Expansive Soil
Professor Doctor Anil Kumar Mishra
Department of Civil Engineering
Indian Institute of Technology Guwahati
Lecture 10
Factors Controlling DDL Thickness

Hello everyone, welcome to the course on expansive soil.

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In continuation with this, learning about the swelling behavior of expansive soil, today we will learn about the different factors which controls the diffuse double layer thickness. In the earlier classes, we learned about the different clay minerals, their properties, their formations, their structures, and also we learned about the different attractive and repulsive forces and also the diffuse double layer thickness, how to determine the diffuse double layer thickness, and what are the zeta potential what are the stern potential. So, today we will learn about the different factors which controls the diffuse double layer thickness.

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In continuation with the diffuse double layer, just I would like to remind you about the diffuse double layer thickness, here we have a clay surface which is negatively charged. So, you know how the clay has got their negative charges. And there are exchangeable cations which are present over here. When we add some salt solution to it, this the equilibrium between the cations and the clay surface will get disturbed. Initially when the soil is dry, these cations will be strongly attracted towards the clay surface, but after adding some water or some liquid, this equilibrium get disturbed.

Because there will be a concentration gradient developed between the clay surface and a distance away from the clay surface. The cations concentration was initially higher near to the clay surface; it was low far away from the clay surface. As a result of which the cations which were earlier attracted by this negatively charged plates will try to move away from the clay plates because of the process of diffusion.

So, this is quite similar to our Earth's atmosphere, where the gravitational pull of the Earth try to pull the air molecules towards its direction whereas, the process of diffusion will try to pull the air molecules in the upward direction. So, this two competitive forces then will be in equilibrium and there will be a distribution of the air molecules in the atmosphere, that is called atmospheric distribution, and the density of the air molecules will keep on decreasing as you move away from the Earth's surface.

So, similar kind of distribution takes place with these cations and the water molecules over here. The concentration of the cations will keep on decreasing as we move away from the clay plates. And next to the clay plates there will be a large amount of cations but as we move away from the clay plates, the cation concentration will decrease. So, finally, there will be an equilibrium until the anion concentration and cation concentration will be almost identical. And this distribution will be known as the diffuse double layer of clay water system.

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If we look into the clay plates and different types of water molecules present in the clay-water system, there are three main types of water present in a clay-water system. The first layer is known as adsorbed water, which is three to four layer of thickness and the thickness is around 10 angstrom, this water is being very strongly attracted towards the clay plates. So therefore, the engineers try to avoid this because it needs a large amount of pressure to remove these water molecules. Therefore, it has been taken as an integral part of the clay surface.

Next comes the diffuse double layer water. Generally the thickness of this water is quite large in comparison to adsorbed water and this water is less strongly attracted towards the clay plates in comparison to the adsorbed water and the thickness of this double layer water can be changed by changing different parameters. So therefore, this water plays an important role in defining clay behavior. And next to the double layer water there will be free water which is like not at all attracted by the clay plates. And this is a normal water which we see. We will study about how this double layer water gets affected by different factors.

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This is the equation which governs the diffuse double layer thickness, which we studied in the last class. So, if we look into this equation, this the Deby’s length is controlled by these parameters. So, before going into details, we can see this variation of the electrical potential with a distance and we can see next to the clay plates, there is a surface potential and Stern layer, there will be Stern potential, but after this Stern potential there will be diffused double layer water or diffuse double layer.

So, in diffuse double layer the electrical potential varies like this one and this distance is known as Deby's length and which controls the diffuse double layer thickness. So, here we can see the Deby's length is a function of dielectric constant, permittivity of the medium, temperature, then the concentration of the ion and the valency of the ion or valency of the counter ions. So, these are the different factors which controls the diffuse double layer thickness.

And since, the Boltzmann constant K and is the electrical charge e are constant one, so we are not considering here. So, these are the factors which controls the diffuse double layer thickness of a clay-water system. And we will learn how this individual factors controls the diffuse double layer thickness.

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If we look into the different parameters, which controls the diffuse double layer thickness, we will come across two different types of factors. The first factors depends on the soil and the second factors depends on the pore water chemistry. Here pore water means the water which is present in the pore space of the soil particles. We know that soil has pore spaces or void spaces those are filled with water. So, if we change the chemistry of that water by changing the electrolyte concentration, the valency, the dielectric constant, the temperature, the size of the hydrated ions, then that will controls the diffuse double layer thickness.

So, therefore, there are two factors which generally governs the diffuse double layer thickness. First comes from the soil itself, second comes from the pore water chemistry. Talking about the factors of the soil which controls the diffuse double layer thickness, first comes the types of mineral. We have studied about different types of mineral like montmorillonite, illite, kaolinite, halloysite. So out of this minerals, montmorillonite generally poses a very high value of diffuse double layer thickness in comparison to illite and kaolinite.

