Environmental Geotechnics
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Lecture – 47
Electrical characterization-5

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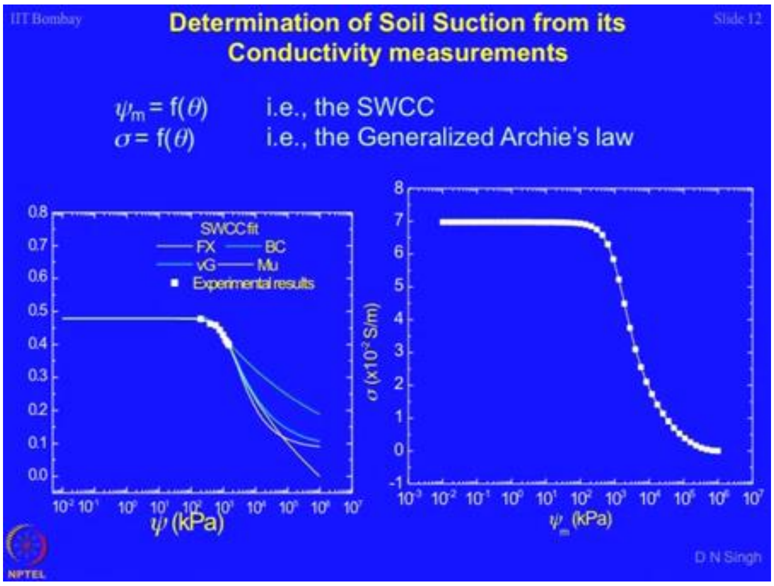
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Slide 12

Determination of Soil Suction from its Conductivity measurements

$\psi_m = f(\theta)$ i.e., the SWCC

$\sigma = f(\theta)$ i.e., the Generalized Archie's law

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Now, this is the major concept we have somebody would like to correlates while suction with conductivity measurements. Or in other words you have seen that it is very difficult to measure soil suction and to develop soil water characteristic curves.

So, then the question comes in mind my indirectly can we measure suction and if you can measure the suction then we can complete the SWCC or the Soil Water Characteristic Curve. So, this is where we were working in this direction to show that if you measure the electrical conductivity of the soil mass on the porous media, you can easily obtain its suction value. And this paper has recently been accepted by ASCE; it is not come in the print yet by Dr Hanumanth Rao.

The basic philosophy here is that metric suction of the soil is a function of volumetric moisture content. So, this is nothing, but your you know classical SWCC; the relationship between metric suction and volumetric moisture content. At the same time, we have seen that sigma is the function of theta is it not; so, conductivity is also a function of volumetric moisture content this is Generalized Archie’s law.

So, if you mix these two together and we will say psi m is a function of theta and function of theta is psi sigma; what it ends with this that psi m is a function of sigma. So, what it indicates is I can measure suction of the soil if I can measure its conductivity. So, this volume short the thesis of Hanumanth Rao and he has published quite extensively in different journals by using this philosophy.

So, this is the classical SWCC curve where you are plotting volumetric moisture content with respect to suction. So, you get some experimental data point and these experimental data points are fitted by using a standard fit which are available in literature; FX corresponds to Fredlund Xing, Brooks and Cory; these are the scientist on the researchers who have given the equations for the best fits.

So, by using different fitting functions you can obtain the soil water characteristic curve; even if you have a little bit of data point for all these points, you can find out what is the regression coefficient. And the best regression coefficient can be used as the most suitable SWCC. Now look at the situation by following this law that is psi m is a function of theta and sigma is a function of theta. If you plot sigma with respect to psi m; what you get is the nature of the relationship which again is equivalent to SWCC.

But we should appreciate it point here that measuring conductivity is much easier as compared to measuring suction of the soil. So, it is very easy as well as a very rapid method to determine SWCC. So, if you go through the; if you go through the works published by Hanumanth Rao; we will say some more time maybe 6, 8 months; then you will notice that we have shown that how these philosophies are working perfectly in order.

