Soil Mechanics
Prof. B.V.S. Viswanathan
Department of Civil Engineering
Indian Institute of Technology, Bombay
Lecture – 19
Effective Stress-I I I

Welcome to the third lecture on effective stress. In the previous class we have discussed about the effective stress concept for saturated soils and partially saturated soils. We also discussed about effect of the fluctuations of water table on the effective stress. Then we also introduced another definition of pore water pressure that is neutral stress. In this lecture we will understand the situation which is above the water table. As you all know depending upon the climatic condition and size of a particular soil or pore spaces of a particular soil, the soil which is above the water table can also remain in saturation or in partially saturation. That means a coarse dense soil can be partially saturated above the water table or a fine grain soil even if it is such a meter above the water table, it can remain in a completely saturated condition. So this particular behavior is called capillarity. So this we will be discussing in this lecture. This is an effective stress III.

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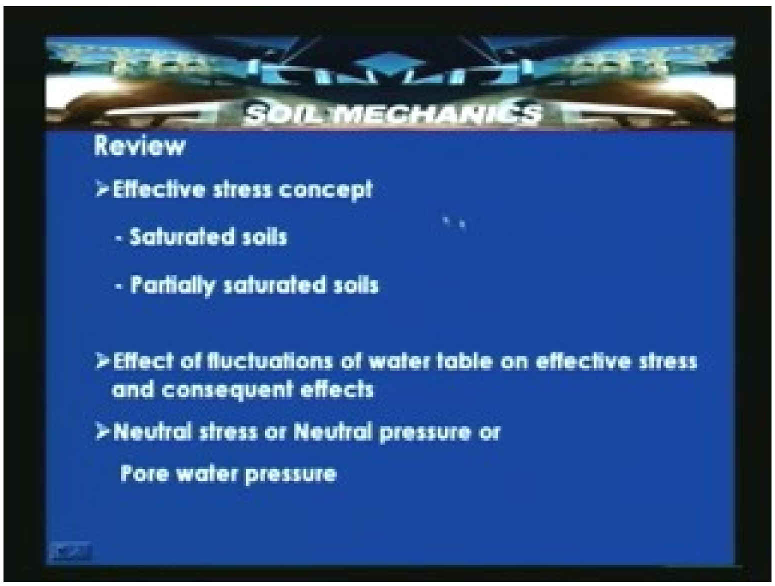

So in the previous class we have discussed about the effective stress concept and for saturated soil and partially saturated soils and effect of fluctuations of water table on effective stress and consequent effects. Also neutral stress or neutral pressure or pore water pressure difference we have understood. And why the effective stress is called effective and why it is very important in geotechnical engineering also we have discussed. So in the beginning of this effective stress concept we have defined the ground water table. So let us look the definition of ground water table once again.

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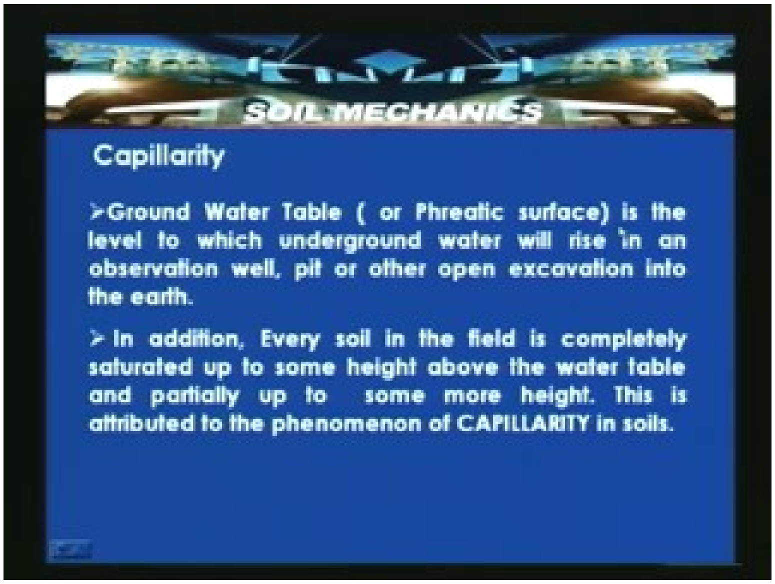

Ground water table or phreatic surface is the level to which the underground water will rise in an observation well, pit or other open excavation into the earth. So in addition every soil in the field is completely saturated up to some height above the water table and partially up to some more height. So we are going to discuss the reasons behind this particular behavior in this class.

So this particular behaviour is attributed to a phenomenon called capillarity of soils. So this particular behaviour of soils remaining saturated even above the water table is called or attributed to capillarity of soils. So capillarity arises from a fluid property known as surface tension which is a phenomenon that occurs at the interface between different materials. Like in case of soils, what we have is the water, air and a mineral grain that is the inner walls of mineral grain surfaces will act as some boundaries for the water to rise above the ground water table. So as long as the raising water remaining in contact with ground water table, then it tries to rise above the ground water table. This depends upon the climatic conditions and the gradation or a particle sizes or a pore spaces of the soil mass.

So for soils surface of water, mineral grains and air are the three different materials which are required to be considered. So as you all know the definition of surface tension that is caused by each portion of the liquid surface exerting tension due to the molecular attraction. Because it has got attraction towards other material which is adjustant to it and adjacent portion of surface or on objects that are in contact with the liquid surface. So this is something like property of fluid which is interacting with different materials. In the case of soil it is the mineral grains, air and water.

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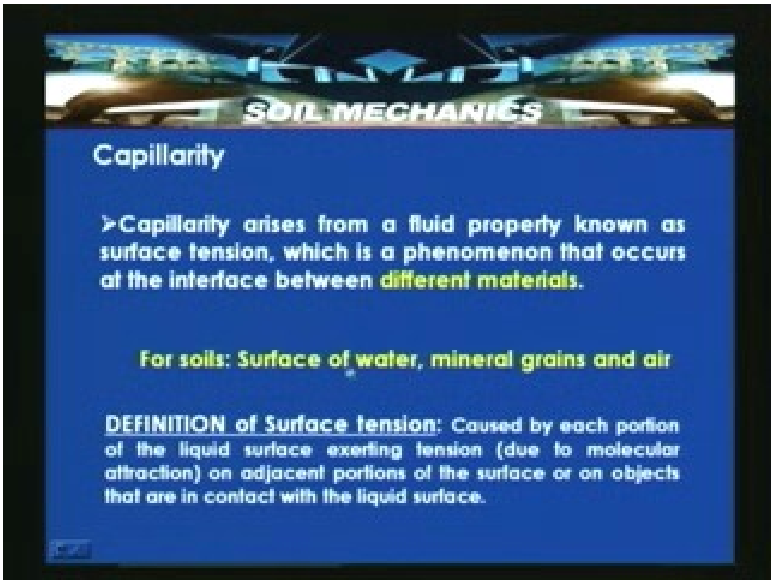

The phenomenon in which water rises above the ground water table against the pull of gravity but is in contact with water table as its source is referred to as capillary rise. The rate of capillary rise is also defined as capillary conductivity. The rate at which this capillarity raise occurs is called capillary conductivity. So water is sucked up in to the pores of the soil mass in this zone on account of the surface tension of water, a manifestation which is referred as a capillary phenomenon.

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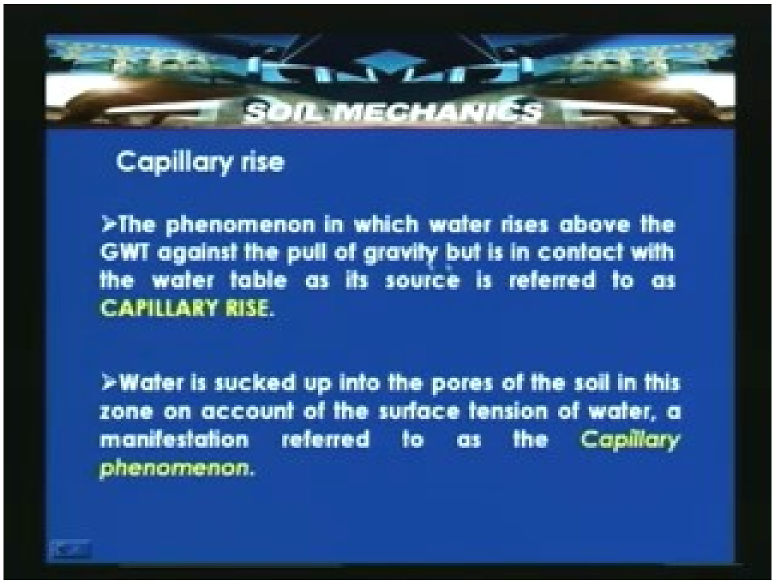

Because of this molecular attraction between materials like inner walls of grains and water and air interface, this water is drawn into the columns of water which are there above the ground water table. So water is sucked up into the pores of the soil mass. This pores when they get filled with water, they become something like columns of water. Water is sucked up into pores of soil in this zone on account of surface tension of water and this manifestation is referred as capillary phenomenon. So these capillary phenomenons has got many practical examples like, around the behavior of the soil in and around the beach where the soil which is slightly away from the portion where the wave breaks is ready to offer you resistance for walking or motorcycle riding. Or away from that zone again it is very difficult to walk or very difficult to ride a motorcycle, or within that zone where the wave breaks it is difficult even to walk or stand on that particular zone. So this particular behavior is attributed to the capillary phenomenon, which we will be discussing at the end of the lecture.

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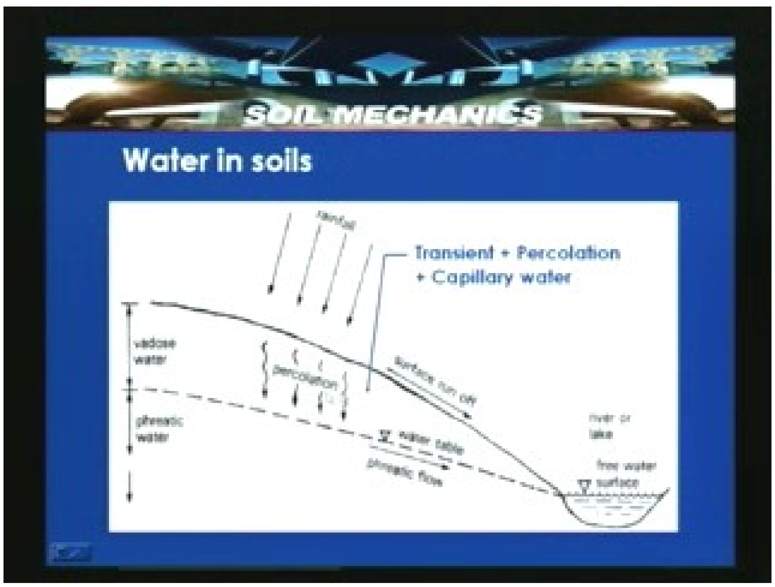

So here different cases like water in soils. Generally what happens is that for a given terrain, the rain fall which has got a surface run off and percolation that is whatever the rain fall occurs that is one part of the water is percolated and the other part undergoes a surface run off. This zone above the ground water table is called vadose zone or vadose water. The water in the zone above the ground water table is also called vadose water. So here this particular surface is also indicated as a water table or phreatic surface where the atmospheric pressure is zero. So here it is a free water surface and this is a typical schematic representation of river or lake. Here in this zone there is a transient and percolation and capillary water. So this capillary water which is occurring because of the phenomenon which we discussed just now. It is because of the surface tension which is the property of the fluid which is actually, sucking the water and drawing the water into the pores spaces of the soil above the ground water table, with ground water table as its source.

