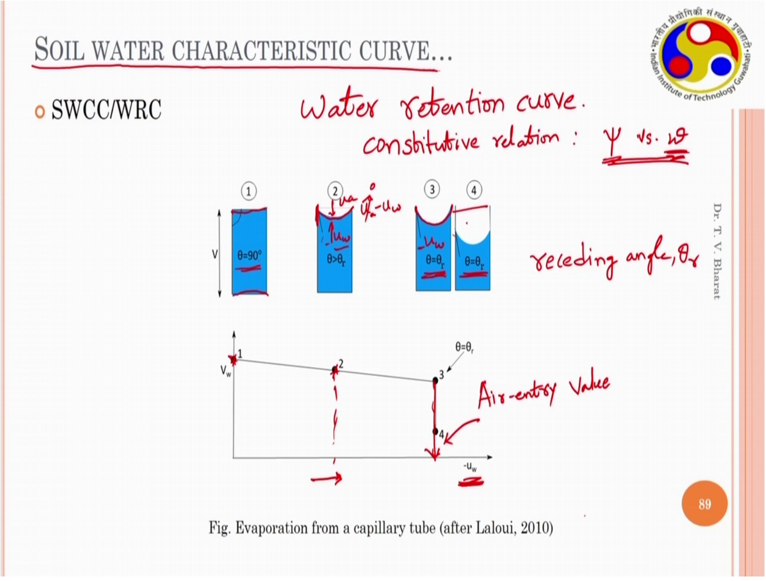

SOIL WATER CHARACTERISTIC CURVE…

- SWCC/WRC

Water retention curve.

constitutive relation : ψ vs. w

receding angle, θ_r

Air-entry Value

Fig. Evaporation from a capillary tube (after Laloui, 2010)

Water retention curve is a terminology used in water resources and soil chemistry there is a agriculture ect, soil physics and soil chemistry there is a in agriculture agricultural science. So, where the soil water characteristic curve is a terminology used in soil mechanics geotechnical engineering. So, the soil water characteristic or water retention curve is a important constitute relationship of unsaturated soils, which is a psi versus water content water content here I am writing gravimetric.

But generally we use volumetric water content I will explain why in a bit very soon, which forms a very important constitutive relationship unsaturated soil mechanics for understanding the flow behavior or for understanding the shear strength of the soils or volume change etc, this constitution relationship is a very important this is the central to the entire soil mechanics. So, let us try to understand how this suction and water content are related. If you consider the simple capillary the single capillary tube initially the water may be completely filled or slightly it may have some meniscus due to the interaction between the water molecules and the capillary tube. So, the adhesive forces would dictate what is a angle that would that it would have it may 90 degrees or it may be less than that.

So, when there is a continuous evaporation of water that is taking place, so as there is a good interaction between the water molecules of the pore fluid and the wall surface a good adhesive forces that exist, so water cannot leave even though there is a evaporation that takes place or the energy is applied. So, it changes it is curvature of the meniscus so that some water can be taken out. So, without losing the interaction between the wall surface and the water phase it loses some water molecules some water, so which is a negligible. So, there is a point one initial state and there is a 0.2 that is a state here. So further if you wait for some more time or further energy is given, so the energy that is given is indicated with the suction there is a negative pore water. As we have seen earlier that if you consider soil column immersed in a water reservoir you would see that there is a rise of water or water content is increasing, but the water pressure within the soil mass above this level is negative, so water pressure is negative this is less than the atmospheric pressure.

So therefore, there is a negative pressure due to the potential drop, so therefore this is the potential that is increased. So, the evaporation is taking place because of the it is as like a suction you are taking a thin straw and keeping it in a juice glass of juice and sucking you are applying energy and then sucking it. When you are sucking this is what is happening water is lost because of the sucking action that is this is a suction pressure or simply the suction negative pore water pressure, which creates a negative pore water pressure initially. There is no water pressure inside here you would see that there is a pressure that is build up because, u a minus u w if you see here there is a negative pressure that a that is developed here, this is the atmospheric pressure this is water pressure water pressure is lower than atmospheric pressure. If you consider gas pressure the water pressure is negative that is what is indicated here if this is 0 then the minus u w is plotted here.