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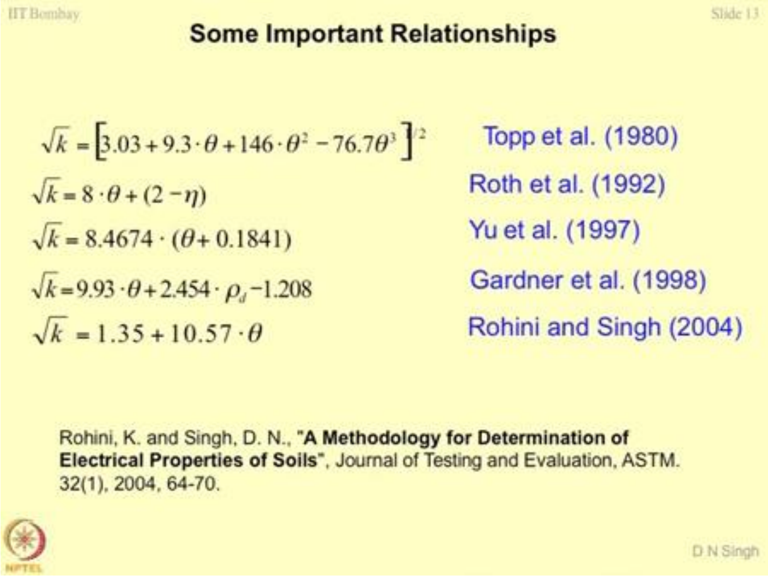

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Some Important Relationships

$\sqrt{k} = \left[3.03 + 9.3 \cdot \theta + 146 \cdot \theta^2 - 76.7\theta^3\right]^{1/2}$	Topp et al. (1980)
$\sqrt{k} = 8 \cdot \theta + (2 - \eta)$	Roth et al. (1992)
$\sqrt{k} = 8.4674 \cdot (\theta + 0.1841)$	Yu et al. (1997)
$\sqrt{k} = 9.93 \cdot \theta + 2.454 \cdot \rho_d - 1.208$	Gardner et al. (1998)
$\sqrt{k} = 1.35 + 10.57 \cdot \theta$	Rohini and Singh (2004)

Rohini, K. and Singh, D. N., "**A Methodology for Determination of Electrical Properties of Soils**", Journal of Testing and Evaluation, ASTM. 32(1), 2004, 64-70.

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Now, based on the complete impedance analysis; based on the complete impedance analysis some equations can be derived. Benil the question you asked in the previous lectures, now this is the starting point of the answer to your question about the multiphase material properties and how to determine them if you know the dielectric constant. There are several equations which are available in literature which correlate k which are dielectric constant of the porous media with the volumetric moisture content.

So, we can see it easily that under root of k is this term under root of the entire term; that means, k is nothing, but sum coefficients multiplied by θ. Now this is the famous Topp's equation. If you know theta you know the dielectric constant you can calibrate a mineral and when mineral comes in contact with water. How we are going to use this in real life is; if you know the k value you can measure the k value and you can determine θ. And this is how the TDR, FDR probes work. So, this is where you are measuring k value and you get the value of volumetric moisture content.

The second equation is given by Roth et al. which again is a function of volumetric moisture content theta and the porosity. So, this is a mapping of two phenomena; one is the matrix of the soil porosity and the volumetric moisture content theta all right; this was given by Roth. The third equation was given by Yu et al, where the dielectric constant is a function of volumetric moisture content of the soil mass. Then some efforts are been made to correlate the electric constant with ρ_d; ρ_d is nothing, but dry density of the soil mass.

Now, this equation was further refined by my student Rohini, where the philosophy was that it is difficult to measure the dry density of the soil mass; is it not? The way you measure it is you know the total volume which you measure physically and where the sample get the moisture content and say total; $\rho/(1+w) = \rho_d$

It is a very non precise way of getting the γ_d; rather if you use this concept of measurement of k. And if you know theta very precisely which can be measured with the help of any advance instrumentation; what you will end up is with knowing the value of rho d.

So, that will be a very accurate measurement and this philosophy was proposed by Gardner et al in 1998. So, this was the contribution of Rohini who published this paper and Methodology of Determination of Electrical Properties of Soils in Journal of Testing and Evaluation, ASTM. And we extended this relationship for determining the in-situ dry density of the soil mass.

The reason is theta can always be correlated with w and γ_w; that is $\theta = w.\ \gamma_d/\gamma_w$ all right. So, γ_d/γ_w will be a non-dimensional term multiplied by gravimetric moisture content and that will be the value of theta.

So, if you know the dielectric constant of the soil system or a porous media; you can obtain its dry density very easily. All the equations are valid for single phase minerals assume to be all right.