So this particular water table, particularly this saturation of a vadose zone also depends upon climatic conditions. For example this particular water which remains saturated because of this particular phenomenon can undergo some drying in case of arid climates because of the temperature. So in that case the water which is stored in the pores of soil can get evaporated. So more or less it is a climatic function of the climatic conditions.

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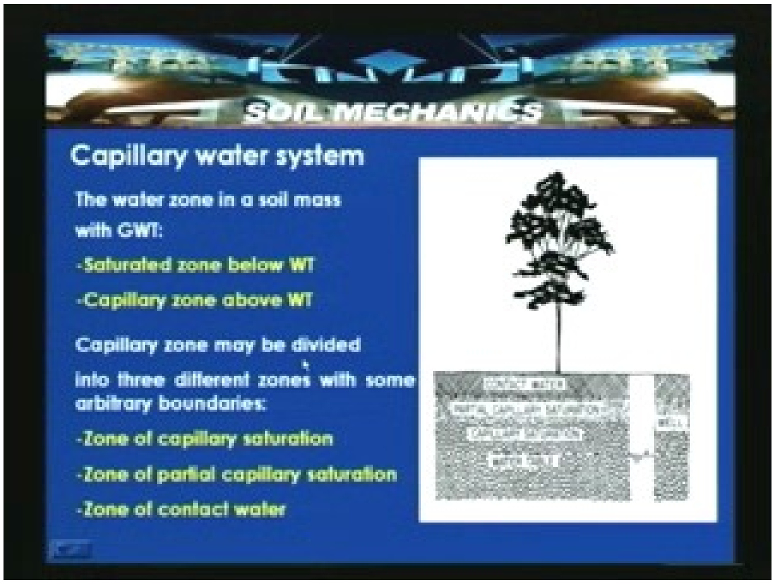

So let us look into the capillary water system. In the above slide different zones are shown here and we will try to define this zone and we will try to understand. So here the topmost zone is contact water. So when you come to the bottom, this is the ground water table where the pre surface or phreatic surface exists. Above that when it is very close to the ground water table there will be a certain zone which remains 100% saturated. That is called capillary saturation. Above that is a partial capillary saturation and above that is the contact water which is arising because of the percolation of the water which is because of rain fall or so. So in the process this water which is stored in the contact zone is called contact moisture. The water which is stored in the pores of soil because of this percolation which occurs is called contact moisture. So here in this partial capillary saturation and capillary saturation which is attributed to the phenomenon again like surface tension.

So here the water zone in the soil mass with ground water table can be divided. The saturated zone below ground water table and capillary zone above ground water table. So this capillary zone again divided into capillary zone with complete saturation and partially saturation zone. Capillary zone may be divided into three different zones with some arbitrary boundaries. These boundaries are very arbitrary because it varies with time and climate. The zone of capillary saturation that is where the complete saturation is said to prevail, even above the ground water table and zone of partial capillary saturation and zone of contact water. So this capillary zone we have divided into 3 different zones. One is zone of capillary saturation and zone of capillary partial saturation and zone of contact water.

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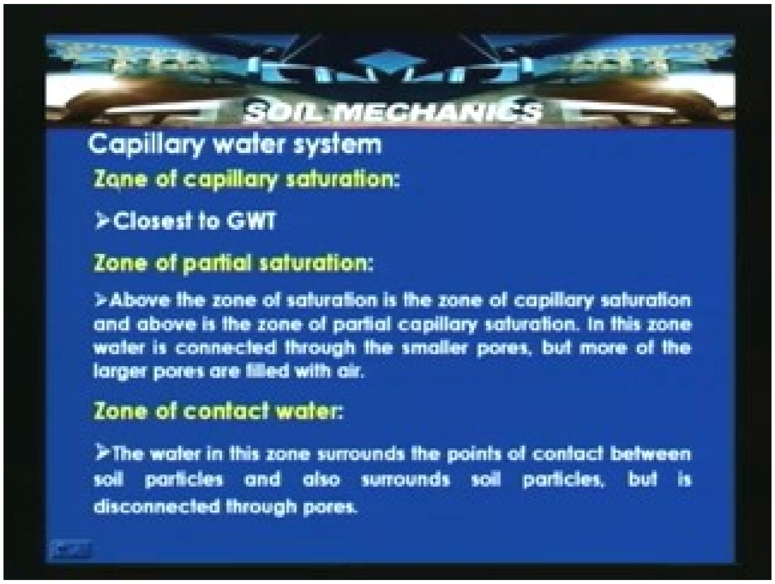

Let us look into details like zone of capillary saturation which is the closest to the ground water table which remains in contact with water and which has got columns of water which is occupied in the pore spaces of the soil which is resulted in saturation of the soil mass even above the ground water table. So above the zone of saturation is the zone of capillary saturation and above is the zone of partial capillary saturation. In this zone water is connected through smaller pores but more of the larger pores are filled with air. So when the more of the larger pores are filled with air then that tends to be a partial capillary saturation.

The zone of contact water that is the third zone which we have classified is the zone of contact water. The water in this zone surrounds the points of contacts between soil particles and also surround soil particles but is disconnected through the pores. So the water in this zone surrounds the points of contacts between soil particles and also surrounds soil particles but something like contact moisture or it is something like films of water surrounded and it is kept within the pore space of the water. So either due to some flooding or due to evaporation this contact moisture can be lost.

So here in this particular diagram which is given below shows, for example a trench excavated with a retaining structure. This particular water level is saturated with phreatic water where 100% saturation prevails. And here it is saturated with capillary water, even when it remains in contact with ground water table, it has got the 100% capillary saturation resulting due to capillary phenomenon even above the ground water table.

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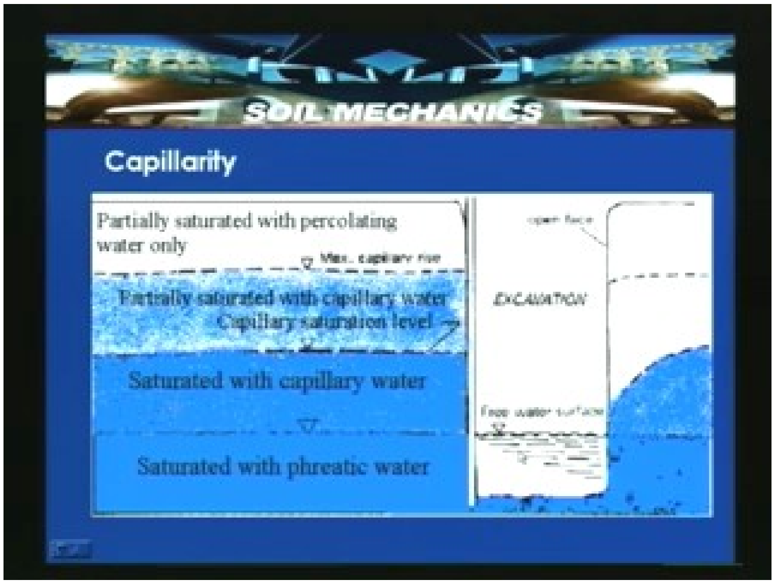

So partially saturated with capillary water that is, this particular one is called a partially saturated with capillary water. Then above that is the percolating water which is nothing but contact water and (Refer Slide Time: 13:37) this is partially saturated capillary zone and this is completely saturated capillary zone and this is our conventional saturated zone which is below the ground water table.

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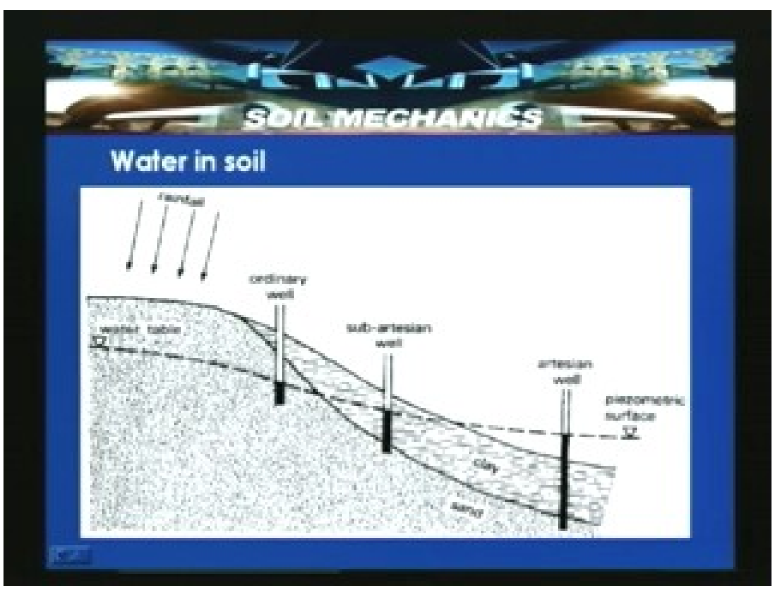

So these are the different conditions like water table conditions which can be possible in this particular subject, when the rain fall occurs then we have discussed that percolation will occur and then the contact water table is kept within the vadose zone. For example this particular portion of sandy soil is receiving certain water under pressure because of some source of water either because of the some river or lake. So that can be said it is under artesian condition. So if a well is driven into this particular strata and the well which is called artesian well. That means this particular portion of the soil will be having additional pressure than that conventional water table pressure. That means that it has got extra source of water which exerts that additional pressure.

In the sub artesian well where there is a certain amount of pressure but not more than this artesian conditions. This is the conventional ordinary well which actually appears with ground water table. So what we have seen in this slide is the ordinary well, sub-artesian well and artesian well. So many times when we are constructing structures on a soil strata's under artesian condition or excavations which are carried out under artesian conditions, one has to ensure the stability. If the stability is not ensured then effective stress tends to become zero then there is a chance of failure or caving in or collapse. So there are also some situations like localized pockets of water table which can be possible when there is a lens of clay. Those types of water table are called perched water table.

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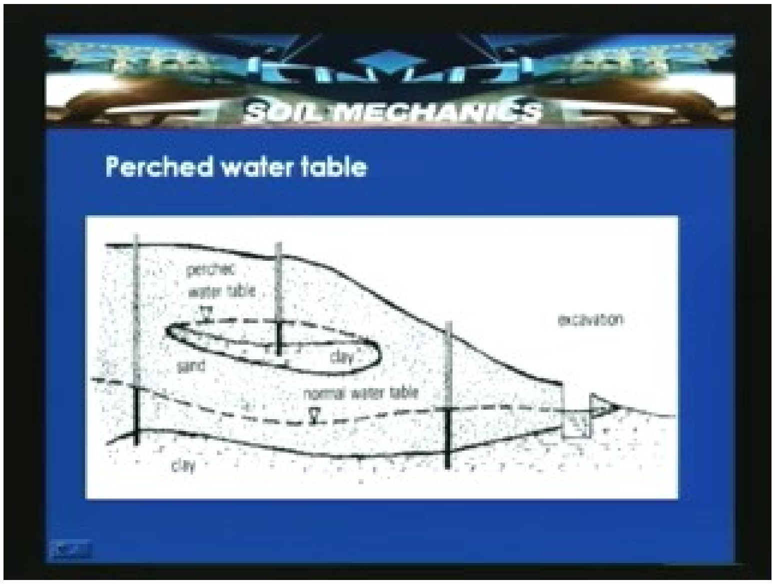

So that is what shown in the above slide, a perched water table condition. This is the normal water table but this could be the localized condition where the water is under perched water conditions, so it is called perched water table.

