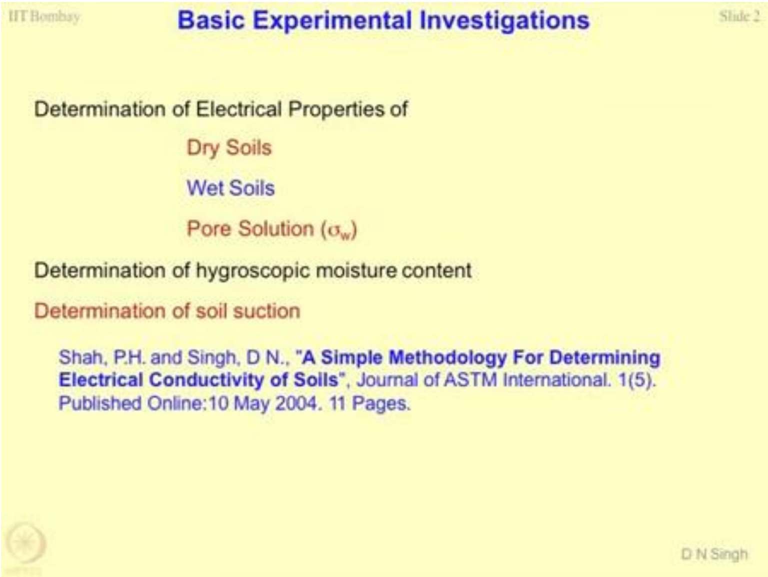
Environmental Geotechnics
Prof. D. N. Singh
Department of Civil Engineering
Indian Institute of Technology, Bombay

Lecture – 46
Electrical characterization – 4

(Refer Slide Time: 00:16)



So, as far as basic experimental investigation is concerned the main intention of conducting these experiments is to study the properties of dry soils that is number 1. So, if you can model the properties of dry soils you know the mineralogical properties in short and this happens to be a single-phase system mostly is it not. Now, if you are considering air also into the soil which is dry then this becomes a two-phase system with soil and minerals which are present in the material.

So, the first intention of doing these experiments is to determine electrical properties of the dry soils, so that we know the properties associated with grain boundaries and the grains of the soil mass, electrical properties. Then another intention is to study the wet properties of the soils, so when soils are wet what type of layers are formed, what happens to the microstructure of the soil in the wet condition. This again is a two-phase system with water and soil minerals present in it.

So, in short when you are studying these two extremes that is a dry soil and the wet soils what you are trying to do is you are trying to capture the dielectric constants for the two extreme conditions of the soil mass is it not. So, in one case the minerals are submerged in air another case minerals are submerged in water. So, this gives you a fair idea about the properties and their fluctuation on a scale of dielectric constant or the conductivity.

Now, most of the time we have been talking about the pore solution; so, the biggest question is how to give due weightage to the pore solution? Now, if you can extract the pore solution from the soil sample and you can characterize it by using electrical properties and if you can superimpose these properties on a two-phase system of soil air or soil water, then your modelling is complete.

So, it is something like extracting the pore solution from the soil, characterizing it separately and then superimposing it on the matrix of the soil or the grain structure of the soil and then seeing whether your modelling is valid or not. Is this part clear? So, this is the basic intention when we conduct any experimentation for understanding the geomaterial properties or characterizing the geo material properties.

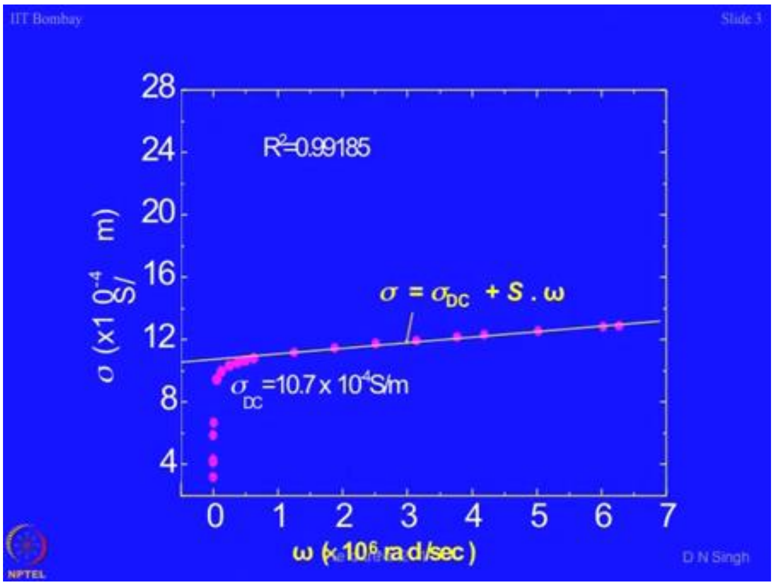
And of course, another important issue here is how to estimate the hygroscopic moisture content of the soil mass. Because, when you differentiate between dry and wet conditions of the soil this is the prime parameter what is the amount of hygroscopic moisture content of the soil mass.

