

Environmental Geomechanics
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Lecture No. 53
Electrical Characterization – III

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State-of-the-art

Researcher	Contribution	
Coulomb (1736-1806)	Developed Coulomb's law	
Maxwell (1881)	Electrical conductivity of a heterogeneous media	
Fricke (1924)	Extended Maxwell's equations for ellipsoidal particles	
Archie (1942)	Formation Factor = η^m (FF: electrical resistivity of saturated soil divided by the electrical resistivity of its pore fluid)	

Researcher	AC	Soil Property
Smith and Rose (1933)	100 kHz - 10 MHz	Determination of Water content
Arulanandan and Smith (1973)	1 - 100 MHz	Soil structure/Particle orientation, electrolyte effect
Topp et al. (1980) Arulmoli et al. (1985)	20 MHz - 1 GHz DC	Determination of water content soil liquefaction, relative density

A bit of the idea on what is state of the art on the subject because this is a research area, which is open for research and people should contribute, a lot of things are to be answered, I am sure that state of the art tells you that you need not conduct any of the conventional experiments in the laboratory intoday's world because people have no time and look at the size of the infrastructure which is being developed.

Thousands of acres, thousands of kilometres and also gone are the days, and people used to take out the samples and bring them to the laboratory and test them then-contemporary thought process is that I should be getting in-situ properties and which are more reliable, and this is the fashion. So, all this started since 1736 when Coulomb came out with the theory which is known asCoulomb's Law. Maxwell, Frick and Archie. So,Archie's factor that is formation factor is a function of porosity is what is being used by the guys who are in the realm of geotechnical engineering and those who are geophysicist.

So, this formation factor basically tells you what is the contrast of the electrical conductivity perpendicular to the plane of the deposit and parallel to the plane of deposits your K_H/K_V . This concept is being utilized in understanding how the formations were created and whether these formations should be bearing minerals petroleum or not. So, if you get a chance to work in the petroleum geophysics, you will find that form factor is utilized there a lot which is the electrical resistivity of the saturated soils divided by the electrical resistivity of its pore fluid.

And this is a function of the porosity; there are people who have done a lot of studies since 1933, it has picked up this subject people have worked in the frequency ranges of hundred to 10 megahertz, kilohertz to megahertz, megahertz range 20 megahertz, one gigahertz range and the soil properties which have been determined of water content, soil structure, particularly orientation, electrolyte defect, determination of water content, relative density, and soil liquefaction. So, this motivated us to take research in this area.

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State-of-the-art

Researcher	AC	Soil Property
Lovell (1985)	4 Hz	porosity, permeability
Loon et al. (1990)	0.1-1 GHz	Conductivity of soil
Arulanandan (1991)	50 MHz	Porosity
Thevanayagam (1993)	All ranges	porosity, pore fluid
Knoll and Knight (1994)	0.1-10 MHz	clay %, porosity,
Shang et al. (1995)	60 Hz	conductivity of clay
Thevanayagam, (1995)	1 MHz - 1 GHz	electrical dispersion in soils

And if you further look at the list, you will try to see that you will you might find that people have been very ambitious and they have been talking about the clay fraction directly as a function of electoral property, porosity, the conductivity of the clay, what is the electrical dispersion and soils for different applications. And even some people have worked on the permeability of the soil.

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Electrical Properties of Geomaterials

Electrical properties (conductivity, σ , and dielectric constant, k) can be used for geomaterial characterization.

Electrical conductivity is a measure of charge mobility in response to an electric field.

Dielectric constant is a measure of the capacity of a material to reduce the strength of an electric energy field and to behave like an insulator.

Variation in electrical properties with the frequency of AC

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Having a relook at the electrical properties of geomaterials, as we discussed the conductivity and dielectric constant are the two major parameters which are used for defining the state of the material and conductivity comes because of the movement of the charges. A dielectric constant is a measure of the capacity of the material to reduce the strength of an electric field and to behave like an insulator. So, here we talk about the variation of the electrical properties as a function of the frequency of AC and this is what is known as the dispersion of electrical properties or delicate dispersion in the material.

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Electrical Properties of Geomaterials

- Electrical conduction in moist geomaterials occurs as a result of the movement of ions
- These materials are dielectric material (characterized by polarization)
- However, they behave neither as a conducting material nor as a perfectly dielectric material, and hence they can be modeled as a 'lossy dielectric material'.
- A frequency-dependent complex permittivity, k , is used to capture both amplitude and phase information.