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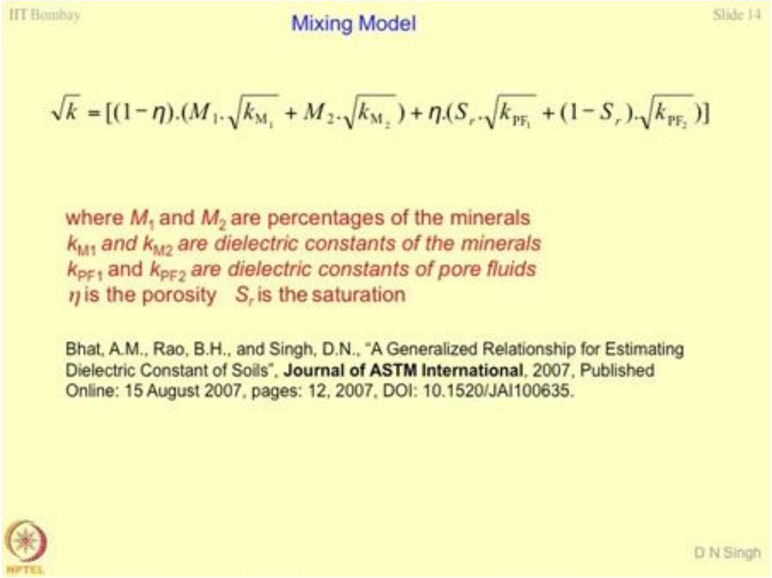

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Mixing Model

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$$\sqrt{k} = [(1-\eta).(M_1.\sqrt{k_{M_1}} + M_2.\sqrt{k_{M_2}}) + \eta.(S_r.\sqrt{k_{PF_1}} + (1-S_r).\sqrt{k_{PF_2}})]$$

where M_1 and M_2 are percentages of the minerals
k_{M1} and k_{M2} are dielectric constants of the minerals
k_{PF1} and k_{PF2} are dielectric constants of pore fluids
η is the porosity S_r is the saturation

Bhat, A.M., Rao, B.H., and Singh, D.N., "A Generalized Relationship for Estimating Dielectric Constant of Soils", **Journal of ASTM International**, 2007, Published Online: 15 August 2007, pages: 12, 2007, DOI: 10.1520/JAI100635.

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But when you talk about the multi-phase minerals, then what happens? I think this is what your question was Benil; if I remember correctly. So, this is that we talk about the mixing models.

So, certain weightage is given to; certain weightage is given to each mineral of known dielectric constant. So, I will come back to this equation slightly later; if you know the phases of the minerals which are present in the soils defined a M_1 and M_2. So, these are composition let us say 80 percent quartz 20 percent Illite or whatever. So, if you know the phases of the minerals which are present in the soil and if you were dielectric constants of these minerals that is k_{M1} and k_{M2}.

And if you know the dielectric constants of the pore fluids; so, this could be a situation dealing with only water then the pore fluid is only one. It could be partially saturated soil there the pore oscillations could be two air and water; it could be soil contaminated with some organics. So, if you know the dielectric constant of the organics, you have me have two or three phases of the liquid itself. So, one more term will come over here it becomes a three-phase combination for dielectric constant determination.

Eta is the porosity of the porous media and S_r is the saturation of the porous media. Now the question is how do you find out dielectric constant of the minerals? Take the mineral in the purest form, put it in impedance cell and you can measure its dielectric constant. How would you find out the dielectric constant of the pore fluid? Extract the pore solution by using the pressure membrane extractor; again, put this solution in a impedance cell and measure its dielectric constant. M_1 and M_2 how would you find out? How would you find out the percentage of the minerals?

Student: (Refer Time: 10:29).

Excellent; that is right. So, that is the reason why XRD analysis is so important, so that you know what are the minerals which are present and then one is quantitative analysis or XRD. So, you can quantify the percentage of the mineral which is present in the soil; this is difficult to achieve and difficult to work on very difficult. So, quantification of minerals which are present in the soil mass takes big amount of time.

Porosity is a macro term which can be obtained very easily by any of the method which you adopt and saturation can also be find out very easily. Now you look at this equation, so, the equivalent dielectric constant of a multiphase system would be; these are the equivalent terms that is under root of k of the first mineral under root of k of the second mineral multiplied by their mass phases or the percentages; this multiplied by 1 minus porosity.

So, 1 minus porosity term will give you what is the solid phase of the material which is present in the matrix. When you multiplied by the porosity this becomes the liquid phase is it not? You agree or not V_v upon capital V is the porosity term. So, volume of voids would be porosity multiplied by total volume.

So, if you multiply the porosity with total volume; this is the volumetric form in terms of saturation of water. So, this is where your saturation term comes for the pore fluid 1 and pore fluid 2 and then this is nothing, but the super imposition effect of pore fluid 1 on pore fluid 2; so, this is how you have created a two-phase system. Now if you are working with a mineral with a soil which has let us say multiphase of the minerals and multiphase of pore fluids what will happened to this term?