Now, one step ahead of this would be to determine the soil suction alright because this happens to be an interface between the dry state and the fully saturated state of the material. So, if you can quantify soil suction you can study three phase of the soil mass may be in a better way that is soil minerals, air and water combination.

Now, most of the work which I am going to discuss in today’s lecture is from this paper which was published by Paresh Shah one of my PhD scholars a simple methodology for determining electrical conductivity of soils. Though the word is simple here which is I have included, but the methodology is very intricate, but even then, this methodology is supposed to be a preliminary one quite simple. And, whenever you get time you can go through this paper which was published in ASTM international which talks about the philosophy of studying dry soils, wet soils, pore solutions and how you can link these properties to the soil suction.

And then once you know these parameters how we can extend this philosophy further to characterize swelling and non swelling type of soils clear. So, the scope of this study is quite big.

(Refer Slide Time: 04:36)



Well, if you conduct any experiment in a impedance cell as shown in the previous lecture, the basic relationship which you get is between the conductivity and the frequency of AC. So, on x axis if you plot the frequency of AC and on y axis if you plot the conductivity what you will be getting is you will be getting a response which is shown as a pink dotted curve.

What it indicates is as far as the frequencies are very low this is nothing, but the DC zone alright and when the frequency increases you are going from DC to AC region to study the response of the material. So, basic shape of the curve indicates as frequency increases, the conductivity increases. Now, what is that we want to do from this relationship? From this relationship we want to obtain one reference conductivity for the soil mass.

Now, when I use the word reference conductivity normally this is defined as DC. What is the meaning of this? It is very difficult to measure the conductivity at pure DC value of frequency. Why? Because of electrode polarization and all other problems which are associated. So, what we do is we basically complete this spectrum and then extrapolate this line in such a way that wherever this cuts the frequency f or omega equal to 0 line, so this point is considered as σ_{DC} alright.

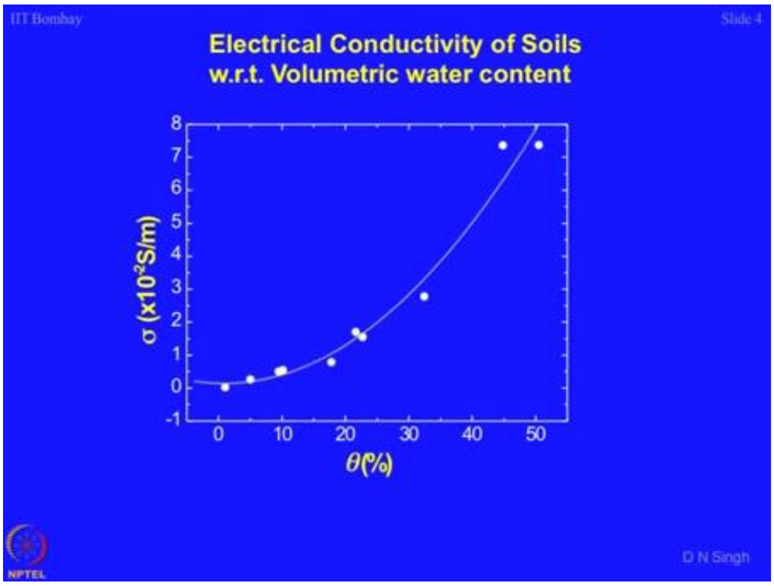
So, this is obtained by simple geometrical construction and this is what is also termed as a reference frequency, your reference frequency can be any frequency at which you want to study the response of the material. So, for that matter I can consider this also as a reference frequency.

So, in short what the basic equation can represented as is, the total conductive of the soil mass would be combination of σ_{DC} and some combination of frequency multiplied by some constant term alright. Now, later on we will see that this effect is nothing, but the effect of the pore solutions and the soil matrix which is present in the system alright.