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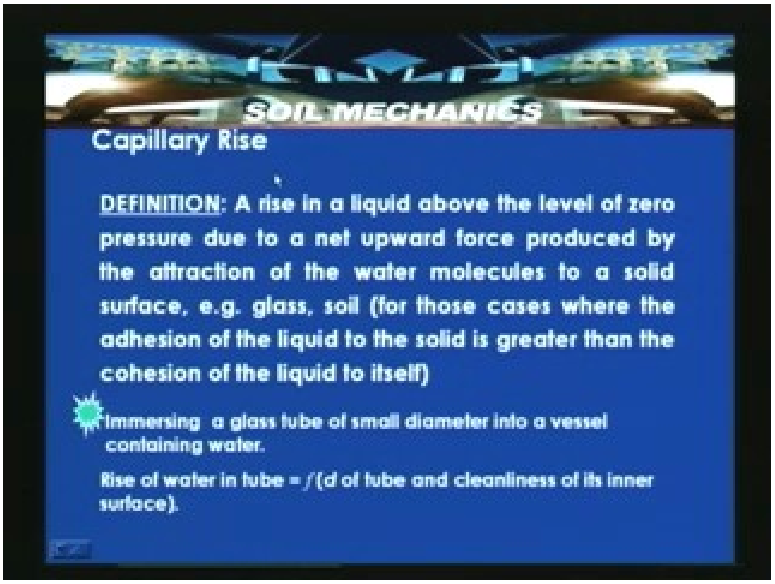

So in previous slides we have defined and we have introduced capillary rise phenomena. Let us look into the theory behind the capillary rise phenomenon and let us look how this can affect the effective stress. So here the definition, a rise in a liquid above the level of zero pressure. That is at the free water surface, the ground water table is a zero pressure. Due to a net upward force produced by the attraction of water molecules to a solid surface that is a glass and soil.

This particular capillary phenomenon in soils can be demonstrated by immersing a glass tube of open ends in the vessel of water. If that is done what will happen is that the water will rise in to the glass tube. The rise of this water which depends upon the diameter of the glass tube and cleanliness of the inner surface of the glass tube. So here the surface tension phenomenon, molecular attraction occurs between 3 different materials that is air, water and glass surface. So the rise of water which is the function of, particularly the diameter that is nothing but the diameter of a tube. So in real cases this diameter of the tube is nothing but the pore size or the size of the pore spaces within the soil.

So a rise in the liquid above the level of zero pressure due to net upward force produced by the attraction of the water molecules to a solid surface. Example here is glass and soil. For those cases where the adhesion of the liquid to the solid is greater than the cohesion of the liquid to itself. So here this can be demonstrated by immersing a glass tube or small diameter into a vessel containing water. So we will consider this and then we will try to derive the theory behind this capillary rise.

It is shown in the below slide, that this a-a is the level at which the ground water table exists. That is the free surface where the pressure is zero and here the black color is the path taken by the capillary rise. So this h_c is the height with which it could rise depending upon the pore space or cleanliness of the inner surface of the mineral grains or the grain wall cleanliness. This particular behavior can be simulated by something analogues to a capillary tube phenomenon where immersing an open tube in a vessel of water can simulate this particular condition. So let us look into this and see how this works. So this is a ground water table that is a free water surface which is nothing but the level a-a. And this is the diameter of the tube which represents the pore size.

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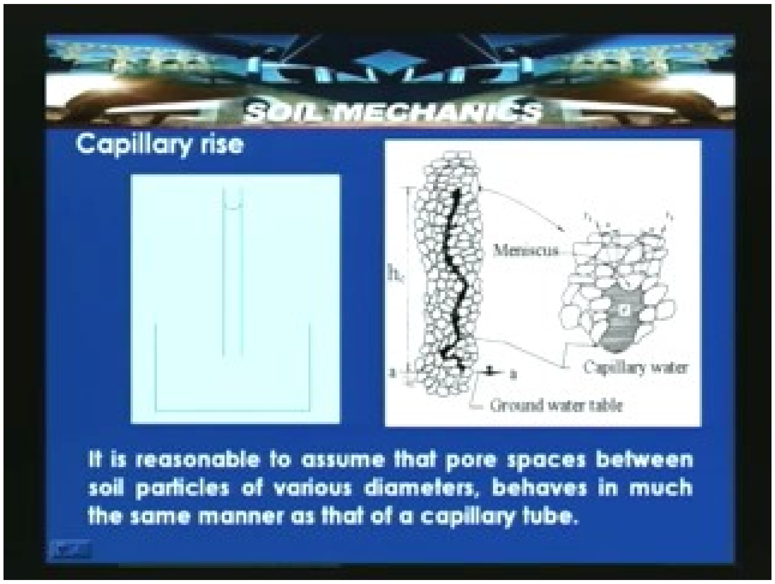

The d may be the pore size then this is the rise. So h_c is nothing but the rise which is obtained here. The d size which is referred here is the pore size and you can see the meniscus formed at the top surface. So it has got something like an upward pull and then it is resisted by the self weight of the water column which is within the glass tube. Similarly here also the same phenomenon that water is pulled against gravity above the ground water table and which is resisted by the self weight of water which is within that column.

So it resembles to assume that pore spaces between soil particles of various diameters behave in much the same manner as that of capillary tube. So it is reasonable to estimate the pore spaces between soil particles of various diameters or it is very close to the analogues behavior as that of some capillary tube immersed in a vessel of water. Vessel of water is that particular surface which represents the free surface, which is nothing but a ground water table surface.

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So in soils, shapes of void spaces between soil particles are unlike those in capillary tubes. Definitely the pore spaces or void spaces which are not as regularized as capillary tubes. However the voids are of irregular and varying shapes and size, and interconnected in all directions. That is also there. Hence, accurate prediction of the height of capillary rise in soil is next to impossible. However the features of capillarity rise in tubes are applicable to soils as they facilitate an understanding of the factors affecting capillarity.

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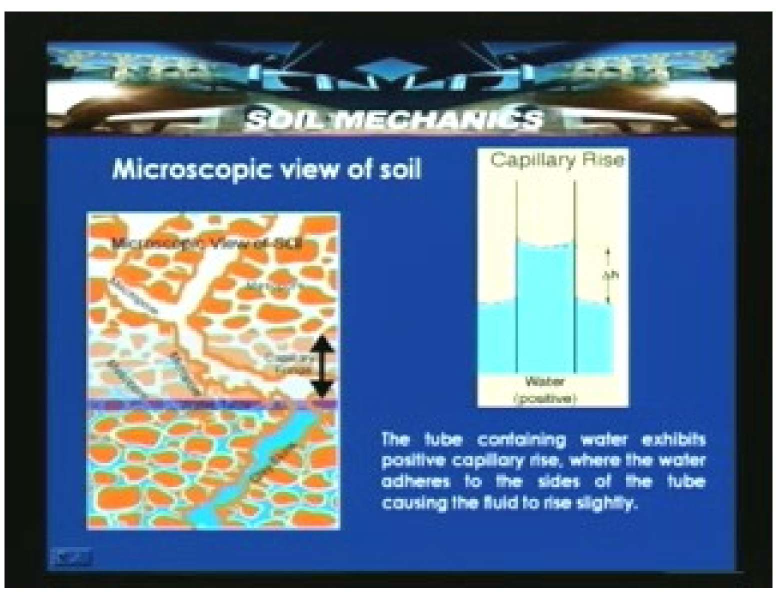

So as long as they provide an understanding of the process of the capillarity, then this can be simulated or to facilitate the understanding of the capillarity behavior. The soil microscopic view is shown in the slide above. So what has been discussed is that the soil can have interconnected pores of different spaces. So it can have this pore spaces or pore channels in any direction or in any shape. We have discussed that it is very difficult to simulate that. But to understand the behavior, to a great extend this capillary tube behavior very closely represents this particular behavior which occurs in this nature. If you can see in the above slide, this is the tube and then the meniscus is formed because of the attraction. So the tube containing water exhibits positive capillary rise, where the water adheres to the side of the tube causing the fluid to rise slightly.

Suppose in this case if you substitute with mercury, then the behavior is slightly different instead of raising it exhibits something like sinking. The water in the capillary tube sinks down. So the tube containing water exhibits the positive capillary rise where the water adheres to the sides of the tube causing the fluid to rise slightly. So this is the microscopic view of the soil. So this zone above which the saturation is maintained is called capillary fringe.

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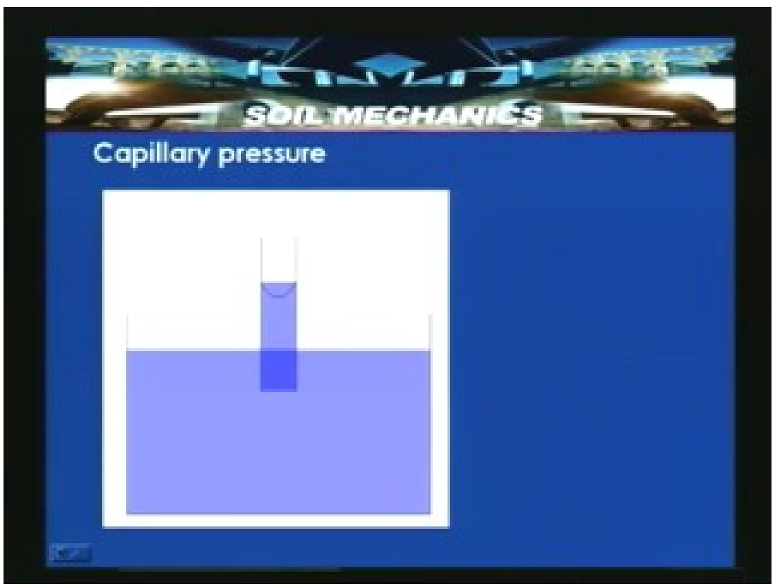

Let us look how this capillary pressure acts on the walls of the pore spaces or along the periphery of the glass tube under consideration. So that is the free water surface (Refer Slide Time: 22:50). This is water which rose depending upon the diameter of the tube. So that is the force with which it could pull the water column that is the water which is occupied in the tube against the gravity. These are the surface tension forces acting all around the periphery of the tube. The d is the diameter of the tube which is nothing but the pore size in soil. So if you look into it, the f with which it could draw the water into the glass tube of diameter of d is nothing but T_0, which is the surface tension and which is the property of the fluid. For water the surface tension is 0.00075 kilo Newton per meter. So T_0.pie.d.cos (alpha), where alpha is the contact angle. This is that alpha which is the contact angle here. For a clean tube or mineral grains with clean surfaces this contact angle alpha is equal to zero.