This term will get further expanded by taking into account k M 1, k M 2, k M 3 and so on. Similarly, k PF 1, k PF 2, k PF 3, k PF 4; so you think of a system where you have a frozen soil which is contaminated that is right; that is right; that means, then what that is what I have I was telling you just now; if you think about its multiphase system of soil what will happen in saturation term? Right now, the way you have define saturation is only volume of voids with respect to volume of solids.

Now, your S r term it is still will get fibre bifurcated; that means, the saturation with respect to the vapour phase; the saturation with respect to the liquid phase so; that means, you will be having S_r’ which will be equal to S_{r1} and 1- S_{r1}. So, those comes get applied into this equation. I think this what precisely was asking in the previous lecture that how would you talk about the material inhomogeneity.

I thought that this will you good example to show to you that how equivalent models can be developed. And the state of the art is that most of the minerals are known for their dielectric constants, most of the pore fluids are known for their dielectric constants. So, if you use let us say remote sensing equipment or imagery. So, what essentially you get is; k value is it not how do you get k value by remote sensing device.

You can transmit electromagnetic waves and then you can find out how much time they take to reflect from the surface and that time lag between the waves will give you the dielectric constant. So, once you know the dielectric constant k; you know the mineralogy of the entire soil and you can find out how much saturated the system is.

So, depending upon this concept you can locate a reservoir which is full of water; underground. It will be a good source of fresh water supply or whether the water is a brain solution or brackish water or whether the pore solution happens to be an oil reserve or whether this soil mass happens to be having more crude oil or some soil contamination and so on.

So, these types of models which are known as mixing models are utilized for ascertaining different compositions of the soils; this is a very big subject I on the lot of people are still working. And this must give you an idea about how small concepts can be put together to characterize the entire soil mass all right.

Some efforts were done by one of my masters of students Azaz Bhat and Hanumanth Rao in publishing this work which came up as Generalized Relationship for Estimating Dielectric Constant of Soils. This was also published in journal of ASTM International in 2007; is this part clear or something else you are asking.

Student: (Refer Time: 16:09).

That is right. So, here the saturation is it is; with respect to the fluid one because that is why you are noticing here the moment you talk about the fluid 2; it becomes 1 minus S r. So, here the intension is let us say we are talking about partially saturated soil; so, still the saturation term is here saturation or water saturation. So, if you define S_r as the saturation which is water saturation then 1- S_r is nothing, but air saturation. So, k PF 2 becomes the dielectric constant of air and k PF 1 become dielectric constant of water.

The perception changes the moment your profession or the requirements change as the geotechnical engineer we are more interested in water in the soil. But somebody is more interested in let us say oil rather than water, another person could be more interested in vapours present in the soil rather than water or the liquid form and so on.

A geologist will be more interested in no saturation, but only minerals. So, for him everything is submersed in water let us say. So, he does not talk about any of these phases, but he is more interested in the values of the percentages of the minerals so that he can that ultimately what is that you are trying to do. If you have this type of model you can match the left-hand side value of k with the right-hand side value of the parameter and see where you are going to converge.

And that type of model is going to describe whether this location is having a resource or not so that later on intense activities can be taken up. I suppose this is how the whole mining process or the identification of the minerals must be getting guided by your imagery; satellite imagery you want to add something Sangeetha?

Student: (Refer Time: 18:37).

Yeah.

Student: (Refer Time: 18:39).

What happened?

Student: (Refer Time: 18:42).

Fever, ok please take rest.

Student: (Refer Time: 18:50).

But then reflectance will also depend upon the dielectric constant of the material of the minerals. So, the basic concept has to be same, another good application would be in GPR whether your concrete is cracked or not or some microfiches are there microcracks are there. So, what happens in the regular concrete phase the moment cracks take place; then the air impregnates into the system and the dielectric constant of the air comes to the picture.

So, there is becomes a two-phase system of concrete which is cracked and hence air is present in it. You can use this equation again for finding out the composition of the composites which were developing each phase will be having its own peculiar property all right ok.

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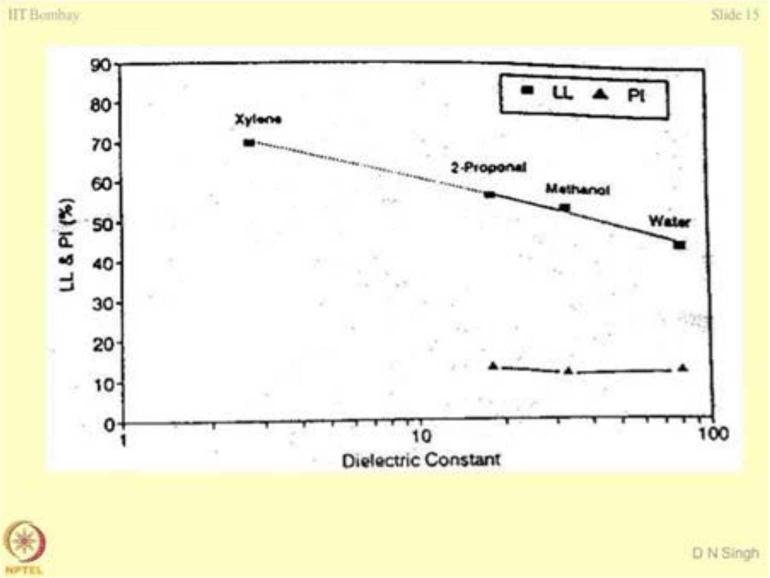