Now, because I am plotting this graph on a normally scale it is a straight line, if I plot it on a log scale this again would be a straight line. The basic form of this equation could be a non-linear curve also because if you see the response of this curve is non-linear in nature alright. Now, sometimes this reference frequency is also defined as the threshold frequency; that means, most of the conduction takes place in the material beyond this frequency. So, you have to overcome this frequency level to achieve certain amount of conduction of ions in the material.

So, this becomes a good characteristic curve and depending upon the R^2 value you can say whether your fitting function is good or not and the value of σ_{DC} which you are getting is ok or not. So, this is the first response which you get by conducting any impedance analysis. So, just to remind you again take any impedance cell which has two parallel plate capacitors or two electrodes, fill up the soil mass, conduct this simple experiment by changing the frequency of AC. And, then you get this relationship from where you can obtain σ_{DC} which happens to be a standard value for a given material.

(Refer Slide Time: 08:44)



Now, using this σ_{DC} what can be done? This σ_{DC} when it is plotted with respect to volumetric moisture content or for that matter even the total conductivity or the bulk conductivity of the soil when it is plotted with respect to volumetric moisture content what you will notice is there will be a increasing pattern non-linear increasing pattern. So, what this indicates is as the moisture content increases conductivity of the material increases.

Why it is so? When you add more and more moisture into the system the ionic conductivity increases alright. So, ionic conductivity will always be more for a soil which is in a slurry form as compared to a semi solid or a solid state of the material. So, this curve basically shows how conductivity will vary with respect to volumetric moisture content.

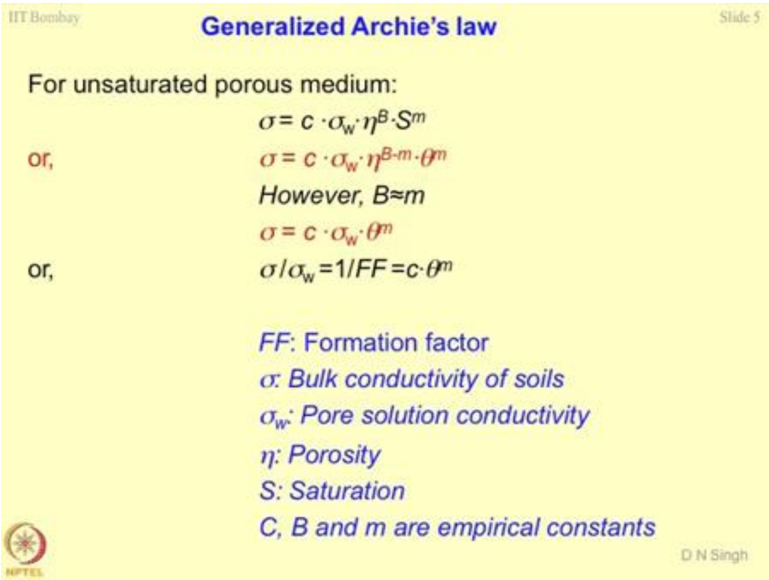
Now, where we can use this type of relationship any idea or can you guess of a situation where this type of relationship can be utilized in practical or real life? I can design a probe which will give me the volumetric moisture content of the soil mass or a geomaterial or a porous media how just by measuring its conductivity.

So, once you have trained this type of a relationship or once you have this type of a calibration curve this can be utilized for measuring volumetric moisture content or vice versa, if you know the volumetric moisture content you can find out its conductivity. That means, depending upon these two philosophies I can utilize this curve for different real-life situations. Any idea or any guess where I can utilize in what type of situations these type of information? One is a let us for profiling the water in the soil mass clear. So, you measure the conductivity and depending upon the conductivity you can say what is the volumetric moisture content.

The reverse case would be suppose, if I want to develop some alarm system automatic alarm system, to trigger let us say a sprinkling of water, irrigation. So, you think of a electronic circuitry; the moment theta drops below its certain value, what will happen? If theta drops let us say below the yield point of the crop let us say 15 to 10 percent if it drops. What is going to happen? There is a change in the conductivity and this change in the conductivity can be will trigger the alarm system clear.

So, this is a very good application in real life where simple curves like this can be utilized for achieving lot of benefits, know that is right correct. So, any phenomena where the moisture content is increasing or decreasing can be translated to its conductivity which is very easy to measure and very easy to monitor. And, then you can connect it to some electronic algorithm or electronic circuit to achieve whatever you want to achieve alright.