Next comes the specific surface area, we know that specific surface area controls the amount, total amount of negative charges, higher is the specific surface area, higher will be the total negative charge and more is the total negative charge higher will be the diffuse double layer thickness.

If we compare with the different type of minerals, generally montmorillonite has a higher value of specific surface area in comparison to illite and kaolinite. Therefore, montmorillonite will have higher value of net negative charges. And therefore, higher value of the diffuse double layer thickness in comparison to illite and kaolinite.

Next comes the exchangeable cations. We also study that how the different type of exchangeable cations are present in say montmorillonite soil. These exchangeable cations can be sodium, potassium, magnesium, and depending on whether it is a sodium or potassium or calcium or magnesium, the diffuse double layer thickness will be different.

Say for example, sodium, generally sodium are lightly attached or attracted towards the clay surface in comparison to calcium. Being a di-valent, calcium will be very strongly attracted. Therefore, the diffuse double layer thickness of calcium, as an exchangeable ion will be less in comparison to sodium, because sodium will be very lightly or less strongly attracted towards the clay surface. Similarly, if we compare the size of the cations, generally larger is the size, larger will be the force of attraction. So therefore, what type of cation we have in the exchangeable side, the diffuse double layer thickness will be different.

Next comes the pore water chemistry. So, pore water chemistry means in the electrolyte concentration like what is the concentration of the pore water, if the concentration is more than the more amount of counter ions will be there, more is the counter ions, the thickness of the diffuse double layer will be less. Similarly, the valency of the cations of the pore water, if the ion valency is more, so it will be attracted more strongly towards the clay surface and diffuse double layer thickness will be more.

Dielectric constant, temperature, size of the hydrated ions, pH, anion adsorptions all these factors also contributes to the thickness of diffuse double layer or all these factors controls the diffuse double layer thickness of a clay-water system. We will learn individually how these factors controls and in what way they controls.

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But question is how this behavior of the soil gets changed, when there is a change in the diffuse double layer thickness. We can see that, with increasing the diffuse double layer thickness, these are the factors get affected. As, we increase the diffuse double layer thickness the amount of water present in the diffuse double layer will also increase. As the amount of water present in the diffuse double layer will increase these properties will get changed.

So, if we look into this, this are the index property and these are the engineering properties. Now, first look into the index properties. First is a free swelling; free swelling means, so will allow the soil to swell without putting any overburden pressure to it. So, when there is an increase in the diffuse double layer thickness, the free swelling of the soil will increase. Because it can absorb more water, therefore, the swelling will be more.

Similarly, the liquid limit will also increase, as the liquid limit increases, the plasticity index will increase, as a plasticity index increases that means the soil can be molded into different shapes at a large amount of water content. Talking about the engineering properties the compression index increases indicating the soil will be compressed to a large extent, the swelling pressure will increase that means, the soil will exert a large amount of pressure on the structure above it.

Swelling potential will increase that means the the total swelling which should be expected will also increase. The hydraulic conductivity will decrease that means water cannot pass easily through the soil. Coefficient of consolidation decreases that means the rate of consolidation will decrease. So, consolidation will take place very slowly.

Unconfined compressive strength will decrease, that means the soil will possess less value of strength when there is an increase in the diffuse double layer thickness. And, the reversing happens when there is a decrease in the diffuse double layer thickness. So, these are the various factors on how they got changed when an increase in the diffuse double layer thickness takes place.

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Here we will learn how they get affected by changing the one parameter keeping the other parameters constant. So, to summarize those things, that diffuse double layer thickness will increase with increasing the montmorillonite content, the specific surface area and the exchangeable sodium percentage. So, this comes from the soil factors.

The diffuse double layer thickness will increase by decreasing the electrolyte concentration and decreasing the ion valency and the diffuse double layer thickness will increase by increasing the dielectric constant, size of the hydrated ions, pH, anion adsorption and temperature. So, this comes from the pore water chemistry.

We will learn individually how these factors affect the diffuse double layer thickness. First comes the electrolyte concentration. Here, we will change one parameter keeping the other parameters constant. So that we will learn or we will see how this one parameter will control the diffuse double layer thickness.

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If we look into the previous equations, we will see the diffuse double layer thickness d is inversely proportional to square root of the electrolyte concentration. That means if we change the concentration, say for example, if we take sodium chloride solution of concentration 0.01 N and if we take another concentration 0.1 N, 1N. So, here we are changing the ion concentration by changing this ion concentration that diffuse double layer will change.