So, the new w is negative here within the water column, so if you increase the suction further or more water is lost. So, then there is a change of contact angle from earlier angle to the new angle and further water is lost when the curvature of the meniscus increases, there is more water pressure inside more negative pressure in within the column so water pressure here is increasing. So, here this is a water pressure corresponding to second figure and this is a water pressure corresponding to third figure and beyond that with a small change in the suction you would see that the with the same angle the water drops drastically and this particular point is called receding angle theta r.

So therefore, one water is slowly lost from the column of water due to the evaporation. You would see that there is a built up of negative pressure within the water because, there is a concave meniscus that is developed and because of that there is a negative pressure and more water is lost the u w here increases or more negative pressure that is built up within the system within the soil within the water and beyond that the water simply decreases by decreasing it is level with in the capillary.

So, this particular point is also called air entry value, air entry value or air entry suction the suction corresponding to this particular point is called air entry value or air entry suction. So, because until then the air into the enter into the system but here air has entered. So, we have air here so you have air here so this is called a air entry value.

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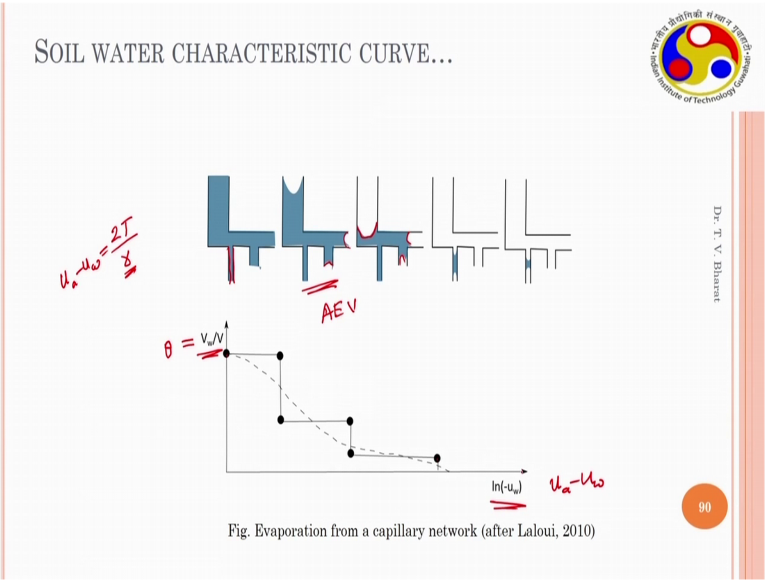

SOIL WATER CHARACTERISTIC CURVE...

Fig. Evaporation from a capillary network (after Laloui, 2010)

So, that was a most idealized system where you have a single capillary, but when it comes to the soils you have a network of pores which can be idealized as a capillary network like this. So, you have one capillary which is larger capillary here so you have a you have thick capillary here and there is a thin capillary here, there is a thickest and this is a thinnest capillary and in between you have these 2 capillaries. If you take such a system where the water is completely present in the capillary, so initially the entire capillary network is completely full of water.

So therefore, here we plotted with respect to volume of water earlier and again we are plotting with respect to volume of water per total volume of pore space. If you plot and which is we hear x axis is plotted with respect to the suction are the negative pore water pressure in log scale, then you would see that initially the suction would be 0 because this is a flat. So, the this is flat so u a is equal to u w or u a minus u w is cos 90 is 0, so u a is equal to u w or u a minus u w is 0 so the suction is 0.

So however, that particular point cannot be pointed because it is a log scale, but a small value if you consider and corresponding value is equal to 1 this cannot this could be 1 only at you have u w is u a or u a minus u w is 0. But he because it is a log scale that cannot be represented here this cannot be1 this could be small value here. So, when there is a evaporation that is taking place because the we have seen that the pressure drop across a across a water air water interface is inversely proportional to the radius of the capillary tube. So, pressure drop in the larger capillary tube or the thicker capillary tube would be smaller, therefore water will be lost first from the larger capillary tube and followed by this tube and followed by this tube.