(Refer Slide Time: 12:37)



Now, based on these experiments what researches want to do is they want to come up with some generalized models and these models are known as Archie's law. So, I am considering the ultimate stage of the material where thus material is unsaturated.

Now, this is the most general form of the equation which is used in practice. The bulk conductivity $\sigma = c.\ \sigma_w.\ \eta^B.\ S^m$.

What is S? Saturation to the power m alright.

Now, if you want to solve this equation, how many sets of parameters are required? You have 1, 2, 3 unknowns; at the same time the porosity would also be unknown, saturation would also be unknown and what you are measuring is conductivity. So, you think of a situation where you have so many unknowns and what you can measure is only one parameter either you can measure porosity σ_w is known most of the times, so you can find out the for a pore solution conductivity. So, in order to reduce the confusion what you can do is you can convert this equation in this form. What is theta? The volumetric moisture content and theta is equal to porosity into saturation.

So, if you take out this term of porosity into saturation to the power m:

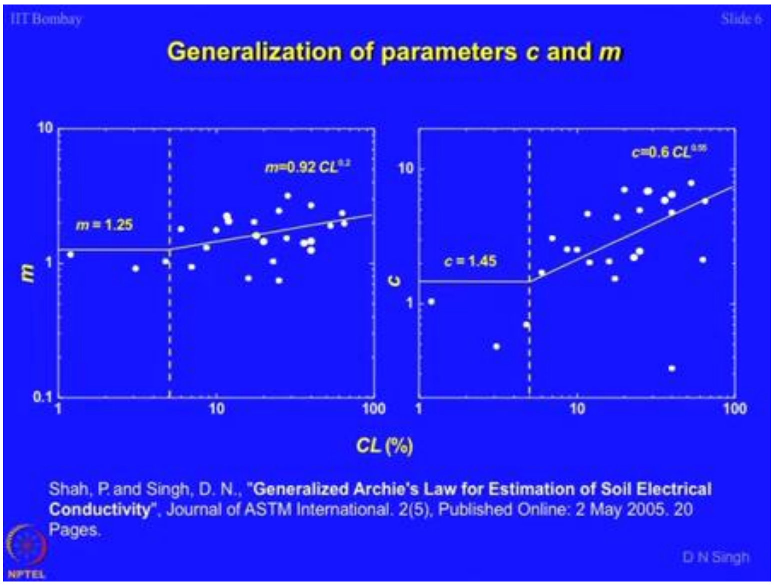
$\sigma = c.\ \sigma_w.\ \eta^{B-m}.\ \theta^m$. Incidentally, σ/σ_w will be what? This is the inverse of the formation factor. That means which will talk about the anisotropy of the soil mass or the stratification of the soil mass and so on.

Now, most of the time B is equal to m for most of the soils, so this term disappears from here and then what happens is you get the famous law of Archie which is $\sigma = c.\ \sigma_w.\ \theta^m$. That means, if I know the formation factor and if I know these coefficient c and m, I can obtain volumetric moisture content. Or, if I know the volumetric moisture content and if I know c and m coefficients for a certain type of soil, I can obtain the formation factor.

It is easy to get σ_w, so you can obtain σ it is depending upon your requirements you can use these equations the way you want. So, this is a function which is relationship between formation factor and porosity or the volumetric moisture content. Most of the geologists and people in engineering geology they utilize this concept much more; is it not because the formation factor is very; very important term for understanding the history of formation of a deposit.

Again, I repeat the word this is history of formation of a deposit; that means, if you are studying how deposits are formed and what is their life, geological life you can use this term formation factor to derive some information about the sedimentation and so on ok.

(Refer Slide Time: 16:58)



Now, regarding this parameter c and m, yes Paresh Shah actually what he did is he generalized these coefficients m and c. And this was published in generalized Archie's law for estimation of soil electrical conductivity journal of ASTM in 2005, what we did is we realized that parameter c and m they have a strong bearing on clay content.