Say for example for 0.1 N concentration, the diffuse double layer thickness will be higher and for 1 N it will be lower or it will be lowest in comparison to this three concentrations. So, that means, the diffuse double layer thickness is inversely proportional to square root of this concentration. Because, higher is the concentration, higher will be the number of counter ions and higher will be the force of attraction between the clay plates and this counter ions, therefore, the diffuse double layer thickness will be less.

With increase in the concentration of the pore fluid, the swelling will decrease. Here we can see at 1 N the swelling will be less in comparison to 0.1 N of sodium chloride. The liquid limit will decrease, the swelling pressure will decrease, swelling potential will decrease, the compressibility will decrease, the hydraulic conductivity will increase and the unconfined compressive strength will increase. So, this things takes place when there is an increase in the concentration of the pore fluid.

Here in this graph, we can see how the diffuse double layer thickness gets affected by changing the concentration. This is a plot between the electrical potential with the distance for two concentration 4C and C. The green line indicates the distribution of the ions or diffuse double layer for a concentration of C, whereas, this line indicates the, for its concentration 4C.

We can see that the diffuse double layer thickness is large for the concentration C in comparison to 4C. Now, if we compare these properties for this type of pore water, say for example, for 1 N of sodium chloride solution, the swelling will be least, the liquid limit will be least, the swelling pressure will be lowest, swelling potential will be lowest, compressibility will be lowest. However, the hydraulic conductivity will be more and unconfined compressive strength will be more.

If we compare with 0.01 N of sodium chloride the swelling will be highest, the liquid limit will be highest, the swelling pressure will be more, swelling potential will be more, compressibility will be more, but on the other hand the hydraulic conductivity will be less and the unconfined compressive strength will be less. So, electrolyte concentration is inversely related with the thickness of diffuse double layer.

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Next comes the cation valency. Diffuse double layer thickness is inversely proportional to the valency of the cation. In this plot, we can see how the diffuse double layer thickness of two salt solutions gets deferred with the change in the valency.

Here we can see, the green line indicates the diffuse double layer thickness for a salt solution with a constant of the cation of valency v and the red line with for cation 2v and we can see that with increase in the cation valency, the diffuse double layer thickness is decreasing. That means if we take equal concentration of sodium chloride solution and calcium chloride solution then we will observe this kind of plot for sodium and this kind of plot for calcium. That means, the sodium will have a higher value of diffuse double layer thickness in comparison to the calcium.

This relation indicates, with increase in the valency of the cation, the swelling decreases the liquid limit decreases, the swelling pressure decreases, swelling potential decreases compressibility decreases, but hydraulic conductivity increases and unconfined compressive strength increases.

If we compare with this two salt solution of sodium and calcium ion of 0.01, say for example, then we will observe that for sodium chloride solution the swelling will be more, the liquid limit will be more, the swelling pressure will be more, swelling potential will be more compressibility will be more, but the hydraulic conductivity will be less and unconfined compressive strength will be less. This is because of this attraction for calcium and sodium by the clay plates.

Since it is mono-valent, the force of attraction will be released in comparison to the divalent. Since the force of attraction will be less, so, it can be removed and water can go in into the system. Therefore, the diffuse double layer thickness will be more for sodium in comparison to the calcium.

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Next comes the dielectric constant. As per as the equation the dielectric constant is directly related with the diffuse double layer thickness. The diffuse double layer thickness is directly proportional to square root of the dielectric constant. So, that means with a decrease in the dielectric constant the diffuse double layer diffuse double layer thickness will decrease or with an increase in the dielectric constant the diffuse double layer will increase.

If we plot for two different dielectric constants say D and 4D, we can see the variation in the distribution of the diffuse double layer thickness. When the dielectric constant is D, the plot will be this one. Whereas, with increasing the dielectric constant the plot will be given by this line.

So, say for example, we can take carbon tetrachloride and say the water. Generally, carbon tetrachloride or organic compounds have a lower value of dielectric constant. So, CCl_4 has a dielectric constant of 4 and similarly, the water has a dielectric constant of 80. So, that means, for dielectric constant of 4 the diffuse double layer thickness will be less. Since diffuse double layer thickness is directly proportional to the dielectric constant, the lower value of dielectric constant will yield a lower value of diffuse double layer thickness.

Similarly, for water the diffuse double layer thickness will be more. So, with a decrease in the diffuse double layer thickness, the swelling of the soil will decrease, the liquid limit of the soil will decrease, the swelling pressure will decrease, swelling potential will decrease, compressibility will decrease, but the hydraulic conductivity will increase and unconfined compressive strength will increase.

So, if we compare between these two pore water, carbon tetrachloride will have low value of swelling or in expansive soil in presence of carbon tetrachloride will have low swelling value, lower liquid limit value, lower value of swelling pressure, lower value of swelling potential, lower value of compressibility, but a higher value of hydraulic conductivity and higher value of strength.