Now, this is another interesting relationship its shows how Atterberg limits change as a function of dielectric constant. So, for a given soil if you contaminated with different organic and inorganic materials, xylene, propylene, methanol, water what you will notice is that the plasticity index does not change much.

But with dielectric constant it will change a lot; however, you can find out easily that the soil is contaminated with what type of chemical; if you talk about its liquid limit. So, most of the time we talk about liquid limit with water or soils which are contaminated with methanol other organic components for them the liquid limits are going to be much more higher.

The question is then how would you identify whether the soil is contaminated or not? Take the soil sample, check its electrical property, take out its pore solution. So, now you have divided in two parts; one is the pore solution characterization another one is soil matrix characterization. And then come follow complete analysis again and see what fraction of contamination was present in the soil mass is this part clear?

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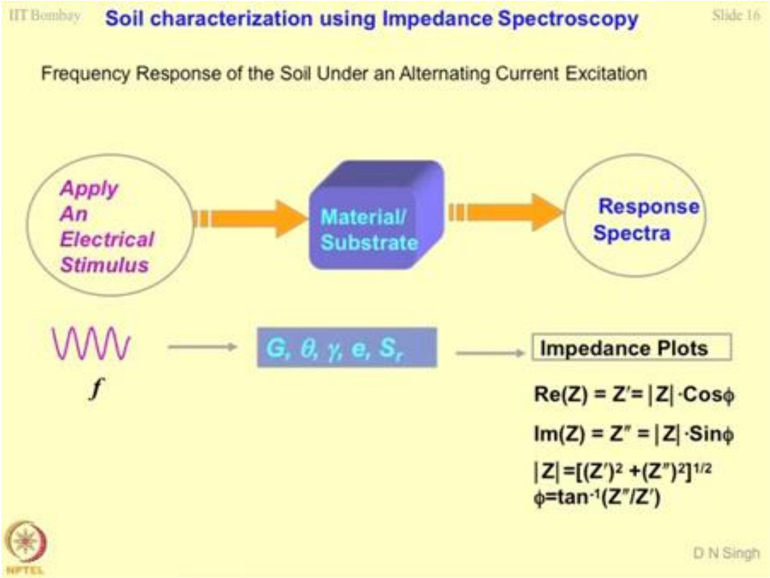

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Soil characterization using Impedance Spectroscopy

Slide 16

Frequency Response of the Soil Under an Alternating Current Excitation

Impedance Plots

$Re(Z) = Z' = |Z| \cdot Cos\phi$

$Im(Z) = Z'' = |Z| \cdot Sin\phi$

$|Z| = [(Z')^2 + (Z'')^2]^{1/2}$

$\phi = tan^{-1}(Z''/Z')$

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So, then the question is that what are the basic concepts of the impedance spectroscopy and how to utilize the response spectra which you get for engineering application. The basic idea here is that what we are trying to do is we are trying to study the response of the material under alternative current.

So, you apply any electrical stimulus on the material or a substrate is nothing, but the pore solution and you try to get its response spectra. So, for that matter if any sinusoidal wave is passing through this of frequency f; the material of substrate properties would be specific gravity in case of soils, volumetric moisture content, unit weight, void ratio and its saturation.

So, we want to get the answers to all these parameters; we want to identify these parameters. So, what you are going to get is you are going to get response spectra in the form of impedance plot. What are the impedance plots? Radial part of this impedance could be Z cos of time; imaginary part of that would be Z double prime modulus of Z sin phi, where phi is the angle between the two components that is imaginary part and imaginary part and the real part of Z. So, this is what basically you are trying to do.