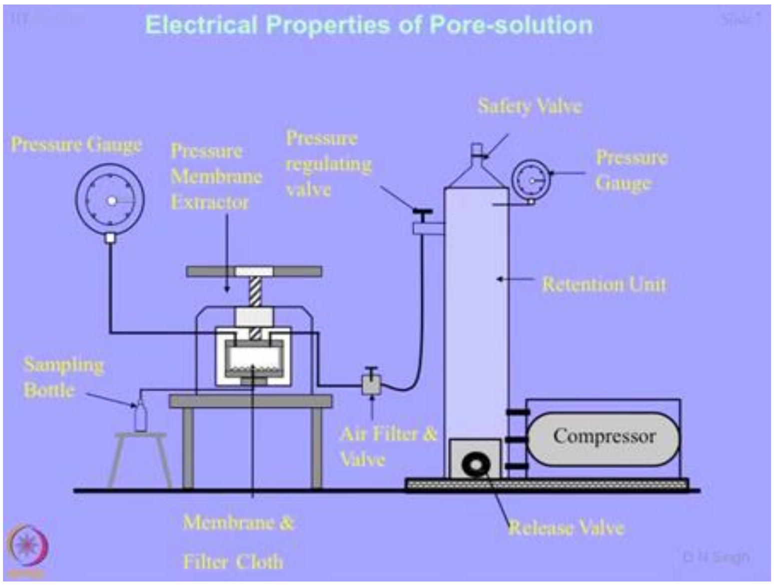
So, we did lot of experiments and lot of literature collection and synthesis of the literature and when we plotted it on a scale with respect to m and c what we observed is that this type of relationship exists. That means, up to a certain value of clay content approximately 7 percent or 8 percent, the value of m remains constant beyond which it increases linearly as a function of clay content. Similarly, c also remains constant up to a certain limit and then beyond that limit of clay content, the value of c increases linearly with clay content.

So, in short if you know the clay content of a soil mass which is quite easy to obtain because by doing hydrometer analysis. So, the moment you know clay content you know parameters m and c which you can substitute in the previous equations. So,

$\sigma = c. \sigma_w. \theta^m$.

So, a generalized law is ready to be used for different practical applications. This was a very significant contribution to the profession.

(Refer Slide Time: 18:49)



Now, you must have recognized this figure which I have talked about earlier also. Basically, this type of setup is used for characterizing pore fluid or pore solution. This is a pressure membrane extractor which is connected to a retainer unit and retainer unit is connected to a compressor unit.

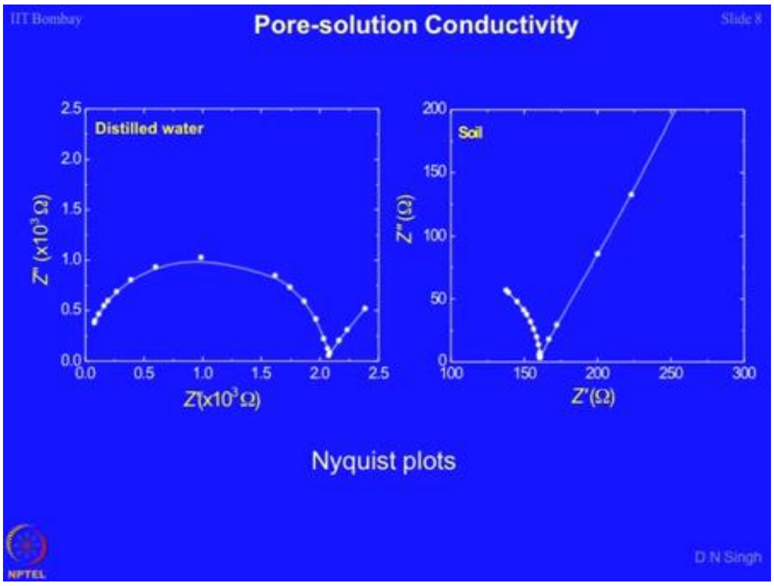
So, air is compressed and it is retained in this retainer unit at a certain pressure. From this the compressed air goes into the pressure membrane extractor where soil samples are kept on a filter cloth and a special membrane which is known as a PVC membrane, but cellulose acetate membrane. This experiment you will be you will be demonstrated when you come to the lab for conducting the soil suction measurements.

You can measure the inside pressure chamber and that will be equal to the suction pressure, but in this context which we are referring to when you apply certain pressure on the soil samples which are kept here, the pore solution drains out and can be collected in a sampling bottle. And this pore solution if you remember can be analyzed further by using atomic absorption spectroscopy for the heavy metals which are present in it or ICP unit depending upon the accuracy you require or this pore solution can also be utilized for determining its electrical property clear.