So, as they approach the receding angles corresponding the receding angles the water beyond that it drops and this is the point this particular point say water drops beyond this particular point. So, this is this particular point corresponding to the air entry air entry value and beyond that the water content decreases drastically and when or after sometime you would see that all other capillary tubes would be completely empty, but thinnest capillary still contains some water so that water is remaining here and even some more suction is applied or some more negative pore water pressure is developed then also you have small water.

So, this is the relationship that is shown between water content or volume of water park total volume, so this is nothing but theta. So, this volume of water part total volume is theta with respect to the u a minus u w or if you consider gas pressure, then it is simply minus u w in log scale this is considered this is a unique relationship for a given material.

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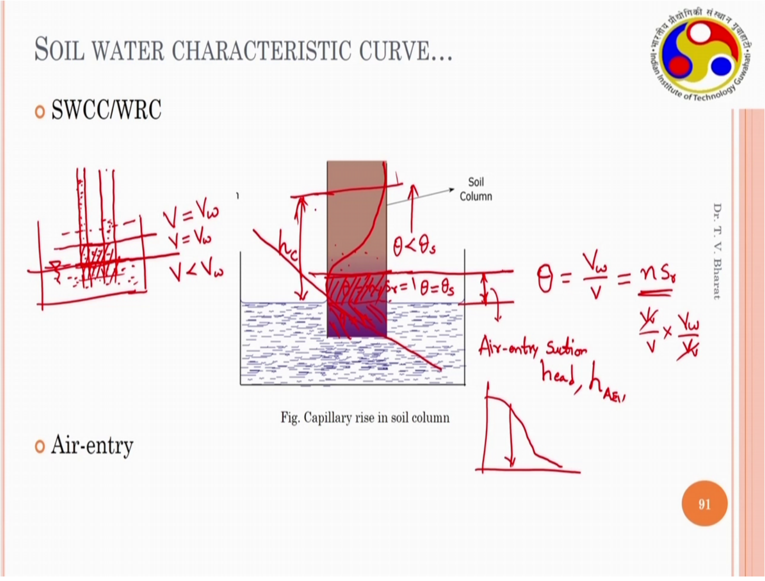

SOIL WATER CHARACTERISTIC CURVE…

- SWCC/WRC
- Air-entry

Fig. Capillary rise in soil column

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91

So, if you consider a soil column in a water reservoir, so then you would see that there is a rise of water or the water content of the soil mass increases with time water content decreases with depth. So, you would see that there is a up to here the water content within the soil mass will be is equals to the saturated water content. So, here in case if you consider volumetric water and this volume of water by total volume. So, this is a nothing but porosity times porosity is volume of voids by total volume times S r is S r is volume of water by volume of voids. So, this is n S r so when degree of saturation is 1 that is fully saturated case this equals to porosity and interestingly beyond that also up to some particular depth the water content is equals to the porosity or S r is equals to 1 degree of saturation is equals to one up to second depth

Beyond that the water content decreases from theta, so let us understand why this particular soil mass can be idealized as number of capillary tubes. So, this is 1 capillary tube this is a bigger capillary tube this is another capillary tube, so this is a thinnest capillary tube this is a widest capillary tube and this is in between. So, if this is immersed in a water reservoir, so then you would see that the capillary raise would be smallest in this particular capillary tube and highest in the thinnest 1 you would see that capillary rise is would be highest in the thinnest capillary tube and this would be medium.

So, this the condition when you have a 3 capillary tubes together when they are immersed in water reservoir so this is a condition. So here if you see at this particular section at the free water surface level you would see that the water content within this pore space or the capillary tubes water content is a completely full. So, this is fully saturated capillary tubes are fully saturated at this particular case. So, if you consider volume of the capillary tubes at this particular section is equals to volume of water, volume of this capillary tube at this particular section is equal to volume of water.