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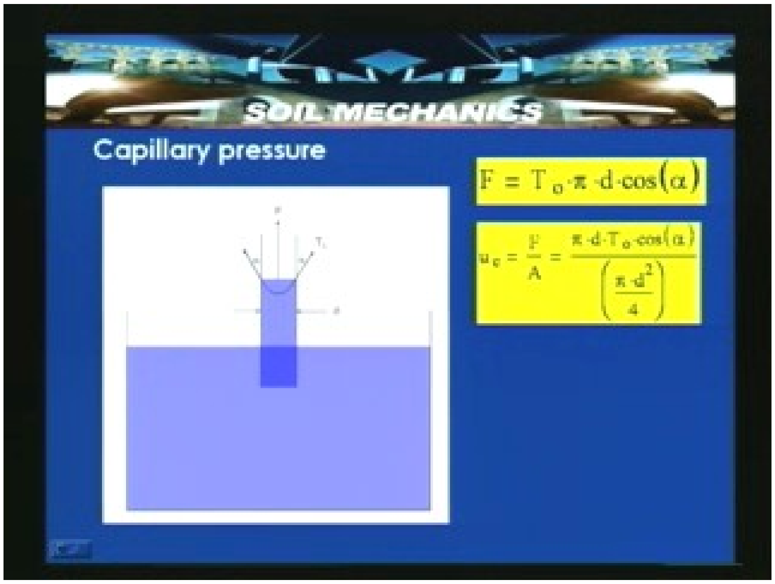

Now capillary pressure is nothing but force divided by area which is pie d T_0 cos (alpha) divided by pie d square by 4. That is the area of the tube under consideration. Now on further simplification this can be written as u_c = 4. T_0. Cos (alpha) divided by d. Now if you see u_c is directly proportional to one by d. The smaller is the diameter the greater is the capillary pressure. So this is required to be understood and kept in mind. Now what has been told is that for chemically clean glass tubes, alpha is equal to zero. That means the u_c will become 4 T_0 by d. So u_c is nothing but, particularly capillary pressure is nothing but four T_0 by d where d is directly proportional to surface tension of the fluid under consideration and inversely proportional consideration of the diameter of the tube or in real terms the pore size of a given soil.

So soil water exists in small spaces in soil as a film around the particles and the small pores can act as capillaries. So a capillary is a very thin tube in which a liquid can move against the force of gravity. That is what we have discussed and water is attracted to the glass tube by adhesion. So a thin film flows up the side of the tube, while cohesion drags more water along. It is something like extended flexible membrane, it pulls the water against the gravity. So the liquid rises to the point where the gravity balances the adhesive and cohesive forces. The narrower the tube the higher the water column can rise. That means the smaller is the size of the pore space under consideration the greater is the height it can raise.

That means if you have got a clayey soil, we can expect that the clayey soils can have very large heights of capillary saturation then say sandy soils. Or a course grain soils can be subjected to capillary saturation only up to certain height, where as fine grain soils can be subjected to saturation up to a greater heights even above the water table.

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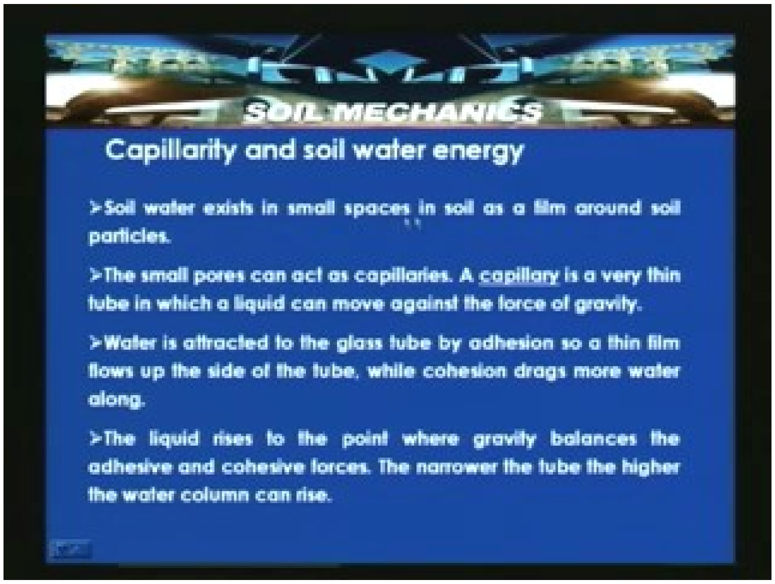

So let us look into this particular derivation which can be obtained to calculate the capillary rise height h_c. So again the water table in the vessel is considered. The f_c is the height to which the water column rose into the tube under consideration. d is the diameter of the tube.

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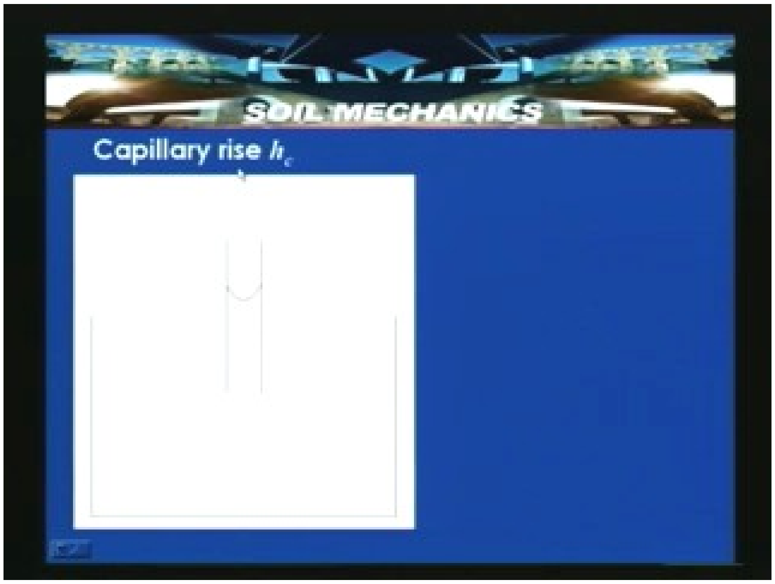

So f is the force with which it has full and w is the self weight of the water in the column of column which is tube in the tube of diameter d. If you take the vertical equilibrium sigma f_v is equal to f - w. So the capillary rise is calculated at which f is equal to w that is the vertical force with which the force which it is pull is balanced by the self rate of the water column.

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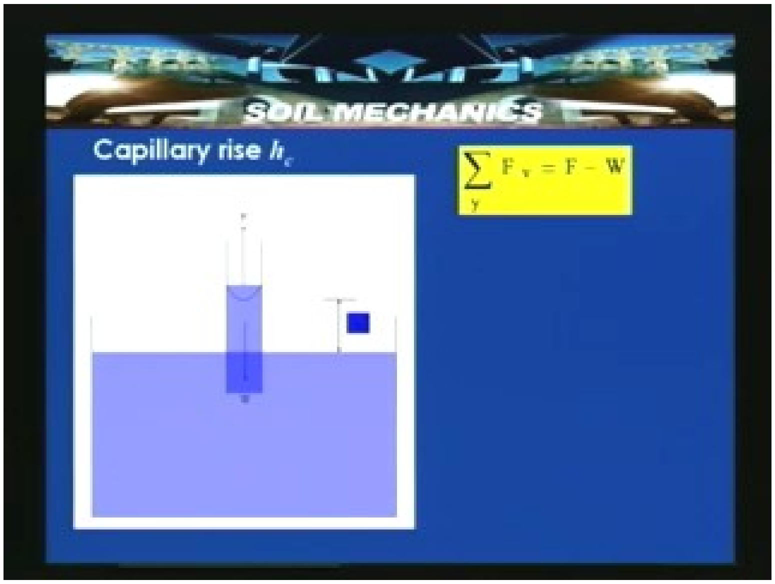

So to that height it will raise then it will stop at that particular portion. That is h_c which we are going to obtain from the direction. So that is what sigma f_v is equal to zero yields f = w condition.

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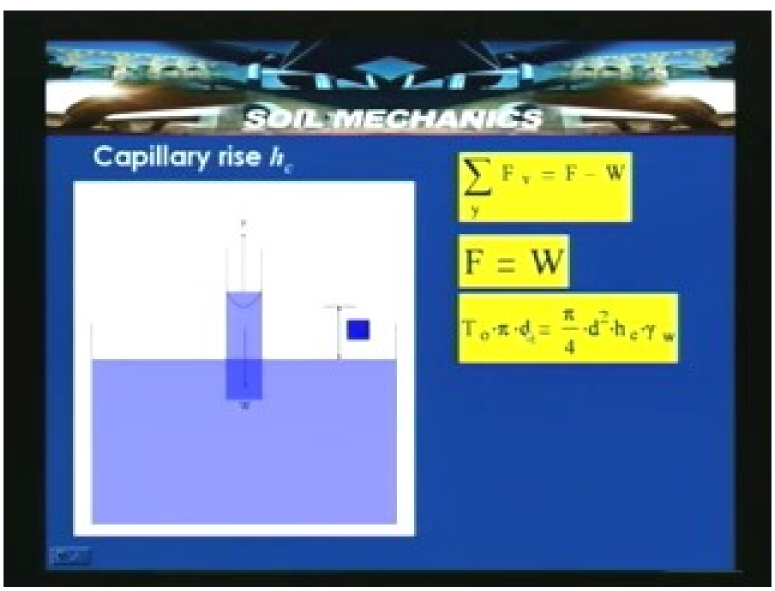

If you write now T_0 .pie .d that is for a chemically clean glass tube alpha =0, then cos alpha =1. So T_0 pie d = pie d square by 4 into h_c gamma w. This is the self weight of the water in the capillary tube. Now at equilibrium, h_c is at a maximum therefore solving for h_{cmax} yields something like h_{cmax} = $4T_0$ by d gamma w, gamma w is the unit weight of the water. So this can be expressed something like h_{cmax} = 0.306 divided by d, where d is the diameter of the tube or in reality d can be pore size. So 0.306 is actually constant which is obtained by considering the property surface tension value of water which is nothing but T= 0.00075 kilo Newton per meter and substituting in this equation and simplifying. So d in centimeter we can yield h_c max as 0.306 divided by d.

So as we said the narrower the tube, the larger is the capillary rise. Let us look into it. For example as we have got different ranges of particles so different ranges of pore spaces can be possible. A course grain soils have very large pore spaces that indicates that the capillary rise in coarse grain soils are supposed to be low. Where as fine grain soils have got very small pore spaces because the spaces are very small. So it is expected that the capillary rise in fine grain soils is very high.