So, this is the way you are filtering out the effect of pore solution from the bulk soil mass. So, you think of a situation where you are talking about the pore solution separately and the solid grains of the soils separately and then you are trying to find out what is the contribution of these two entities as far as conduction of current is concerned through the porous media and this type of model we discuss in the previous lecture. So, the basic question was the philosophies which we are proposing of conduction of AC through porous media how we are going to prove that those philosophies are valid alright.

Somebody was asking in the previous lecture that which out of these three four parts is going to be contributing maximum. So, this would be the best way you filter out the pore solution and then see what type of conduction is taking place whether it is grain to grain or grain surface or the pore solution. And, then you can develop the models to understand how current passes through the porous media and whether it can be utilized for characterization of the porous media or not alright.

(Refer Slide Time: 21:37)



So, these are the typical results which you get for soils and distilled water. The basic idea of showing you this type of relationship is you should get a feel of when you plot the impedance spectroscopy results on Nyquist plots on y axis you have the Z double prime, the imaginary part which is more capacitive in nature and on the x axis, if you plot the resistive part which is pure resistance and not dependent on the frequency.

So, for distilled water you will notice that there is very less electrode polarization see this portion is electrode polarization; that means, a thin layer which is formed between the electrodes and the material. So, because water is the wetting fluid the chances of electrode polarization would be less and that is what actually you are seeing here. On the contrary when you look at the response of the soil there is a contact problem and the contact problem is this portion of the material characteristic corresponds to too much of contact between the electrode and the material in the form of air. So, this could be one of the reasons of electrode polarization.

Now, another thing which I wanted to show here is if you look at the shape of the curve is almost a circular curve. So, unless you increase the frequency it is very difficult to pass current through the solid phase of the soils. So, that is why we could not generate much of data because you are using an instrument which does not work beyond one megahertz. So, we could not get much of the data ideally if you work in the frequency range up to 1 gigahertz you will get a perfect circle over here.

Now, can you guess what would be the beauty of these type of relationships or these types of graphs, what could be the real-life application in engineering if I give you these types of patterns what is that you can infer from them? Binal it’s something to do with your question which you asked yesterday; I can find out what are the phases of the material which are present in the material. So, a metallurgist when he conducts impedance spectroscopy his intention is to find out what is the composition of different metals in a composite. That means, depending upon the phases of the material present you will be getting so many circles in impedance plot.

Here distilled water you have one phase of let us say a small air and water, in this soil you have the solid phase of the minerals and some amount of air contact. So, if the shape of the circle shows you kings: kings means steps, so each step will correspond to a certain phase of the material. So, those of you who might be working in FRPs design of you know Fiber Reinforced Concrete FRCs, there you will use these types of techniques quite a lot. You can fabricate your own composites and you can check the phases of the composites which are present and then you can model this structure in a better way.

Now, where we can utilize this type of concept in civil engineering related to soils and foundation and in the concrete? If you want to know how concrete is setting; so, there are lot of people who have worked in this area, you can find out the aging of the concrete by consecutive freezing of Nyquist plots or the impedance plots. And, that is where you can differentiate between the time when the concrete just starts setting in and the gel formation is maximum and this will also differentiate between the green concrete and the set concrete.

So, what type of admixture should be added, what type of accelerator should be added, what type of retarder should be added. So, in short you can understand a process which is going on at a micro level in the system by conducting these types of analysis, is this part clear, there is scope of these are not only the plots or the graphs these graphs give you lot of information. A biotechnologist or a biomedical scientist will be using these types of relationships to understand whether your bio cells are cancerous or not. Any guess how they will be doing this?