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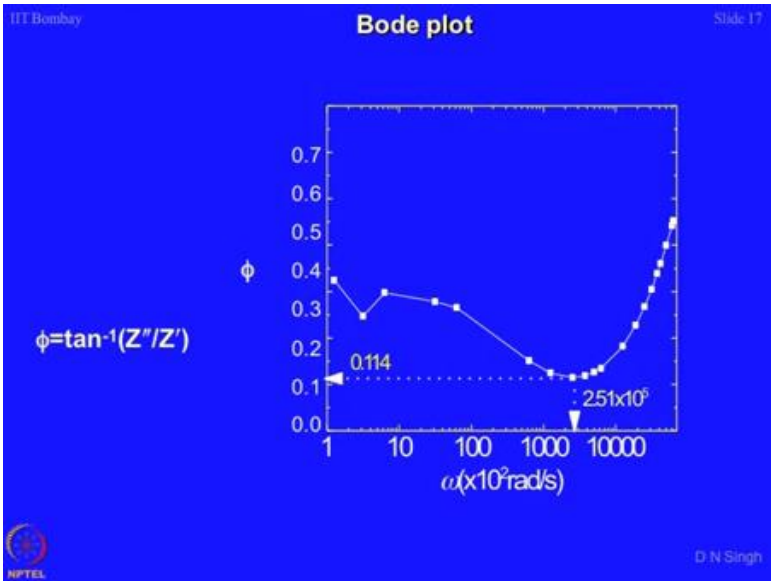

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Bode plot

$\phi = \tan^{-1}(Z''/Z')$

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Now, using this phi parameter which is tan inverse of the double prime divided by Z prime or the imaginary to real part; when you plot it with respect to the frequency whatever pattern you get is known as a Bode’s plot. So, we have talked about mixed plot this is another representation of the data which you get from impedance spectroscopy which is known as Bode plot. It is a relationship between phi angle the n frequency; if you plot the results wherever you get the minimum value of phi all right.

Now, this corresponds to the value of the double prime divided by Z prime, but still most of the time people try to use are they stick to mix plot or even Bode plot. This is one of the ways of getting the information related to the metal properties.

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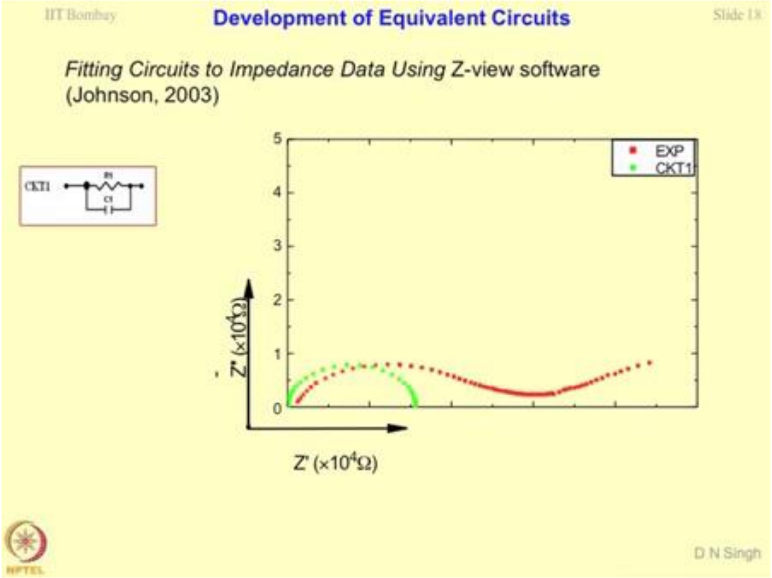

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Development of Equivalent Circuits

Slide 18

Fitting Circuits to Impedance Data Using Z-view software (Johnson, 2003)

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So, this is where the concept of equivalent circuits comes into the picture. What you have done is; you have taken a material put it in impedance cell and then you try to develop the equivalent circuit. What is the meaning of equivalent circuit? You are trying to map the response of the materials in terms of its resistance, capacitance and inductance. And if you are working on soils, you ignore the component of inductance, you are only interested in considering resistive and capacitive part.

So, this is basically fitting of the data which you get from the impedance analysis by using Z view software. So, to start with we always assume soil mass or a porous media to be consisting of a resistance and capacitor in parallel. Saturday, yes please. So, for this circuit when you are starting with you have some R_1 and C_1 values; whatever impedance data you get it is plotted as a red line. This portion you remember is electrode polarization followed by the main part of the circuit. So, this is where if you superimpose the response of RC parallel circuit you will end up with this type of a semicircle.

What is the meaning of this? This much is the total resistance of the circuit and by the time you come over here; the resistance is 0, the capacitance part is also 0 the maximum capacitance capacitive resistance would be somewhere here which corresponds to this value. So, what is your feeling? Is this a good match of the phenomena which is happening in the soil mass or not? No, because your equivalent circuit could not capture the real response of the material.