If you ignore the surface of the capillary tubes or walls of the capillary tubes, so above this up to particular depth particular level at this particular level where the capillary rise into the larger pore larger capillary tube. Here also it is the same volume of the capillaries equals to the volume of water, beyond that if you consider any section the volume is less than the volume of water. So, up to this particular depth the water content remains same as below this level also below this level also, below the free surface also water content how much you have same water content you have here.

So, similarly here also the water content in this particular zone will be same as the water current in this particular zone. So therefore, this is called air entry suction head this is called air entry suction head, air entry suction head is the point corresponding to the suction where air enters into the largest pores of the soil sample. So, here if you consist if you consider this whole soil mass consists of only 3 capillary tubes, so then the air enters into the largest capillary tube here so that is air entry. So, here this air entry head which can be h AEV is equal to is nothing but the suction corresponding to suction corresponding to the soil water characteristic on a which is on the saltwater characteristic of.

The suction corresponding to which the air enters into the largest pore of the soil system is called air entry section, so beyond that thinnest pore still have some water. So, water content here is less than theta s here theta is equals to theta s. So, if you plot the water content versus the suction head because, the negative pore water pressure the pore water pressure within the soil mass if you see that is positive downward and the negative upward. So, with increase in the depth the water content if you see water content depletes like this. So, at some particular depth beyond particular depth this is completely dry water content is 0, so this particular height is capillary height capillary rise h c in the soil mass.

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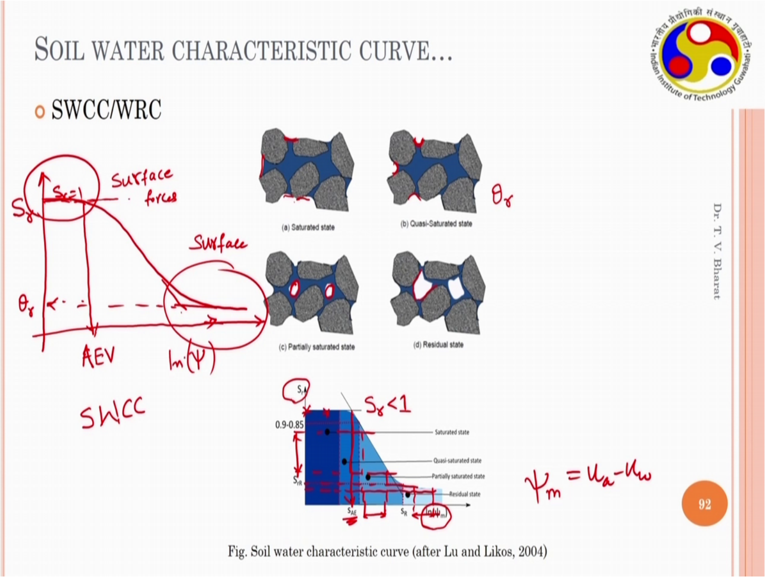

SOIL WATER CHARACTERISTIC CURVE…

- SWCC/WRC

Fig. Soil water characteristic curve (after Lu and Likos, 2004)

So, if you consider the soil mass a one pore structure, if you consider at saturated this saturated state this is the condition of the water phase within the soil mass where you have nearly flat meniscus. So, the point corresponds to degree of saturation versus suction is here as the suction, the here it is written matric suction matric suction here is nothing but u a minus u w. So, the matric suction that corresponding matric suction is a close to 0, but this is log scale so this cannot be 0 this is very small value, here it is a small value as a suction increases to one particular value.

So, the contact angle changes contact angle will become receding angle then it starts decreasing water content decreases gradually because, air enters into the system this is the air this is the air you have air pockets within the soil system. So therefore, beyond the air entry value the water content decreases very fast this is the capillary zone depletes very fast so and again there is another inflection point beyond which the water exists as a thin film around the clay surface. So, water exists in a adsorbed state so when the water is in a adsorbed state for the applied suction the amount of water the decreases is very small.