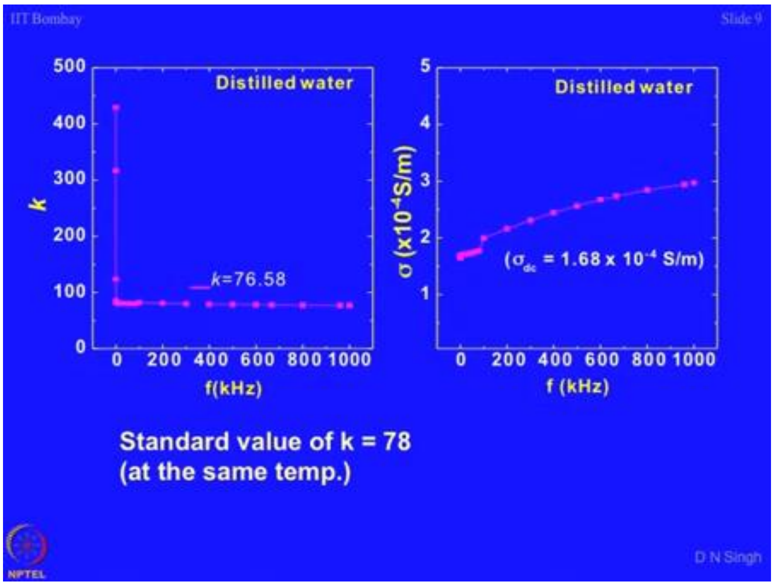
Actually, we have learnt this art from biotechnologists, if the cells are healthy, they will not have much of moisture in them, but if cells are unhealthy, they are cancerous their water storage capacity will be much more. And you know by this time that the impedance of water will be very high, so you can distinguish between the dead cells, healthy cells and unhealthy cells just by looking at their dielectric response or the impedance response you got the point.

So, this is where actually people are utilizing this in aviation industry, where you want to establish after how many runs of let us say a certain equipment or say after how many flights of an aircraft some micro cracks may develop in the wings which are not visible just by naked eye clear. So, any impregnation of air in a system will be treated as a phase of a material into the system and that phase of the system can be captured with the help of impedance response very easily.

Good example of this type of relationship in our studies would be detection of cavities or the microstructure of the soil Suchit we will be discussing much more in details when he presents his seminars. So, you can detect the formation or the you know pattern of the grains formation whether they are dispersed or whether they are flocculated or whether it is a card house structure, its grain to grain structure and so on. So, that means, this type of analysis happens to be a very good tool to study the grain structure and in short, the fabric structure of the soil mass.

So, these are the scopes of the studies which we are talking about here; I hope this part is clear to you now. Anything else which you like to add application wise? So, we have applications in cement any material can be characterized with the help of its impedance response.

(Refer Slide Time: 28:47)

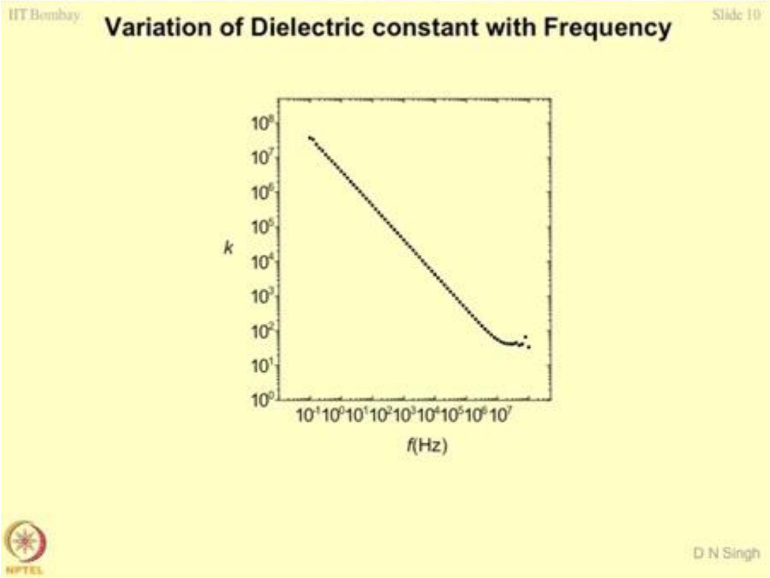


Now, just to give you a feel of how dielectric constant changes with respect to the frequency, I have plotted here distilled water response for dielectric constant as well as conductive with respect to frequency. Distilled water is supposed to be least conducting water, is it not? So, what you notice here is as the frequency increases the conductivity of the distilled water will increase with DC frequency of 1.68×10^{-4} Siemens per meter.

And, look at the dielectric constant; dielectric constant very; very sharply as the frequency increases. What is the meaning of this? Distilled water is a good conductor of electricity or bad conductor bad conductor of electricity that is right. So, but the moment frequency is increased, what happen to the dielectric constant? It decreases very sharply and then it becomes almost constant. What is the value of water we have been talking about? 81 approximately, so we have got say about 76, 78. So, this is how the calibration is done for the impedance cells in which you are going to test the soil samples.

So, before you run any experiment it is always a good idea to calibrate the impedance cells by using different oils, water, different fluids, different standard materials and then go ahead with determination of electrical properties of geomaterials. Is this part clear?