Similarly, if we increase the dielectric constant, the swelling will keep on increasing, the liquid limit keep on increasing, swelling pressure will keep on increasing, swelling potential, compressibility will increase, but the hydraulic conductivity and unconfined compressive strength will decrease.

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Next comes the temperature. The thickness of diffuse double layer varies directly to the square root of the temperature, that means, with an increase in the temperature the diffuse double layer thickness will increase. By increasing the temperature, it will impart some kinetic energy to the ions. Therefore, the ions will be in a vibratory motion and because of that, there will be an increase in the diffuse double layer thickness.

We can see in this two plots. The first plot indicates, the yellow one indicates the diffuse double layer thickness at a temperature T, this one indicates that diffuse double layer thickness at a temperature of 4T. We can see that with increase in the temperature the diffuse double layer is higher in comparison to the previous one.

So, a decrease in the temperature, the swelling of the soil will decrease, the liquid limit will decrease, the swelling pressure will decrease, swelling potential will decrease, the compressibility will decrease, hydraulic conductivity will increase, shear strength will increase.

So, if we take water as the pore fluid and if we increase the temperature, say if we conduct two test at 40 degrees centigrade and 80 degrees centigrade, then at 40 degrees centigrade the swelling will decrease or at 40 degrees centigrade, the soil will possess lower swelling value, lower liquid limit value, lower swelling pressure value lower swelling potential value, lower compressibility value, but it will possess a higher value of hydraulic conductivity and higher value of shear strength in comparison to at 80 degree centigrade.

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Next comes the size of the hydrated cations, we know that because of this hydration energy, the cations can absorb some water molecules. So, this is a cations and the water has, we know that is a dipolar. So, it can absorb some water molecules and again these water molecules attract some other water molecules like this one.

So, generally there will be three to four layer of the water molecules which will be attracted by the cations. And this hydrated cation of different radius also influence the diffuse double layer thickness. Thickness of the diffuse double layer varies inversely to the size of the hydrated cations. With the increase in the size of the hydrated cations, the swelling will decrease, the liquid limit will decrease, the swelling pressure will decrease, the swelling potential will decrease, compressibility will decrease, but the hydraulic conductivity will increase.

Here we can see, sodium with a hydrated radius of 5.6 to 7.9 angstrom will have a higher value of diffuse double layer thickness in comparison to calcium which with which has a 9.6 Angstrom of hydrated radius. So, this indicates, with increase in the size of the hydrated cations the diffuse double layer thickness will decrease.

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Next comes the pH, the thickness of the diffuse double layer varies directly with the pH of the pore fluid. We know pH means the H^+ ion concentration. The clay has negative charge on the surface and with the decrease in the pH that means the H^+ ion will increase. So, this H^+ ion will occupy or will be attracted towards this clay surface and therefore, the diffuse double layer thickness will decrease.

Here we can see with decrease in the pH of the pore fluid that means, we move towards more acidic solution, the swelling will decrease, the liquid limit will decrease the swelling pressure will decrease, swelling potential will decrease, the compressibility will decrease, on the other hand the hydraulic conductivity and shear strength will increase.

So, this happens at low pH, but if we increase the pH then the OH^- will increase and because of that, the soil will have more negative charges and because of that the diffuse double layer thickness will increase and swelling will increase, the liquid limit will increase and so on. So, therefore, pH of a pore water is inversely proportional to the thickness of the diffuse double layer. So, these are the factors which comes from the pore water.

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The other factors, like factors coming from the soil like type of minerals, specific surface area, type of exchangeable, controls a diffuse double layer as I discussed earlier. Like if we take a soil sample with a large amount of montmorillonite content, means it will have higher diffuse double layer thickness and more amount will be swelling in comparison to illite and kaolinite mineral.

Next comes the specific surface area, higher is a specific surface area, higher will be the net amount of negative charges, higher is the net amount of charges, higher will be the diffuse double layer thickness.

Then comes the type of exchangeable cations. As we know that different type of exchangeable cations are sodium, potassium, calcium and magnesium. Since sodium is monovalent and smallest of all this, it will be less strongly attached to the clay surface. So, it can be removed easily and water can go inside, so more is the sodium ion as an exchangeable cations, more amount of water can go in, and higher will be the diffuse double layer thickness.

If we compare with others, calcium because of this divalent and also larger size, the calcium ions will be strongly attracted towards the clay plates and it will be difficult to remove. Therefore, the DDL thickness or diffuse double layer thickness will be less in comparison to sodium or potassium. So, therefore, with an increase in the amount of sodium as an exchangeable cations or increase in exchangeable sodium percentage of a soil, the diffuse double layer thickness will be more and the swelling liquid limit, swelling potential, swelling pressure will be more and higher conductivity and shear strength will be less.