So, for as change in suction in this particular region the change in water content is significantly high. So, this much of water content decreases this much of water content decreases. In this particular zone for the same change in the suction the change in water content is significantly small water exist in adsorbed state in this particular case. So, suction corresponding to this particular value where the degree of saturation decreases degree of saturation S r is less than 1, the point where degree of saturation decreases from 1 or is less than one is called air entry and this particular, so mi will re draw this for clarity.

This is degree of saturation this is a matric suction in log scale, assume that the Osmotic suction does not have any role here to play, so then so this is the typical soil water characteristic curve. So, at this particular point the degree of saturation is less than 1 this is S r equals to 1. So, this particular point the S r is slightly less than 1 therefore this is air entry value this is AEV air intersection. So, this particular point is called residual water content this water content sorry, this particular water content is called residual water content. So, beyond the residual water content the decrease in the water content with increase in the suction is negligible.

So, this is a typical soil water characteristic curve for soils, so here the surface forces would predominantly play role because surface forces like, if you take consider Bentonite which has a high percentage of monumental content. So, then the negative charge on the surface would play a lot of rule in arresting any water movement water to take out water to leave from the soil system. So therefore, the receding angle again should depend on the surface forces here and here again after the residual state are within the residuals state.

The soil water characteristics of depends on the surface forces here also, surface forces predominantly this is because water exists as a thin film adsorbed around the clay particles and here also the surface forces predominantly exist. So, in between you have a capillary range capillary zone where the cap due to the capillary action the water increases or decreases depending on whether the section is increased or decreased these are typical soil water characteristic curve.

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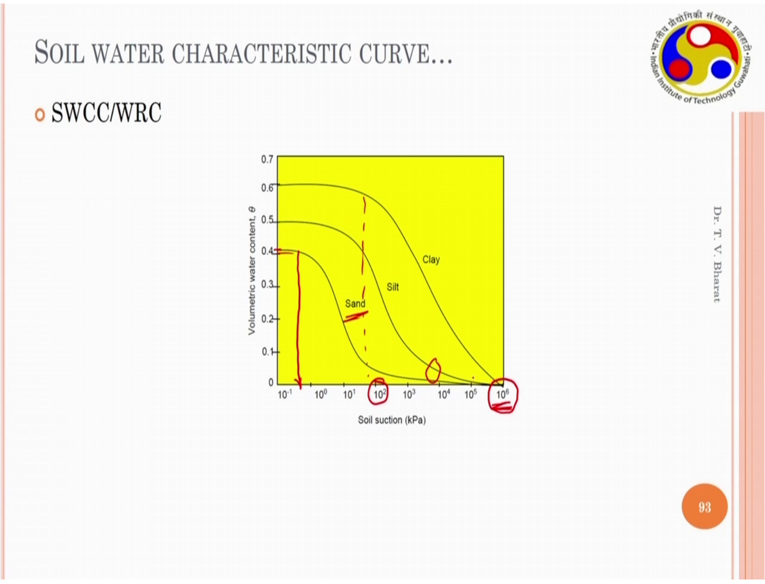

SOIL WATER CHARACTERISTIC CURVE…

- SWCC/WRC

For different soils for sand this is a initial water content represented with volumetric water content, it has a very small air entry the air entry suction is very small for this particular sand hardly less than 1 kilo Pascal or usually it will be around 2 kilo Pascal are also and then within the section of about 100 kilo Pascal it reached to the residual state.

In case of silt the air entry value is slightly higher more than 10 kilo Pascal and residual nearly at 1000 kilo Pascal or more than that it soil reaches the residual state. In case of clays the air entry values are used very high nearly 100 kilo Pascal, sometimes it could be more than 1000 kilo Pascal also depending on the clay type. If you take Bentanite compacted at very high densities, you would see that the air entry values are more than 1000 kilopascals and the residual state is reached nearly at 10 power 6 kilo Pascal or 1000 mega Pascal’s such a huge section is required to take out the water from the soil clay.

So, from thermodynamic concepts it is observed that at 10 power 6 kilo Pascal suction clay particles the water content is closed to 0. This is the theoretical value so generally when we estimate the suction values we see that the water contents are closed to 0.1 at a 10 power 5 kilo Pascal also for Bentonites or clays expensive clays.