(Refer Slide Time: 30:25)

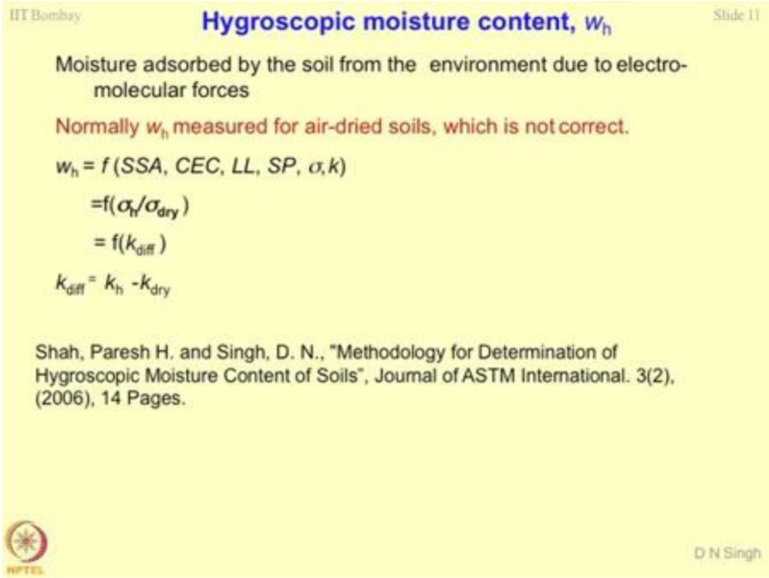


Another good example is how dielectric constant changes for soils as frequency increases, there is a drop in dielectric constant of several cycles you know log cycles starting from a very high value of 10^8 to almost very close to 80, 81 less than 100 at very high frequency. What is the significance of this?

Whenever you use any advance equipment the first question is in which range, I should study the material property? What it indicates is if you measure a electrical property corresponding to this frequency, what you are going to get is the properties which are not stable. However, when you are studying the properties in a frequency range of MHz to GHz, the dielectric constant variation is almost negligible. And, this is the region where you will be getting the properties of the soil mass or any material which are going to be much more reliable and stable.

So, this is how the training is done for selection of frequency, I think you must be having this idea question in your mind that you are doing the complete spectrum analysis, but which frequency should be used for characterizing the material. So, the answer comes from here, wherever the drop in dielectric constant is negligible that is the value of frequency which should be adopted for characterization of material. Any questions here?

(Refer Slide Time: 32:05)



Let us talk about the hygroscopic moisture content which is depicted as w h, basically hygroscopic moisture content is the moisture which is absorbed by the soil from the environment due to electro molecular forces, electromagnetic forces and so on. Normally, w_h is measured for air dried soils which is not correct see thumb rule is clay should never the air dried, sorry clay should never be oven dried alright. So, they should always be air dried and when your air drying them, the hygroscopic moisture content comes into the picture. Basic question is that what is the value of hygroscopic moisture associated to the soils?

Now, this part we have studied earlier also that hygroscopic moisture content is a function of specific soil, surface area, cation exchange capacity, liquid limit swelling potential, but you can extend this series to by including conductivity and dielectric constant as well ok. Truly speaking dielectric constant and conductivity are the parameters which will take care of all other parameters associated in this equation. So, we can say that w h will be a function of conductivity and dielectric constant.

So, the first philosophy is hygroscopic moisture content should be a function of conductivity corresponding to hygroscopic conductivity; conductivity corresponding to hygroscopic moisture content, normalized in with conductivity corresponding to the dried condition of the soil mass of the geomaterial. So, if you take the ratio of these two you will be getting the hygroscopic moisture content w_h, at the same time if I talk about the contrast in k value dielectric k value. So, that should also be linked with w h, where $k_{diff} = (k_h – k_{dry})$

So, hydroscopic moisture content will always give you a higher degree of dielectric constant as compared to dialectic constant at dry state of the material. Now, these concepts are being utilized for characterization of clays in a very well manner. And, this was the contribution again by Paresh Shah, the methodology for determination of hydroscopic moisture content of soils which was published in journal of ASTM international.

And, when you get time please go through his work where you can substitute the values of k difference and normalized conductivities to get hygroscopic moisture content directly. And of course, you can link w_h with SSA a Specific Surface Area, cation exchange capacity, liquid limit and soil in potential of the soils.