The real response is far away from the theoretical response which you have assumed to be a simple R and C circuit. Now in the process what you get is from this graph you can easily measure what is the value of R and what is the value of C_1. So, you know the value of R_1 and you know the value of C_1. So, you are not happy with this what we should do is we should refine this further.

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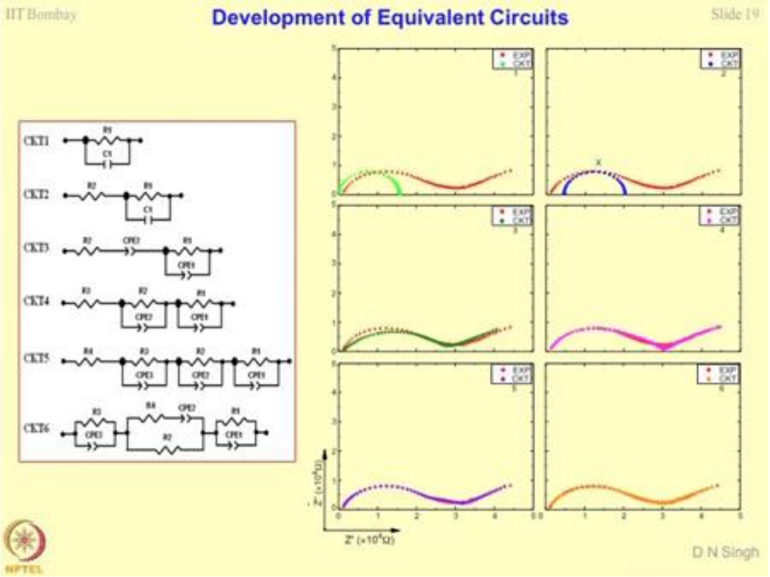

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Development of Equivalent Circuits

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So, if you refine it further you have to try so many combinations. So, starting with this circuit what you should do is; what’s your feeling when there will be a good match when this green circle shapes on the left-hand side or right-hand side? Your right-hand side my right-hand side also. So, if fits on the right-hand side then at least this circle green circle will be embracive the red one. What we should do? We should translate the green circle on the x axis how to do that? By adding a resistance, so you have to get up now.

So, you add a resistance over here to the circuit what happens? You end up getting this circle shifted on the right-hand side, but are you happy this circle? Because this circle was still not capturing the entire response of the material what we should do now? We should slightly spread the diameter of the green circle.

How this will be done? For the initial circuit you have added a resistance, you and add more capacitor part to this. So, the moment you do that what happens to the response? Now this response is very much close to the real response of the material, you can see these almost near overlap between the green circle and the red circle; you are still not happy; let is it. So, what you should do?

Add another circuit like this and then this is a trial and error and it comes by more and more practice and intuition sometimes. So, you take two R and C circuits put them in resistance in series and what you will notice is the discrepancy is almost disappear. But you refined the results further, what you can do is you can go on with another compartment of RC circuit. And what we will notice is this is the perfect match of the results and the best possible fit which you get is when you adopt a circuit like this.

Now, this is where a philosophy is; if you remember in yesterday’s discussion, I was showing you that the impedance cell contains two electrodes and the soil mass in between. So, unless you give due weightage to the electrode and the soil mass contact. So, this circuit of R and C basically defeats the contact between the electrode and the soil mass. So, this is one electrode this is another electrode and in between the soil is represented by this. I have vomited lot of steps in between this was achieved after at least 3 months of every day trail and maybe we tried more than 5, 600 circuits; this was done by Azaz; my M Tech student.

So, you simply cut short all these steps in between and you see it just like building blocks you keep on playing with the circuit and one fine day it will result in a good fit and that suppose which has been shown over here. So, here the R square values are perfect; very close to unity and physically also this circuits seems to be a good circuit, where you have given innovators to electrodes and where given innovators to the soil mass which is encapsulated between the electrodes. So, this became the standard circuits for the impedances which are being used for analysis of electrical properties.

So, Azaz’s contribution is you have made impedance cell, he had derived a methodology to get these type of components and he has come up with a generalized circuit which represents the response of the material. Now the question is how you are going to use this response in geotechnical engineering is this part clear? What are you thinking? this has been achieved by people like you only; now you find it trivial or interesting.

So, now I will be talking about further interpretation of the components of the circuits. Is the basic philosophy clear? The basic philosophy is that we are trying to capture the response of a geomaterial by conducting some test in the laboratory using an impedance analysis. And then each component of the circuit should be giving you some information about the material.