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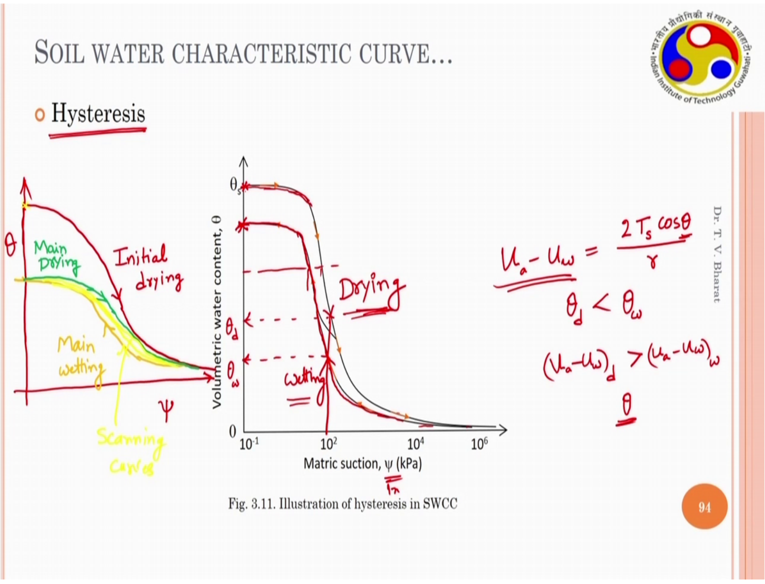

SOIL WATER CHARACTERISTIC CURVE…

- Hysteresis

$u_a - u_w = \frac{2T_s\cos\theta}{r}$

$\theta_d < \theta_w$

$(u_a - u_w)_d > (u_a - u_w)_w$

θ

Fig. 3.11. Illustration of hysteresis in SWCC

We just observe that the soil water characteristic curve is a unique relationship for a given type of soil and a lot of mechanisms would play a role, such as a capillary mechanism electro Osmotic mechanism that play role in matric suction and in a Osmotic suction you have solute presence because the solute presence you have Osmotic suction. So, put together you have a total suction the total suction is uniquely related to water content of the soil.

However this has been observed that the soil water characteristic curve depends on the path, whether soil is wetted or soil is dried it follows different path. For example, you consider soil which is completely saturated see you take care of slurry, you take slurry soil slurry by mixing the soil clay powder with water slightly higher than the equilibrium water content. Then you make a slurry of soil or sand if you take the needle it is completely submerged in this particular case. So, suction is equals to 0 or when you do your new plot in terms of logarithmic scale this is log scale this is log scale, so the suction is very small and corresponding to theta s saturated water content.

So, when the suction is increased or evaporation is allowed then the water content decreases, there is a decrease in the water content with increase in the suction and once it reaches the air entry suction water content decreases gradually and then it reaches the residual state this is drying. The same soil when it is dried now slowly wet it by allowing the water to go in then it follows this particular path, this is wetting path and which increases the water content increases and it reaches this particular water content at when the suction is close to 0 or very small value this is the water content.

So, the drying path is different from wetting path in soils, in all different soils sands clays silts etcetera you see that the draying path always differs from wetting path. For a given suction value the water content on drying path is higher than the wetting path, this is a water content on wetting path this is water content on drying path at the same suction value. So, it exhibits something called hysteresis, so soil water characteristic curve the soil water characteristic curve of soil exhibits hysteresis drying SWCC above the wetting curve, when it is plotted matric suction in the x axis and volumetric water content on y axis.