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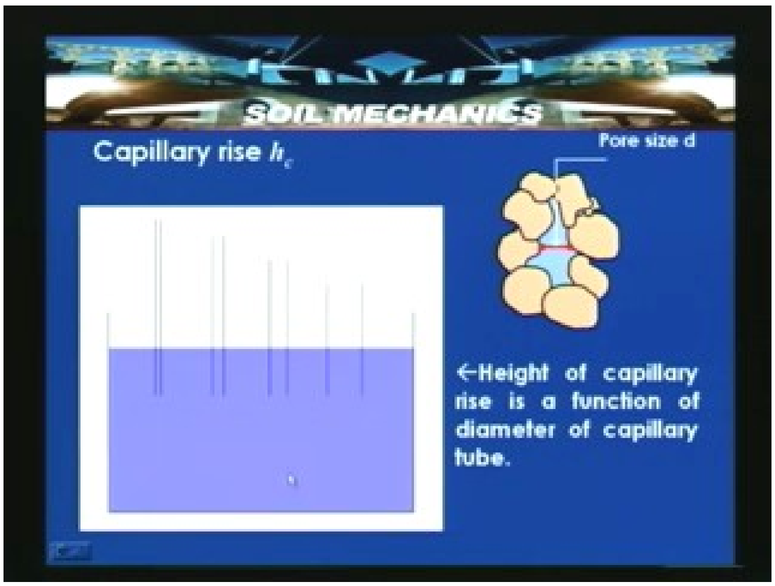

So let us look into this. Here again the vessel which is having different tubes of different diameter where this d_1, d_2, d_3 and d_4. The d_4 is greater than d_3, d_3 is greater than d_2, d_2 is greater than d_1. So let us look how the capillary rise can be understood from the previous deduction. So here h_{c1} which is the capillary rise in the tube one, where d_1 is the diameter which is the smallest considered. In this case the h_{c2} which is the rise which is obtained for diameter d_2 where d_2 is larger than d_1 and h_{c1} is greater than h_{c2}. That is one thing required to be kept in mind.

Here which is nothing but h_{c3} where h_{c2} is greater than h_{c3} or h_{c1} greater than h_{c2} and d_3 is greater than d_1 and d_2. Finally the diameter of the tube d_4 which is larger than all other tubes which are considered. So the height capillary rise is around h_{c4}. So for soils this pore space is approximated as 20% of the effective particle size. So effective particle size we have discussed and introduced earlier, the d_{10} is the effective particle size. That means

90% of the particles are larger than the particles only 10% of the particles are finer. So d_{10} is the effective particle size. So one fifth of the d_{10} particle size is referred as a pore space.

Suppose a d_{10} of a coarse grain soil is 1mm, then the pore size is around 0.2mm or so. For example the d_{10} of the fine grain soil is 2micron, so one by fifth of the 2 micron is very small pore space for a fine grain soil. So this deliberation can tell us, the smaller is the pore space the larger is the capillary rise. That is what we have understood, the smaller is the diameter of the tube the greater is the capillary rise. That is what we have understood and proved from discussions whatever we had so far. So here the pore size d is shown, this depends upon the type of the soil. So the d can be very small for fine grain soils, the d can be very large for course grain soil that means sandy or a gravelly soils.

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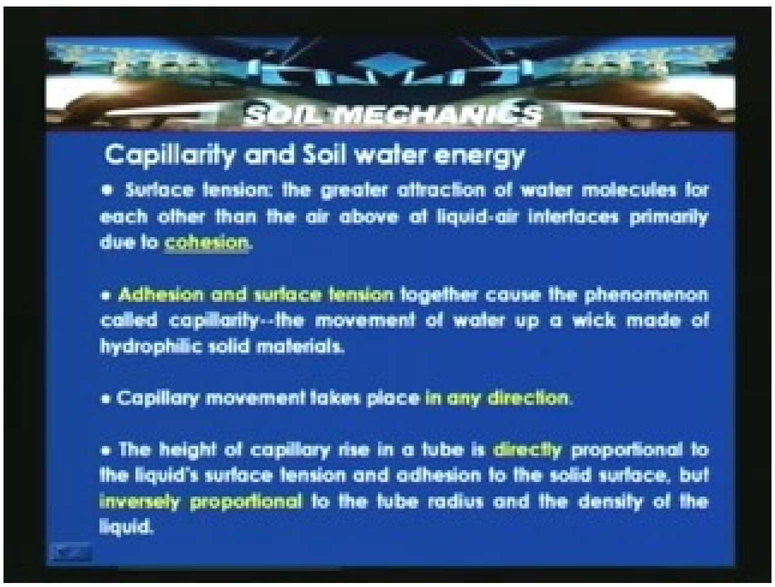

Let us look into the capillarity and soil water energy. In surface tension, the greater attraction of the water molecules for each other than the air above of liquid air interfaces primarily due to the cohesion. So the adhesion and surface tension together cause the phenomenon called capillarity. That is what we have discussed, adhesion and surface tension together cause this phenomenon which can actually draw the water against the gravity and can be kept within the pore spaces. So the movement of water up a wick made of hydrophilic solid materials, which is nothing but the movements of the water is a wick made of hydrophilic materials.

So capillary movement takes place in any direction. It can be vertical or it can be any direction in which actually this particular phenomenon is occurring. The height of the capillary rise in a tube is directly proportional to the liquid’s surface tension and adhesion to the solid surface. That is very much important. But inversely proportional to the tube radius or diameter and the density of the liquid. So inversely proportional to the density of the liquid because in the derivation we have discussed the density which is in the denominator. So inversely proportional to the density and to the diameter.

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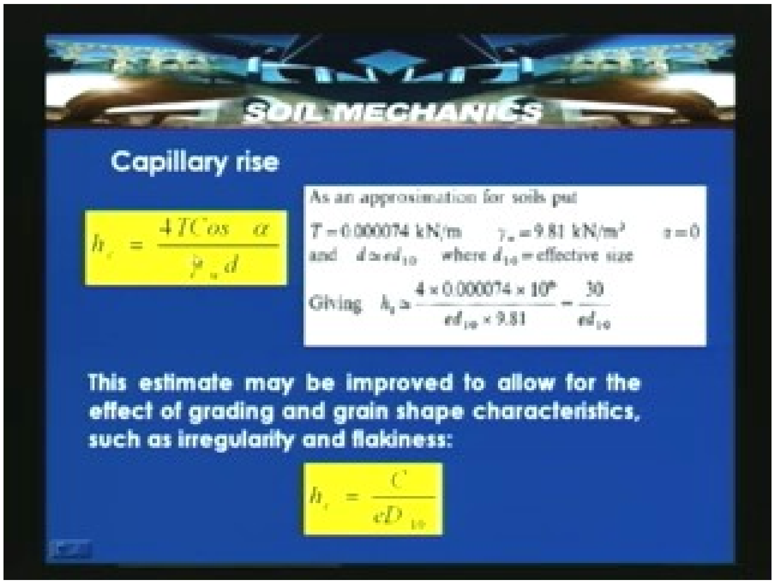

So we can also extend this particular discussion to see whether we can generate any correlation or approximate estimation based on the effective particle size and void ratio of a given soil. So as we have derived h_c is equal to 4t cos alpha divided by gamma w d. That is what we are discussing in the previous slide. The capillary rise is inversely proportional to the unit weight of water or the density of liquid. The d is the tube diameter or pore size and alpha is the contact angle. For a chemically clean surface alpha =0, T is the surface tension.

So here it is given as an approximation for soils, if we put T= 0.000074 kilo Newton per meter. The gamma w is equal to 9.81 kilo Newton per meter cube, alpha =0 and assuming and approximating that d = ed_{10}. That is d = ed_{10} where d is the pore space and d_{10} is the particle size. So e is the void ratio of a given soil where d_{10} is the effective particle size. Then h_c is given by an approximation of some thing like 30 by ed_{10}. So this 30 is nothing but a constant, so this can be deduced to something like h_c = c by eD_{10}, where c is a constant. So the estimate may be improved to allow for the effect of grading and grain shape characteristics, such as irregularity and flakiness. So h_c = c by eD_{10}.

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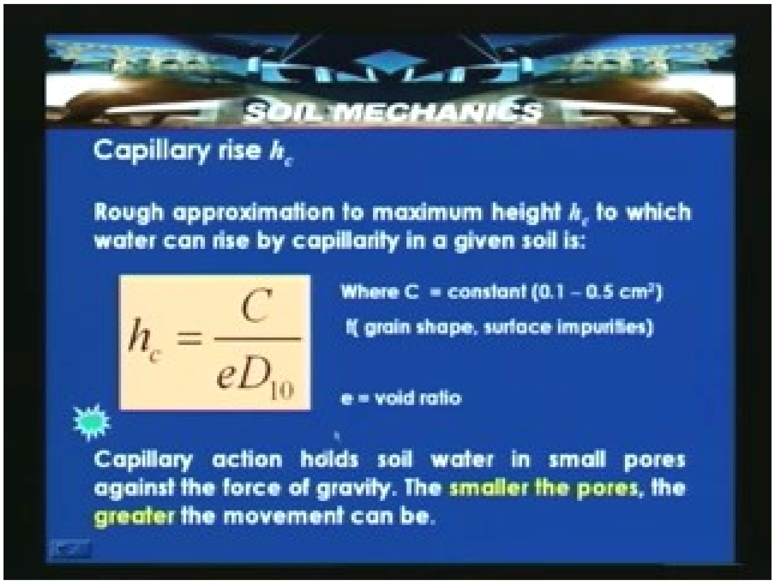

So this can be further discussed here, so rough approximation of maximum height h_c to which the water can rise because of the capillarity phenomenon can be said as h_c = c by eD_{10}, where c is a constant which has got units in centimeter square or meter square. In case of centimeter square, c is equal to 0.1 to 0.5 centimeter square and which is a fine grain shape and surface impurities and e is the wide ratio. So capillary action holds the soil water in small pores against the force of gravity.

The smaller the pores, the greater the movement can be. That means with this we can say the pore spaces in fine grain soils are very small, though the void ratio is high for fine grain soils, the pore spaces are very small. Because of the virtue of small pore spaces and this particular phenomenon, the property of the surface tension and adhesion of the water, it exhibits this particular capillary phenomenon. And because of this particular phenomenon it can draw and it can keep water within the pore spaces to keep the soil even above the water table under complete saturation. So when you consider different soils let us look when they are having different effective particle sizes and how far they can rise above the ground water table and remain saturated.

Typical coarse gravel which is having a d_{10} say 0.82 mm can have a capillary head that is h_c of about 6 centimeter only. So fine gravel of 0.3 mm can have a 20 centimeter capillary head only. Silty gravel of 0.06 mm can have a capillary head of around 68 centimeter. Medium sand can have 120 centimeter. Silt can have 180 centimeter that is around 0.18 meters and clay which is having d_{10} less than 2 microns can have something like capillary height which runs around meters.