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Next, we will learn how the properties of the clay gets affected by the diffuse double layer thickness. We will start with the arrangement of the clay particles.

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This is clay particles, we know that there is a negative charge on the clay surface and at the edge there are positive charges. These clay particles can be arranged in this three manner. The first one is edge to edge. So, this one is called face of a particle and this is called the edge of the particle. Now, the edge this plus and this plus can be brought together, so this arrangement is called edge to edge arrangement.

Next comes the edge to face. The positive end, or positive edge of this clay particles can lie on the negative surface on the clay particles. So, that is called edge to face. The third one is known as face to face. The negative end of the face can be brought to negative end, or negative surface of the other clay plates. So, that is called face to face.

Now, here we need to remember one thing that since the same charge repel, we need additional pressure to bring this two kind of arrangement or to bring this kind of arrangement to the clay-water system, we need external pressure because the natural tendency of the charges will be repelling when the charges are same.

So, plus plus will repel in this case, the minus minus will repel. So, by adding some additional or external pressure, the particle can be arranged in this two manner. On the other hand, the edge to face will be a natural arrangement, because the negative charge and the positive charge will attract each other because they are opposite in sign. So, therefore, here we do not need any additional pressure.

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By arranging the particles, we can get a flocculated structure and we can get a dispersed structure like this. In flocculated structure, the negative end and the positive end will lie like this and in dispersed structure, the particles will present like this one. Here, we need to remember that the tendency towards the flocculation will increase when there will be a reduction in the repulsive pressure. Anything which controls the repulsive forces will also controls the structure of the soil.

That means by reducing the repulsive forces, we can bring the structure to a flocculated state in rather than a disperse state. Or in other way, if we reduce the diffuse double layer thickness the particles becomes flocculated structure. So, what are the factors which reduces the diffuse double layer thickness, these are increasing the electrolyte concentration, increasing the ion valency and increasing the temperature or by decreasing the dielectric constant, decreasing the pH or the size of the hydrated ions.

So, therefore, by changing the pore water by this fashion, we can increase the tendency of a soil towards a flocculated state by reducing the repulsive forces. When the particles are in flocculated state, the hydraulic conductivity will be higher, the shrinkage will be higher and the soil will have a higher resistance to the compressibility and the soil will possess low volumetric shrinkage.

So, therefore, by reducing the repulsive forces, the particle will come to a flocculated state and how do we reduce the repulsive forces, by reducing the diffuse double layer thickness or by increasing the electrolyte concentration, ion valency or temperature or decreasing the dielectric constant, pH we can reduce the diffuse double layer thickness which in turns reduce the repulsive forces.

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Next will be the swelling. Swelling of the soil indicates the amount of water the soil is absorbing and the soil which shows the swelling behavior will be known as an expansive soil. More amount of water adsorbed more amount the swelling will take place and more will be the swelling if the diffuse double layer thickness will be more, or higher is the diffuse double layer thickness, higher will be the amount of water adsorbed to the system and higher will be the swelling. So, any factors which increases the diffuse double layer thickness will also increase the swelling of a soil.

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So, what are the different factors which changes the diffuse double layer thickness? Like clay mineralogy, surface area, type of exchangeable cations and pore water chemistry. In terms of clay mineralogy, whether it is a montmorillonite or illite or kaolinite. If it is montmorillonite, the swelling will be more because the diffuse double layer thickness will be more; for kaolinite the swelling will be least because the diffuse double layer thickness will be least developed in kaolinite.

For specific surface area, higher is a specific surface area, higher will be the net negative charges, more amount will be water absorbed to the soil and higher will be the swelling. Presence of an exchangeable cations with lower valency will increase the swelling because that will increase the diffuse double layer thickness.

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Similarly, presence of salt will reduce the diffuse double layer thickness and so, the swelling of the soil will decrease. By increase the dielectric constant the swelling of the soil will increase. So, for example, if we take water and CCl_4, more swelling will take place for water in comparison to carbon tetrachloride because the diffuse double layer thickness will be high for water in comparison to the carbon tetrachloride.

Similarly, if we take here, a two salt solution say for example 0.1 N of sodium chloride and 0.001 N of sodium chloride, the swelling will be least here, the swelling will be more here. Less swelling and high swelling. The less swelling of this one because of the diffuse double layer thickness will be less and for this one the diffuse double layer thickness will be high. Any factors which controls the diffuse double layer also controls the swelling of the soil. Higher is the diffuse double layer thickness, higher will be the swelling, less will the diffuse double layer thickness, less will be the swelling.