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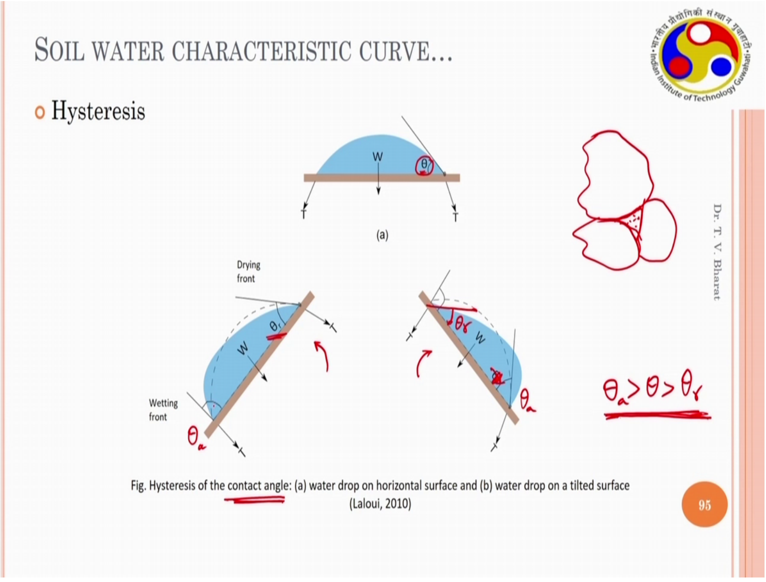

SOIL WATER CHARACTERISTIC CURVE…

- Hysteresis

Fig. Hysteresis of the contact angle: (a) water drop on horizontal surface and (b) water drop on a tilted surface (Laloui, 2010)

There are several mechanisms that would play role in understanding the hysteresis. So, this is one hysteresis mechanism that is contact angle hysteresis which is called a contact angle hysteresis. If you consider water droplet on a surface smooth surface so it assumes theta at equilibrium this is the contact angle that is at equilibrium it is what is exhibited. So, when you slowly start tilting the surface so this surface is slowly tilted, these tilt is exaggerated here, but assume that slight tilt is made. So, then this is the leading surface and this is trailing one. So, at leading surface the contact angle increases and at the trailing surface the contact angle decreases.

So, the contact angle at the trailing surface when it reaches the receding contact angle then it starts flipping from the surface. So, until it reaches the receding angle the water droplets adjust it is contact angle at the leading and trailing surfaces to maintain to maintain contact with the surface and not to slip it adjust it is contact angle at the leading and trailing surfaces. So, when it reaches the trailing value reaches the contact angle trailing surface reaches the receding value, the water slips similarly this is tilted on the other side so this is theta r so.

Therefore between the contact angle at the leading surface and contact angle at the trailing surface. So the for example this is theta a this is theta a between theta a and theta r, there are so many number of contact angles that can exist. So, depending on when you consider a pore geometry or pore structure there is one particle there is another particle there is another particle. So, this is a pore geometry so at this surface whatever the water you have this water you have this, water can assume different contact angles depending on the tilt direction etcetera the tilt angle etcetera. Based on the tilt angle it can have different contact angles contact angle need not be fixed, contact angle from point to point within the soil mass can change which could be in between the contact angle at leading surface and contact angle at the trailing surface in between it can it can have.

So therefore, it can have empty number of contact angles therefore contact angle at the drying will be smaller and contact angle at the wetting front would be higher. So, when the contact angle is the pressure drop the pressure drop across of air water interface in a capillary tube can be written as 2T s cos theta by r. Contact angle and trailing surface is drying that would be drying is smaller than wetting. So therefore the u a minus u w is higher for a same water content, for the same water content the drying suction value is higher. So, u a minus u w drying is higher than u a minus u w wetting for the same water content.

So, the contact angle hysteresis would help in understanding why the draying SWCC value is higher than or above the wetting SWCC. So, there is another mechanism which is called ink bottle hysteresis ink bottle analogy could be also used to understand hysteresis mechanism in soil soils. So, when you take a ink piller this is ink piller and this is a ink bottle where you have the ink up to this level.