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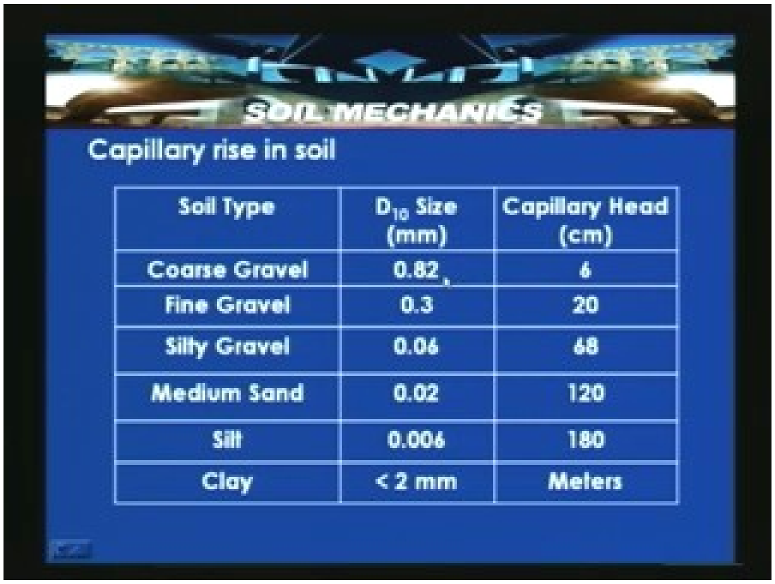

Soil Type	D_{10} Size (mm)	Capillary Head (cm)
Coarse Gravel	0.82	6
Fine Gravel	0.3	20
Silty Gravel	0.06	68
Medium Sand	0.02	120
Silt	0.006	180
Clay	< 2 mm	Meters

Because of evaporation many times it cannot be guaranteed that it remains completely saturated. But chances like theoretically it can remain saturated up to certain meters. But because of evaporation the fringes which are developed which remain in contact with water can be lost and continuity is lost and then it can remain in partially saturated condition. Otherwise it can remain saturated even above the ground water table running into something like 10meters or so.

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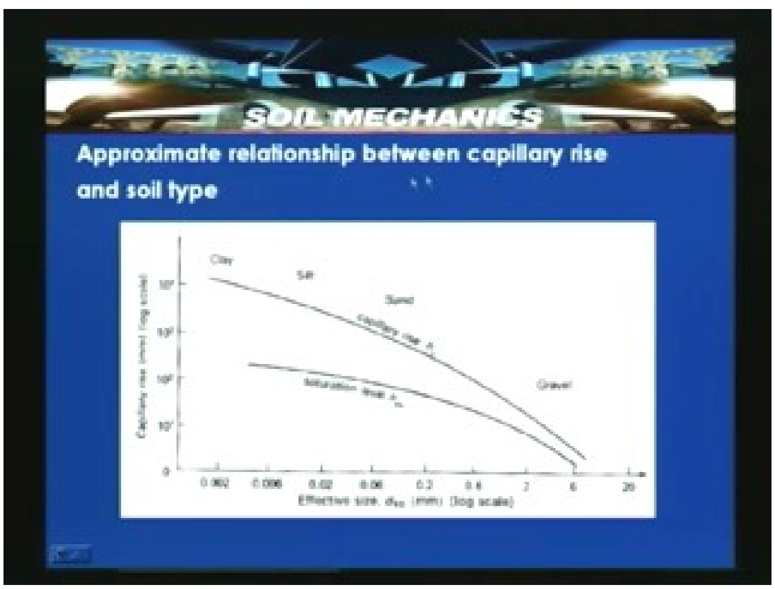

Let us look into the approximate relationship between capillary rise and soil type. The capillary rise is plotted on the log scale on the y-axis and effective size d_{10} is plotted on the log scale on the x-axis. If you see here this is the capillary rise h_c, so clay has got around 10,000 mm that is around 10 meters which is followed by silt and then sand gravel. This particular property is also considered. When you do not want this capillary action to prevail then we use this gravel or sandy soil materials as capillary cut off materials. So they can act as a capillary cut off layers to inhibit the soil. This is particularly adopted for a man made structure where a capillary cut off is provided to see that the water does not remain saturated. Because remaining saturated then there can be changes in the properties of the soil.

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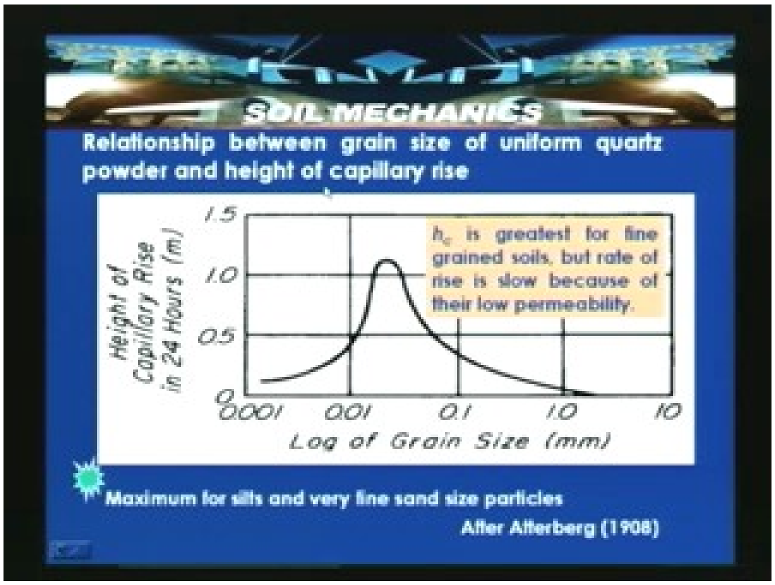

So if you plot this relationship between heights of the capillary rise in 24 hours. Let us consider in 24 hours how fast it can rise and the log of the grain size in millimeter. So if you look into this curve as plotted 0.001, 0.01, 0.1, 1 and 10. So h_c is the greatest for fine grained soils but the rate of rise is very slow because of the low permeability. For example, theoretically this h_c has to be very high for fine grained soils but here within 24 hours it could not exhibit very high rise because of the low permeability of the soil which will be discussing in the next subsequent lectures.

Where as for certain size like slit grade and very fine particles the rise is very high. So you can see the maximum for the silt size and very fine size particles it is very high. How far this particular phenomenon can affect the effective stress? That we have understood. So coarse grain soils are only partially saturated even at elevation close to the water level, whereas fine grained soils may be saturated for a considerable distance above it.

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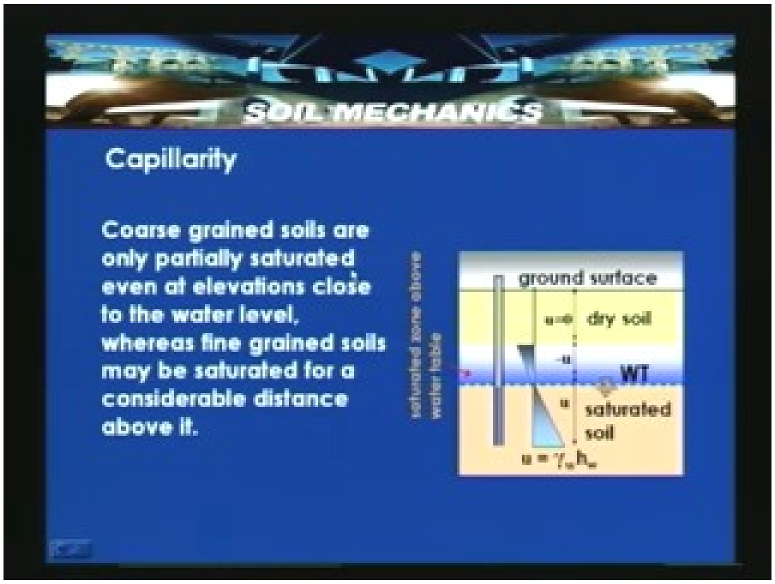

So if there is a coarse grain soil or a sandy layer above the clay layer, it can be said that the sandy layer can remain in partially saturated condition. Suppose a clay layer and ground water table adjust and then if the clay layer continuous above the ground water table, then it can be said that it can be under saturation because of this capillarity phenomenon. In this case of particular diagram where this ground water table is shown and this is that zone at which complete saturation is prevailed because of the capillarity phenomenon (Refer Slide Time: 41:05). And this is the zone say sandy soil where the dry soil. So the pore water pressure can have this particular distribution because here the water which goes above the water table above the zero pressure or atmospheric pressure can be called as negative pressure.

So here the water column which is drawn and kept within the pore space against the gravity, above the water table is said to be in tension. And then here water which is below in hydrostatic condition where no flow is occurring can be said that it is under compression. What you see is that the water above the water table is under tension that is called capillary tension and below is positive pore water pressure. So above this the distribution of pore water pressure, if there is a partially saturated soil then it can have a certain reduced pressure. Otherwise if it's immediately say dry soil is coming where the capillary rise is almost negligible in that case it can run like this a negative pressure. That means this ordinate h_c is nothing but the negative head which is kept above the water table. That is minus gamma w h_c which is nothing but the negative pore water pressure or negative water pressure. That will be there and then immediately the pressure can be dropped to something like zero pressure. So this negative pore water pressure also referred as something called suction pressure. So u or u_w is also minus gamma w h_c which is nothing but also referred as a suction pressure. So by substituting the value of h_c we can also obtain this suction pressure.

So let us see the capillary rise in soil and then stress profile. So this particular case we have got a vessel of water that represents the free water surface or a ground water table and this is the diameter of the tube d and h_c is the capillary rise depending upon the tube diameter. And this is the menisci which is formed but not shown. Here is the capillarity pressure that we have calculated, f divided by area of the tube where f is nothing but T_0. pie. d .cos alpha, which is acting over the periphery of the inner diameter of the tube.

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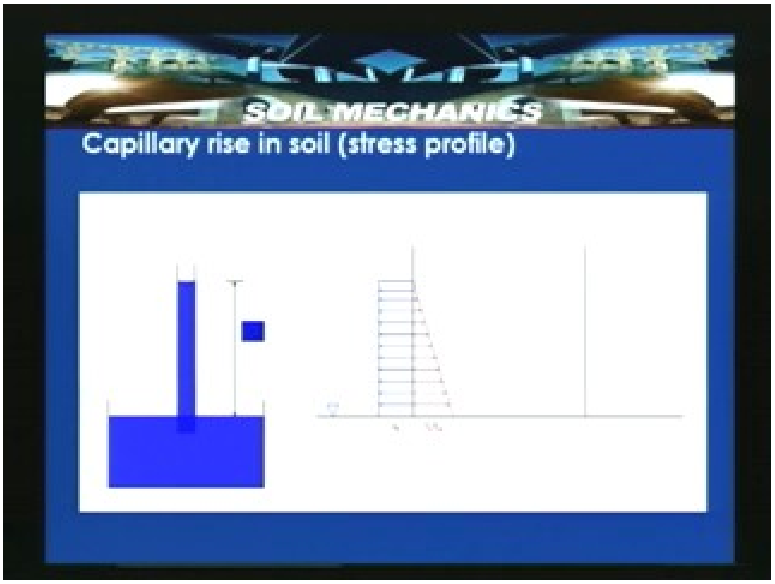

Now this is gamma w h_c, hydrostatic pressure that is water column which is here exhibits zero pressure here and gamma h_c here (Refer Slide Time: 43:58). So the net pressure that is the difference of pressure which is indicated in red line to the blue line. That pressure is referred to as the pore water pressure distribution.

So that we will get here as something like this where minus gamma w h_c something like negative pore water pressure here and zero at the free surface and then below it continuous to be again positive. So here if you look in to this diagram, it looks something like a part of the water above the ground water table is under tension and below is under compression.