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Here we can see, the test was carried out here. This is a swollen soil, this is a swollen soil, if we compare in all these three, this is with DI water that means 0 N concentration, this is 0.1 N, this is 1 N, we can see that with increase in the concentration, the volume of the soil will keep on decreasing or the swelling keep on decreasing.

Similarly, if we compare with the valency, this is sodium monovalent, this is calcium divalent and Fe trivalent, we can see with increase in the valency the swelling of the soil keep on decreasing. Here it compares the swelling in terms of mineral present in the soil, montmorillonite will swell to a higher extent in comparison to illite and kaolinite. Similarly, here compares the dielectric constant. Water which is a dielectric constant of 80 will give the soil to a higher swelling in comparison to carbon tetrachloride which will give the least swelling to the soil.

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Next comes the liquid limit. Liquid limit is defined as the water content at which soil changes from liquid state to plastic state. So, different researchers has given value of shear strength which is indicating the shear strength of the soil at a liquid limit. The liquid limit can also be defined as the water content at which the soil will have least value of undrained shear strength which can be measured in the laboratory.

As per as Mitchell and Soga that shear strength is around 2.5 kPa and for Russell this is 1.7 to 2 kPa. The liquid limit of a soil depends directly on the thickness of diffuse double layer. So, any factors which controls the diffuse double layer thickness also controls the liquid limit of the soil. So, clay mineralogy and pore water chemistry which controls the diffuse double layer also controls the liquid limit of the soil.

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If we compare with the clay minerals, so, since, the diffuse double layer thickness will be more for montmorillonite soil, the liquid limit will be more for montmorillonite in comparison to illite and kaolinite. So, here in this table we can see montmorillonite has a liquid limit of around 710, illite is around 120 and kaolinite, the least one will be 53.

Similarly, if we change the exchangeable cations type present in the mineral itself, the liquid limit also changes. By replacing sodium by calcium the liquid limit got decreased from 710 to 510, and so, the plasticity index. So, therefore, in in terms of clay mineralogy, what kind of minerals and what kind of exchangeable contains controls the liquid limit of the soil. Similarly, the specific surface area, cation exchange controls the liquid limit, higher is a specific surface area, higher will be the liquid limit of the soil.

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In terms of pore water chemistry, the presence of pore water influence the diffuse double layer thickness and consequently it changes the liquid limit of the soil. So, liquid limit can decrease with increase in the valency of the cations and concentration of the pore fluid. That means, if we take two salt solutions, say for example, sodium chloride of 0.1 N and 0.01 N, so, liquid limit for this soil will be more in comparison to this one, because the thickness of the diffuse double layer for 0.1 and sodium chloride will be less in comparison to 0.001 N of sodium chloride solution.

If we take two salt solution of same concentration higher will be the valency lower will be the diffuse double layer thickness. If we take 0.01 N of sodium chloride and calcium chloride we will find that the liquid limit for sodium chloride will be more in comparison to calcium chloride, because the diffuse double layer thickness for sodium chloride of 0.01 concentration will be more in comparison to the calcium chloride solution because the diffuse double layer thickness will be less.

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Similarly, the other parameters we can see the liquid limit and dielectric constant with decrease in the dielectric constant the liquid limit will decrease. So, here we can see this is higher value of liquid limit for water and this is for say for example carbon tetrachloride. So, for carbon tetrachloride the liquid limit will be very low in comparison to water, because for water the diffuse double layer thickness will be more in comparison to CCl_4.

Similarly, with increasing the ESP or Exchangeable Sodium Percentage, the liquid limit will increase because with higher ESP, the diffuse double layer thickness will be more. If we plot for liquid limit with different salt concentration, we can see, for sodium chloride solution generally we have a higher value of liquid limit in comparison to calcium chloride and aluminum chloride for same concentration. If we take the same concentration, the aluminum chloride will have least value of liquid limit in comparison to calcium chloride and sodium chloride.

Next comes the hydrated ionic radius. We can see that with decrease in hydrated ionic radius, the diffused double layer thickness will increase and so, the liquid limit will also increase.

Lithium will have more value of liquid limit in comparison to montmorillonite with sodium and so, the magnesium and calcium. This indicates, if the hydrated ionic radius is increased, that means the liquid limit will decrease.

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Next comes the swelling potential of a soil. First, we try to understand what is the meaning of swelling potential, I will explain this terms and how to determine the swelling potential in the next few classes. The swelling potential of a soil is defined as the percentage swelling of a compacted laterally confined sample soaked in liquid under a surcharge pressure of 4.9 kPa. That means, I will take a compacted sample like this one with an initial height of H and then I will apply a surcharge load of 4.9 kPa, then I will submerge these samples in a liquid, this liquid can be water or any salt solution.