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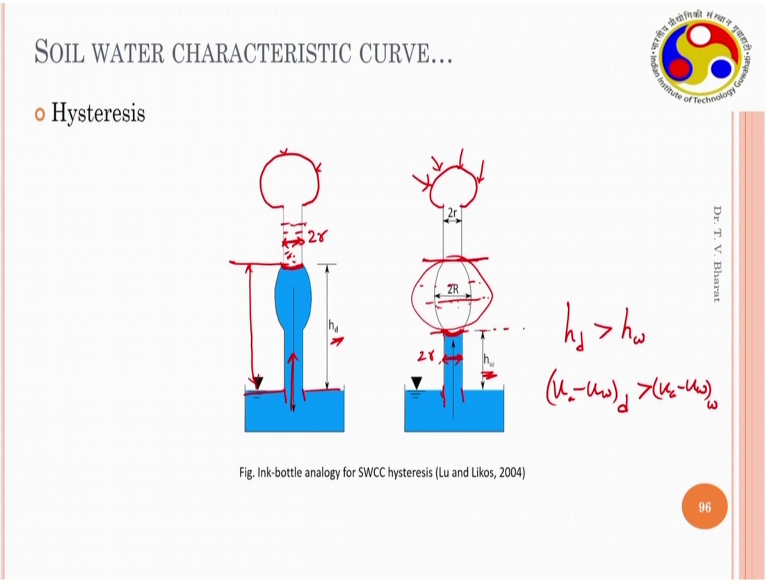

SOIL WATER CHARACTERISTIC CURVE…

- Hysteresis

$h_d > h_w$

$(u_a-u_w)_d > (u_a-u_w)_w$

Fig. Ink-bottle analogy for SWCC hysteresis (Lu and Likos, 2004)

96

So, when the ink bottle is immersed in the reservoir and here create suction by pressing this before putting inside you press it and then keep it inside. Then due to the suction it raises and it rises up to certain value when the pressure is released with stucks to one particular value and then when it is allowed to drain out you would see that it drain outs up to this level here. There is a pressure drop because of this the water the ink stops to flow when it reaches this level. On the other hand when ink piller is when you apply a suction on ink piller and then immerse it in a immerse it in the reservoir, then allow the water to go in then before it reaches this value when you allow to stop it reaches up to here and then drains out and then it reaches equilibrium up to here.

At equilibrium the ink you would see in this particular case is only up to here and beyond that it does not go unless until you give additional suction to cross this particular pore larger pore. So, if the ink is allowed to come up to this level and then allowed to drain, so then at equilibrium it stops here. So, this is the amount of water that exist within the pore you do not allow to come to up to this level, but allow somewhere below this and leave it then it assumes the position here it comes to equilibrium up to here. So, this is a total head h w here. So, h d is more than h w or u a minus u w drying is more than u a minus u w wetting for the same pore geometry.

So, here the pore geometry is same as here, but however pore geometry here if you say this is 2 r this is also 2 r. So, because of this non homogeneous pore structure that may exist within the soil system you may see that the soil water characteristic curve follows hysteresis, it does not the draying path is different from wetting path. So, it is it exhibits typical this particular behavior, so it can it can also be seen the scanning curves. For example, if it is plotted with the theta as y axis and suction has x axis so you take soil sample at slurry state and then when you dry it follows this particular path which is called initial drying.

At this particular point if you start saturating it follows a different path and it reaches this particular point this path is called main wetting. Now at this particular point when you dry it again it follows the different path, so this particular thing this particular path is called a main drying. So, in between main drying and main wetting there are infinite number of scanning curves there are infinite number of scanning curves, so it may ink this follows a different path this is another path so there is there are infinite number of scanning curves.

This is a typical hysteresis behavior exhibited by soils here, so apart from these mechanisms when you have expansive soils so you have when the drying and wetting takes place because of the changes in the volume also. Volume changes that take place when you allow the soil to dry it from the slurry state, there are electrostatic force such as Van der Waals forces etcetera that will cause and particles will come very close to each other and they bind and it becomes very hard when you allow it to wet again it will not come to the original position the water content decreases.

Definitely because of this electrostatic forces present in a expansive clays, so the hysteresis behavior is very significant prominent for sand and other simple soils also other normal coarse grained soil also you would see hysteresis because of these mechanisms.

Thank you.