So let us look into the capillaries in soil and how the stress distribution is affected. This is the discontinuous water which can be in the partially saturated zone and capillary fringe and capillary saturation. So this capillary fringe to some extent also can exist in the partially saturated zone and discontinuous water either because of some contact water or contact zone it can also remain partially saturated.

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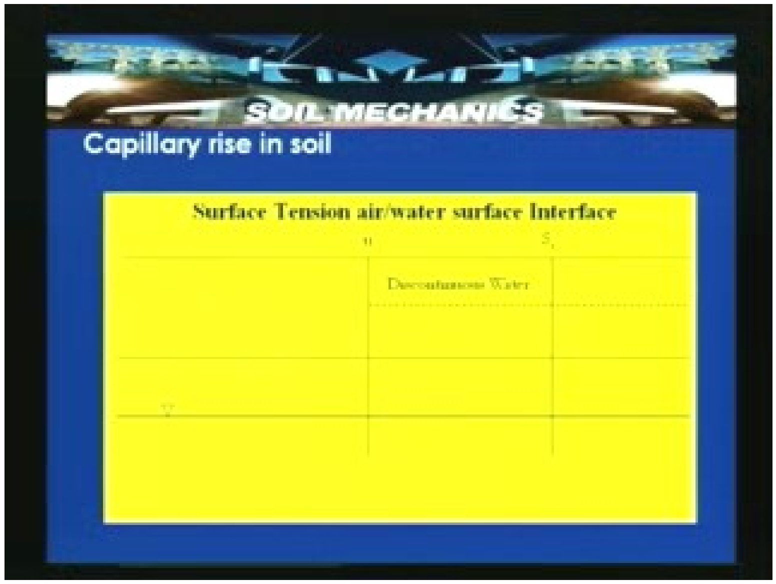

So capillary saturation which is in contact with water table can have a complete saturation. Now what we have discussed is that the minus h_c gamma w is the water pressure that is negative pore water pressure or suction pressure. It sees the capillary rise above the ground water table and here this is again below water table, again positive hydrostatic pressure. So the degree of saturation in this zone can be subjected to variation.

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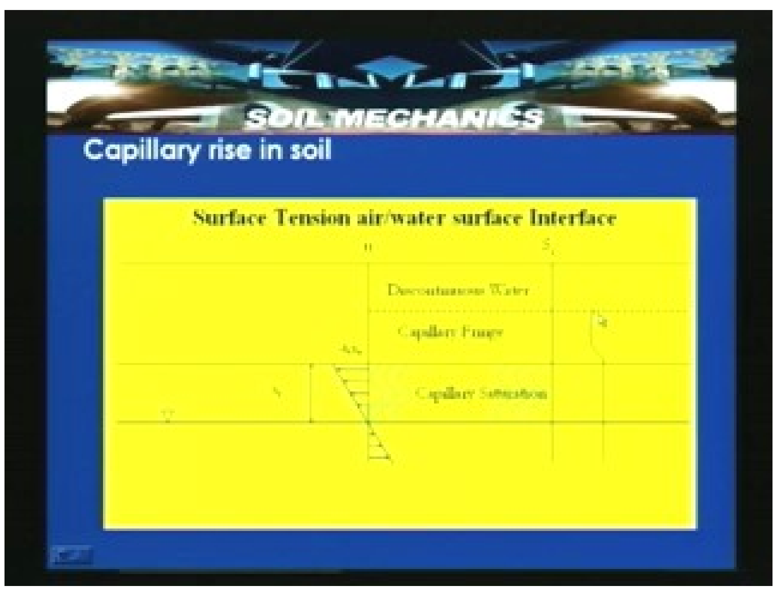

It cannot be easy to estimate but to some extend this can be estimated by considering the value of the… Some correlations are there with the degree of the saturation if you multiply then we can get the suction pressure to some extend in that particular zone. That is s r by hundred in to gamma w h_c to some extend can give the degree of saturation in the partially saturated zone.

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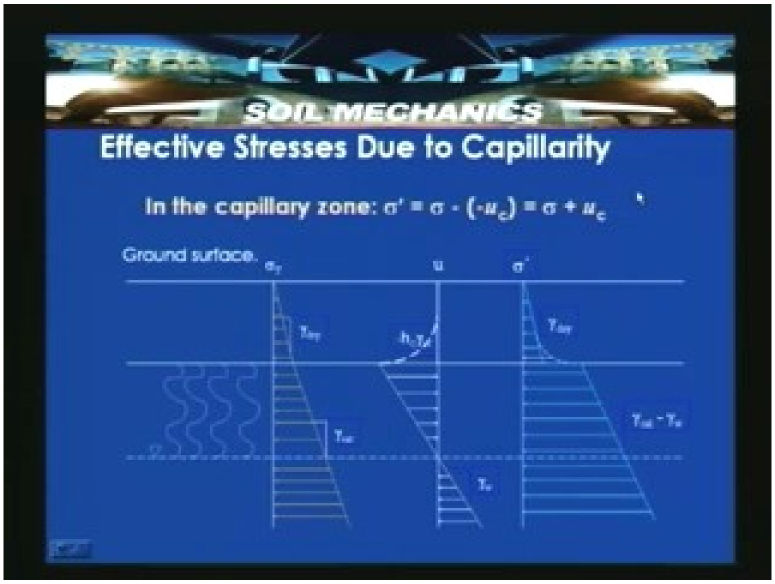

So effective stress how this can be varied with respect to capillarity? In the zone of capillarity what we are seeing is that the pore water pressure is negative that is under tension. When you say that total stress is equal to effective stress plus pore water pressure, so effective stress is equal to total stress minus pore water pressure that is u. So this u is now u = minus u_c. In that case now the effective stress is something like sigma dash is equal to sigma plus u_c. So there is an enhancement in the effective stress because of the particular phenomenon. So this sometimes can also act as giving good support to the soil under consideration.

So here sigma t is the total stress distribution with depth and here is the gamma w h_c and it is explained here (Refer Slide Time: 47:58). In this case when partial saturation is gradually reducing to dry condition here, then this can be said that minus gamma w h_c which is not clearly shown here. But it is minus gamma w h_c and then reduced to zero here and this may be h then gamma w h. If you substitute here then we will be able to get the net distribution like this. This shift increases because minus h_c gamma w which actually gets added to this effective stress. So it is nothing but the total stress. So sigma dash is equal to sigma plus gamma w h_c at this particular point. So it exhibits high effective stress at this particular zone. And then here this particular variation is resulting due to this particular distribution.

So one has to keep in mind that this capillary saturation is not generally kept in design because in case of any flooding or any evaporation, particularly case like when this is evaporated this effective stress can be lost. Because this is subjected to climatic conditions and it is very difficult to consider and keep this in design.

Now let us look this particular phenomenon with respect to the practical examples. We all know when a lump of dry unconsolidated grains are piled then it can form something like a cone of heep. So the angle of inclination of the cone of heep, the maximum slope which can take is called angle of repose. So dry unconsolidated soils will form a pile with a slope angle determined by angle of repose.

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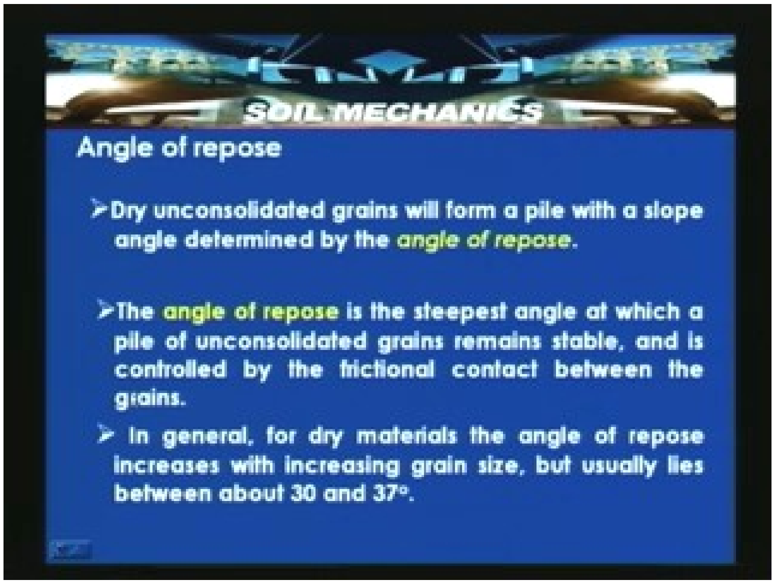

So the angle of repose is the steepest angle at which a pile of unconsolidated grains remains stable and is controlled by the frictional contact between the grains. So in general for dry materials the angle of repose increases with increasing grain size but usually lies between about 30 to 37 degrees. So around 30 to 37 degrees it takes something like a cone shape, then the moment it reaches the particular angle then the soil starts fail.

That is the maximum slope at which the particles can stand may be around 30 to 37 degrees and it can increase with increase in diameter. But however it remains in 30 to 37 degrees. So in the case of dry condition like this but the same soil particularly what we are now considering is that we are having say sandy soil then we will see this role of water with clay soils it is entirely different. So here with the same soil under wet condition is entirely different.

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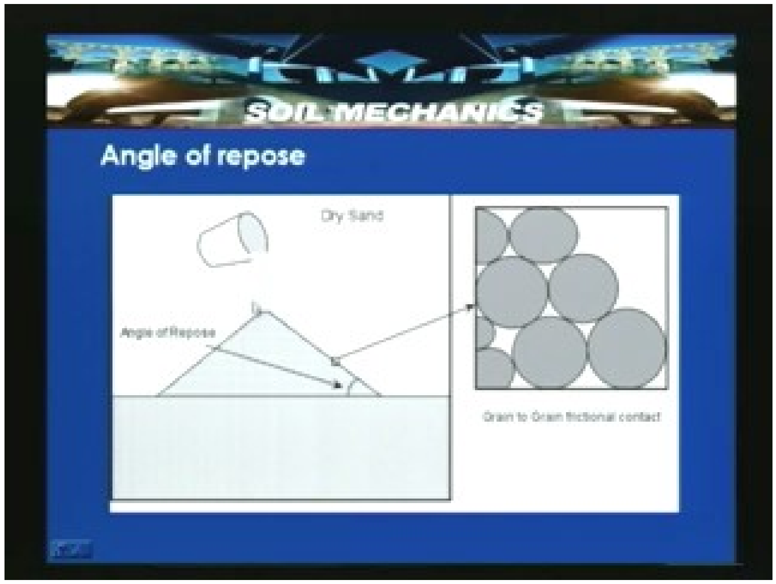

So let us see this is that dry condition. What we are seeing is the angle of repose, so this is that slope which is called angle of repose. What we are seeing is, it can increase with the diameter of the particle. And this angle, suppose if you look through the microscopic view then the grain to grain frictional contact will be there. With that it exhibits this particular type of structure. So what we can see is that as we are pouring the sand, after reaching this angle of repose then soil starts slipping. That means it is the same slope in which the grains can stand. But if the same soil is made wet and then the angle of repose can increase very high.