Now, this sample will try to absorb the water and as a result of which it will try to swell and it will swell by an extent of ΔH or it will swell by an amount of ΔH then it will stop. Then the swelling potential will be defined as the ratio between this ΔH that means, the change in the height to its original height and it is expressed in terms of percentage.

$$\text{Swelling potential} = \frac{\Delta H}{H} \times 100$$

So this swelling potential indicates what is the tendency of a soil to swell or how much or to what extent the soil can be swelled, if it absorbs water molecules.

Now, the swelling potential directly depends upon the diffuse double layer thickness, higher will be the diffuse double layer thickness, higher will be the swelling potential higher will be; higher is the swelling potential. So, any factor which increases the diffuse double layer thickness also increases the swelling potential.

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We know that these are the factors which controls the diffuse double layer thickness. So, the same factor also controls the swelling potential of the soil. Since, these factors increase diffuse double layer thickness, the same factor will also increase the swelling potential. That means, with a decrease in the salt concentration, decrease in the valency of the cations, increase in the pH, increase in the specific surface area, increase in the dielectric constant and increasing the temperature increases the diffuse double layer thickness which in turns increases the swelling potential of a soil.

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Next comes the swelling pressure. If we take a soil sample, which is laterally confined and if we allow the soil to swell or if we put into any liquid, then the soil will try to swell. Now, what we will do is we will put some additional or we will put some overburden load on this soil such that it will or the load will try to prevent the soil from swelling. So, that amount of load which will try to prevent this soil from swelling is known as swelling pressure.

Here we can see this is a sample, this is a height after swelling, if we put an additional load such that this load will bring back or compress the soil to its initial height which was before the swelling then that pressure is known as swelling pressure. Or by definition swelling pressure of a soil is defined as the external pressure required to prevent the swelling of a compacted laterally confined sample soaked in liquid or external pressure required to compress a swollen literally confined soil to its original volume. So, this is the first definition this is the second definition.

This additional pressure is known as swelling pressure of a soil. Now swelling pressure is directly proportional to swelling of the soil and higher is the swelling higher will be the swelling pressure. Therefore, any factors which controls the swelling also controls the swelling pressure or any factors which controls the diffuse double layer thickness, which in turn is controlled the swelling, will also controls the swelling pressure.

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Therefore, the swelling pressure is directly proportional to thickness of diffuse double layer. So, swelling pressure of a soil depends on clay mineralogy, pore water chemistry, type of exchangeable cations and here we can see the swelling pressure of the soil will increase with the decrease in the salt concentration, with decrease in the valency of the cation, increase in the pH, increase in the specific surface area, increase in the dielectric constant and increase in the temperature.

That means, if we take sodium chloride solution of 0.01 N and 0.1 N, then the swelling pressure of this will be more in comparison to this, the swelling pressure will be less here. Why? Because the diffuse double layer thickness will be higher here in comparison to 0.1 N of sodium chloride solution.

Similarly, if we compare with different valency calcium and sodium the swelling pressure will be less here, swelling pressure will be more here, because the diffuse double layer thickness will be less here and diffuse double layer thickness will be more here. So, we can see that the diffuse double layer thickness directly controls the swelling pressure of a soil.

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Next the hydraulic conductivity. So, this is one of the most important properties of the soil which controls the various engineering applications. And here we can see how the diffuse double layer thickness also controls the hydraulic conductivity. Generally, higher is the diffuse double layer thickness, lower is the hydraulic conductivity, we can see how over here. First going by the definition the hydraulic conductivity is defined as the rate of flow of liquid through a soil and it inversely proportional to the diffuse double layer thickness.

Here we can see two clay plates, with this is absorbed water and this is diffuse double layer water. So, similarly other soil has a diffuse double layer water and this is absorbed water. Now, here this thickness of the diffuse double layer water is less. So, therefore, there are free water exists. Now, this free water can easily move through or in other word because of this water, this free water is not attracted by the clay plates, this can easily move from one point to another point. So, in other words, the hydraulic conductivity will be more for this soil.

Now, if we compare with another soil, where the diffuse double layer thickness is more, here you can see this is adsorbed water, this is the diffuse double layer water, diffuse double layer water and adsorbed water. The thickness of diffuse double layer water is significantly high. Therefore, there is no free water present between these two clay plates.

Therefore, the water movement or the free water movement is restricted here, that means the water is moving very slowly, the free water is moving very slowly, therefore, the hydraulic conductivity will be less and in this case, since the thickness of the diffuse double layer is less, this is, the double layer thickness is less the hydraulic conductivity will be more that means the water can move through the soil quite easily or quite fast.