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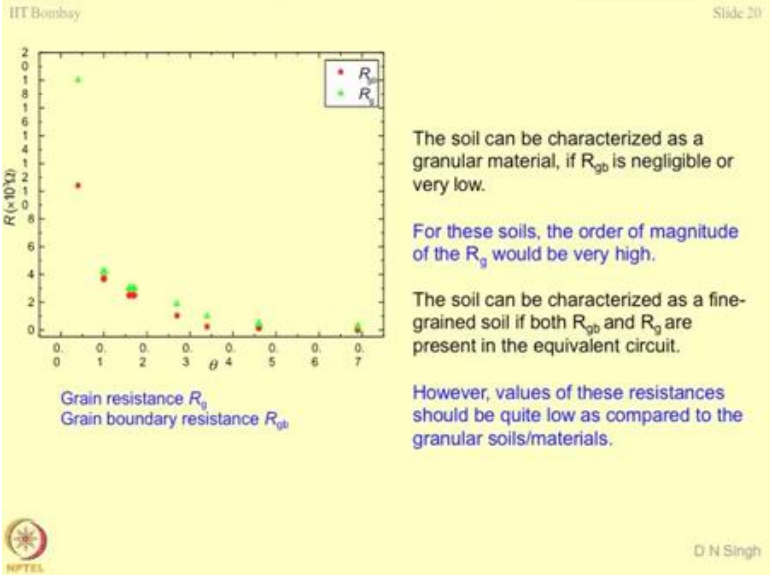

Grain resistance R_g
Grain boundary resistance R_{gb}

The soil can be characterized as a granular material, if R_{gb} is negligible or very low.

For these soils, the order of magnitude of the R_g would be very high.

The soil can be characterized as a fine-grained soil if both R_{gb} and R_g are present in the equivalent circuit.

However, values of these resistances should be quite low as compared to the granular soils/materials.

Now, if you plot the values of the different components in the circuit; if I define it as the resistance. And if I plot resistance with respect to volumetric moisture content; what you will notice is as the moisture content increases, the resistance drops its perfectly all right I will have to go once again back to this figure in yesterday’s class; we were talking about grain to grain contact. If you put two grains together; so it is a sort of a capacitor formation get some fluid in between.

You look at the circuit over here; this is the depiction of grain to grain contact. The resistance offered by the system is associated in the form of R 4; the resistance offered by the pore fluid is nothing, but this resistance clear. So, the issue is it is a sort of a philosophy by which you are trying to study what contacts between the grains is causing in physical sense. The contact between the fluid and the grain all right is a sort of a grain boundary effect.

So, if you plot these types of relationships and if you show R gb; R gb is nothing, but resistance of grain boundary and R g the resistance offered by the grain itself. These two things different things one is the resistance offered by the grain boundaries; another one is the resistance offered by the micro system the grain itself.

And if you put them together to get the total resistance of the circuit, then what happens to the total resistance of a circuit this is what people would like to identify. So, the message which you get from this analysis is you can characterize the soil as a granular material; if R gb is negligible. What is the significance of this? If in this figure the value of R 4 becomes very very small.

So, this shows is a granular material if R 4 is very appreciable is going to be a fine-grained material is this clear. It is basically a philosophy been put in practice to show us enology and this enology captures a real phenomenon in the form of some equivalent models; for these soils R g value will be very very high.

So, if you train a circuit and if you get the components of the circuit and if you find that Rg is extremely high it is understood that this material is going to be a coarse grained material; R grains fine grained material will show you very very less resistance because of the surface charge. So, the soil can be characterized with the fine-grained soil if both Rgb and Rg are present in the equivalent circuits, but their values are less. However, the values of these resistance should be quite low as compared to the granular soils.

So, the basic idea of giving this information to you is just by looking at the values of the components which are appearing in the circuit you can identify whether the circuit belongs to a fine-grained material or a coarse-grained material. Once that ahead of this would be ascertain where whether the pore fluid is contaminated or not; that means, the circuit components corresponding to R 3 you know which is or R 2; which is shunting this process.

If value of R 2 is very very small most of the current will be passing through the pore solution. But if R 2 is very high it becomes a dry soil clear, so based on R 2 value, you can find out in such a distinct state of the material. So, ultimately what was the whole idea? The whole idea was to characterize the soil mass or the porous media. And when you say characterization the basic attributes were grains, how they are located, what are the pore fluid is present, what is the density of the system and so on.

So, the effects our own in this direction to you know most of this subject in such a way that is just take one measurement of the soil. And when you analyze the results and you should be able to diagnose what are this material is; clear? Any questions here; this work is not still complete we have working in this direction fully one day this part should be in a position to be handover to the you know professionals.

But I am sure that you must have got some idea about what are the application of impedance spectroscopy and why people are working in this area and ultimately what do they achieve out of it.