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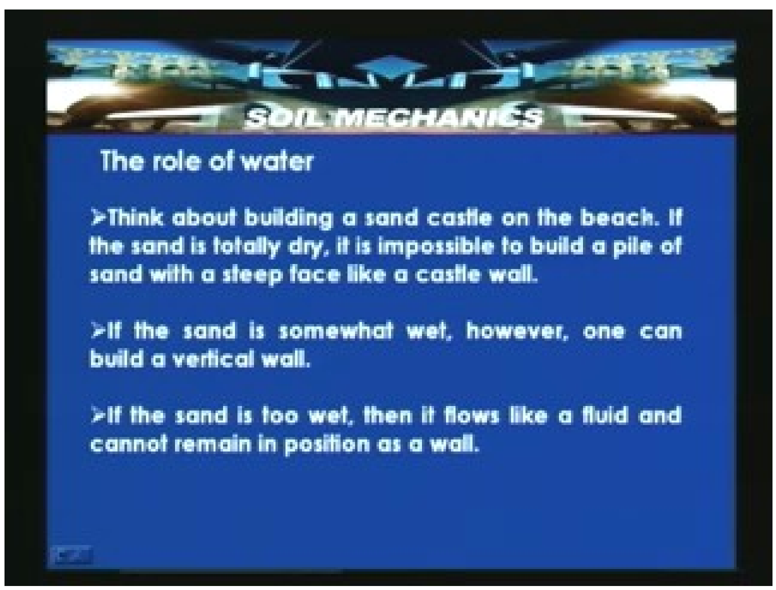

So think about building a sand castle in the beach. If the sand is totally dry it is impossible to build a pile of sand with a steep face like a castle wall. Just now we have discussed, it is very difficult to build steep slope with a dry unconsolidated grain. If the sand is somewhat wet however one can build a vertical wall. So if the sand is too wet then it flows like a fluid and it cannot remain in position as a wall. So if it is too wet then it tries to flow like a fluid and if it is wet then what can happen is that one can even build a vertical wall. We can even get very high angle of repose conditions. So that is what demonstrated here.

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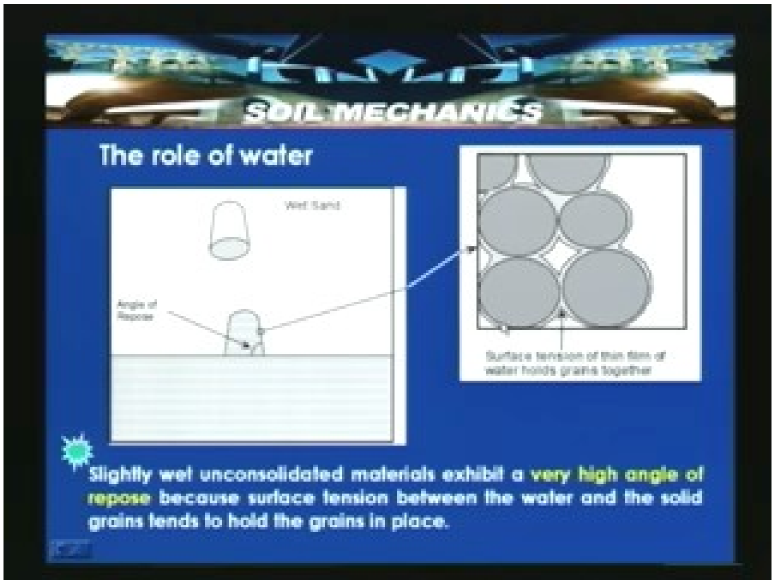

If you take a wet sandy soil, you can make any shape by putting in a glass and then removing that. And that is actually shown here. What you are seeing in the above slide is something like a thin film of water surrounding these particles. So when the water is just sufficient to bind the particles, the film is formed and then it tries to hold the particles but the same water or some films can be lost due to the extra flooding. If you wet the sandy soil completely then this films are lost and then what will happen is that soil starts flowing again. So slightly wet unconsolidated materials exhibit a very high angle of repose because of the surface tension between the water and the solid grains tends to hold the grains in place.

When the material becomes saturated with water, the angle of repose is reduced to very small values. That means here if you see the angle of repose is reduced and the water occupies the space between the grains and the grain contact is lost. So the frictional angles have reduced to very low values. So the material tends to flow like a liquid. This is because the water gets between the grains and eliminates the grains to grain frictional contact. When this happens it starts flowing.

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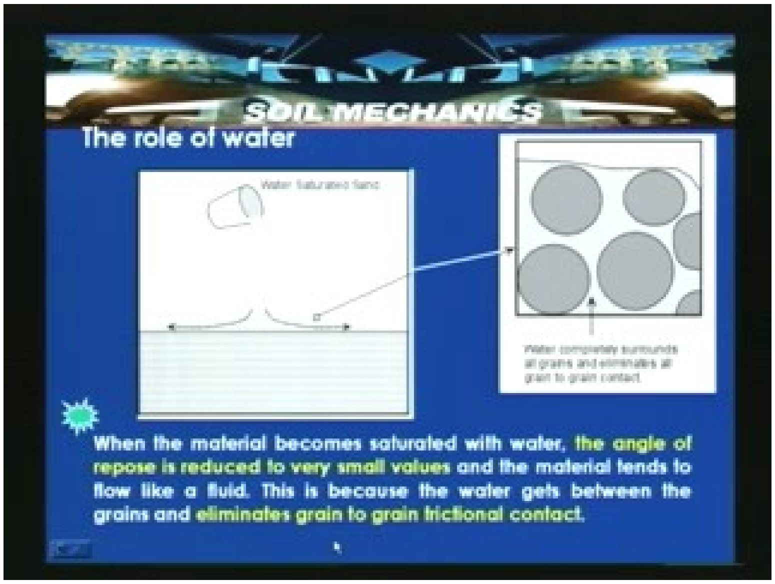

Contrary to this the behavior is entirely different. For a clayey soil or the soil which is having a smectites or montmorillonites, when the water is supplied it tries to keep it or swell or expand. So that particular behaviour is shown in the slide where this is unexpanded clay and this is an expanded clay with pore water molecules. So soil containing smectites or montmorillonites expand when they become wet as water enters the crystal structure and increases the volume of the mineral.

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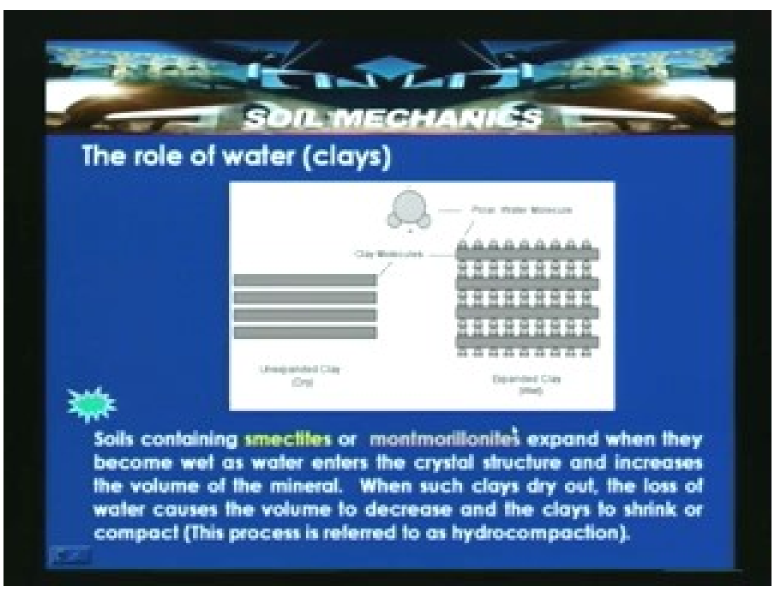

So when such clays dry out, the loss of water causes the volume to decrease and the clays to shrink and compact. So this process is referred as hydro compaction. So when such clays dry out, the loss of water causes the volume to decrease and clays to shrink or compact. So this particular behaviour is called hydro compaction. So we have seen a different role of water with sand and clay.

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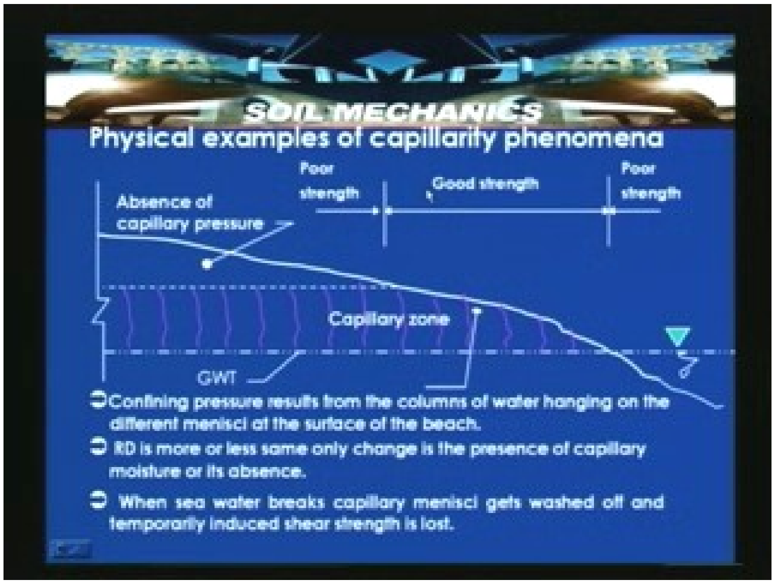

And the physical examples of capillary phenomena we can give something like along the beach. As we said very close to the beach, where it can have very good strength. Away from the beach, the absence of capillary pressure it is very difficult to walk or very difficult to ride. In this zone one can ride the motorcycle or one can chase because the negative columns of water that is these pink lines are nothing but the capillary columns are filled with water under tension. So the effective stress is minus gamma w h_c plus total stress, it becomes something like it has got an effective stress which is nothing but gamma w h_c.

That actually has a positive effective stress here so that actually can provide a good support. Where as when the wave breaks here or almost it is lost here, so it is very difficult to stand even in this zone (Refer Slide Time: 54:28). Away from this zone it is again difficult to walk because it is getting away from this capillary zone. So confining pressure results from the column of water, hanging on the different menisci on the surface of the beach that is because of this capillarity phenomenon. And if you consider relative density, it is more or less the same throughout the area. But even then it exhibits this particular behavior.

So in this class what we tried to understand is that a concept of capillarity phenomenon and its consequent effects on this effective stress particularly what will happen when you have got different soils. Then why the soil tends to remain saturated and we understood that it depends upon the pore size of the soil. The smaller is the pore size then the larger is the capillary height. Then we also discussed the theory behind the particular phenomenon and why the reasons are attributed to something like a surface tension which is a fluid property, then the attraction between the grain surfaces, inner surfaces and air water surfaces. So this phenomenon is something like capillarity phenomenon which we have introduced. And also discussed about the theory behind the capillary rise. We have discussed the rate of capillary rise for different types of soils. Then we said that because of virtue of the low permeability it can exhibit very gradual but it can rise even up to large meters because the pore space is very small. We have seen effective stress in hydrostatic conditions. In the next class when water is subjected to some study seepage conditions and we will discuss how this effective stresses can change.