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So, any factors which controls the diffuse double layer thickness also controls the hydraulic conductivity. As we learned earlier the diffuse double layer thickness of montmorillonite is more in comparison to illite and kaolinite, therefore, the hydraulic conductivity montmorillonite soil will be less in comparison to kaolinite and illite.

Here we can see the variation of hydraulic conductivity at different void ratio for montmorillonite illite and kaolinite. We can see here, this is for kaolinite and this is for montmorillonite or smectite. For any void ratio if we draw a void ratio line over here, the hydraulic conductivity of montmorillonite will be more in comparison to illite and kaolinite.

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Not only the type of minerals, the type of pore water also influence the hydraulic conductivity. We can see here this is water, ethyl alcohol, carbon tetrachloride and this is a permeability and void ratio, this hydraulic conductivity is for carbon tetrachloride and this is for the water.

So, by changing the pore water also we can see the effect on the hydraulic conductivity. That means, this is since this is for carbon tetrachloride the dielectric constant is 4 and this is for water, so dielectric constant is 80. So that means, by increasing the dielectric constant, the hydraulic conductivity will decrease. Similarly, if we take same salt, but different concentration we can see with increase in the concentration of the pore water, the hydraulic conductivity will increase.

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Next comes the compressibility of the soil, we know that the total stress coming to a system can be related with the effective stress, the pore water pressure and the repulsive and the attractive forces. If we can write the equation;

$$P_T = P_c + u + R - A$$
$$\text{or}, P_c = P_T - u - R + A$$

Where, P_T = Total stress, u = Pore water pressure, R = Repulsive pressure, A = The attractive pressure.

By any means, if we change the repulsive pressure that also contribute to a change in the effective stress. We can see any reduction in the repulsive pressure will increase the contact pressure, if we change the repulsive pressure, the contact pressure will also change. More is the effective stress more will be the compressibility more will be the shear strength of the soil.

So, therefore, the compressibility of the soil will increase with decrease in the salt concentration, the decrease in the valency of the cations, the increase in the pH, the increase in the specific surface area, the increase in the dielectric constant and increase in the temperature; because all these factors will reduce the repulsive pressure, reduce R.

And, why that will reduce R, because the diffuse double layer thickness will get reduced, this will reduce the R value here, as the R value will be reduced the Pc will be more, more is the Pc value more is the effective stress value, more will be the compressibility of the soil or more will be the shear strength of the soil.

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Here we can see the effect of the cation valency on the compressibility. This is, the first line indicates for lithium ion, the second one for sodium and the last one for aluminum. That means, with an increase in the valency the compressibility of the soil is decreasing; that means, the soil can be compressed to a lower value if we change the pore water of a higher valency.

Similarly, if we take different concentration of same pore type we can see, if the pore water has higher concentration, then the compressibility of the soil will be less or the soil can be compressed to a lower value.

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Similarly, if we change to different dielectric constant, we can see with the increase in the dielectric constant the compressibility of the soil will be increased, higher is the dielectric constant higher will be the compressibility that means the soil can be compressed to a higher extent in comparison to soil containing a lower value of dielectric constant.

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Next comes the compression index. Compression index generally indicates the extent of the soil which can be compressed. Generally, this is determined from the slope of this virgin portion of the curve. The slope of the straight-line portion of the virgin e-log P is known as compression index or Cc.

A higher value of compression index indicates higher value of the settlement of the soil. Higher will be the diffuse double layer thickness, higher will be the compression index of the soil. So, if a soil having higher liquid limit or higher diffuse double layer thickness will also indicates it will have a higher value of compression index. So, any factors which increases the diffuse double layer thickness also increases the compression index.

We can see those factors like amount of montmorillonite which have a higher value diffuse double layer thickness, will have higher value of compression index in comparison to kaolinite and illite. Similarly, the pore water chemistry that means with increasing the valency and concentration of the salt pore water, the compression index decreases because this will reduce the diffuse double layer thickness. So, which will in turn decrease the compressibility of the soil or compression index of the soil. Here we can see the different ions of a different heavy metals and their effect on the compressibility.

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Next comes the unconfined compressive strength. So, with reduction in the diffuse double layer thickness the repulsion between the particles decreases, with a reduction in the repulsion between the particles the inter particle distance will decrease, as the inter particle distance will decrease the effective stress will increase and once the effective stress increases the unconfined compressive strength also increases.

That means any factors which reduces the diffuse double layer thickness will increase the unconfined compressive strength. So, that means higher valency, higher concentration, low dielectric constant will increase the compressive strength of the soil.

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These are the few points which I discussed in today's class.

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So, these are the different references which are made for this lecture. And with this I will conclude today's lecture. And thank you very much for your attention.