For the parallel plate capacitor

$$k = \frac{C \cdot d}{A \cdot \epsilon_0}$$

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So, this part I have already discussed that the electrical conduction in the moist geomaterials is more and we have talked about the polarization also when you apply the voltage across the sample in electrodes, they get a positively charged we used here the concept of lossy dielectric material. We treat soil as a lossy dielectric material that means there are some losses of the storage of the charges takes this to the soils. So, the dielectric constant of the permittivity is a function of frequency, and we define k as $(C.d)/(A.E_0)$, capacitances $(k.A.E)/d$.

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Dielectric Constant k

$k = \epsilon / \epsilon_0$
where, ϵ = material permittivity
 ϵ_0 = permittivity of free space
 $= 8.854 \times 10^{-12}$ (F/m)

$k = (k' - j \cdot k'')$
 k' = real part of k (depends on polarizability)
 k'' = imaginary part of k (losses due to the conduction and polarization)

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So, what about the dielectric constant? So, the dielectric constant is E/E_0 ; this is the material permittivity earlier I use this term with E_s that was for the soils, epsilon could be any material and epsilon not as the permittivity of the free space, we can represent k in two parts that are the real and imaginary. So, k is the real part $-j$ into the imaginary part of the dielectric constant. So, this is where the interpretation of the measurement of electrical properties starts impedance analysis starts.

So, if I define the dielectric constant as a combination of the real part of the dielectric constant and imaginary part of the dielectric constant, this is the composite function, what we do is we plot many times real against the imaginary part to decipher the information. I will show you how.

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Ohmic Conduction in Geomaterials: Basics

- Conduction of current is due to ionic movement
- $I = \sigma \cdot V$ σ : Resistivity
- Factors affecting electrical conduction in case of coarse-grained soils:
 - void ratio
 - degree of saturation
 - Grain size & shape & orientation
 - Pore structure
 - the nature of the pore fluid and its conductivity
- Negligible surface charge of grains
- Electrical conduction in fine-grained soils:
Complex phenomenon, due to development of double layers around the grains




So, before we go into that, a bit on the ohmic conduction of geomaterials, all of that the flow of current follows the ohm's law, which is because of the ionic movement. So, we write sometimes as $V=i \times R$, where R is $1/\sigma$. So this becomes the resistivity or resistance is R , so, these are the factors which influence the electrical conduction.

Void ratio, degree of saturation, shape, size and orientation, pore structure and nature of the fluid and its conductivity. As I said earlier, unless the grains are charged, the surface conductivity is ignored. What you will realize is that ohmic conduction through pore solution is very easy. But ohmic conduction through the soils and the grains is going to be very complicated. And very soon you will realize this.

The reason is when we deal with the fine-grained soils, there are double-layer formation DDL we call it as a diffused double layer, and that is a consortium of different types of ions on the clay platelets. So, there is a lot of interference which takes place when you measure the electrical properties of the geomaterials, particularly when they are fine-grained, because of double-layer formation.

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Electrical Impedance

- Resistivity term is applicable to DC
- Impedance – Resistance offered by soil mass to AC
- Impedance captures both frequency and amplitude information

$$\begin{aligned}Z &= V(t)/I(t) \\ &= V \cdot \cos \omega t / I \cdot \cos(\omega t - \delta) \\ &= R - jX\end{aligned}$$

where, R is resistance, which is the real part of Z (= Z'),

X is the imaginary part of Z (=Z'')

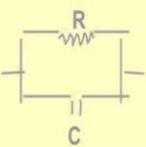
Impedance is frequency (of AC) dependent

So these are the basics of the impedance. That when we measure the resistance, by using DC current, we call it as a resistance. However, when we measure the resistance by using AC current it becomes impedance. And I can define impedance that as V as a function of time upon I as a function of time. Which is nothing but $V \cdot \cos \omega t / I \cdot \cos(\omega t - \delta)$. This is the lag behind between the voltage and the current. So, when you plot voltage and current together, there is a time lag, we can define this term as $R - jX$ in the complex form.

So, R becomes the real part of the resistance and X becomes the imaginary part of the resistance. So, whenever we measure the impedance of the samples, this impedance can be represented in a combination of real and imaginary parts and then these real and imaginary parts can be utilized to decipher a lot of information from the geomaterials. So, these are the basic models which we use, you have studied these RC circuits and all.

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Basic Model



Element	Impedance	Admittance
Resistor (R)	$Z = R + j0$	$Y = 1/R + j0$
Inductor (L)	$Z = 0 + j\omega L$	$Y = 0 - j(\omega L)^{-1}$
Capacitor (C)	$Z = 0 - j(\omega C)^{-1}$	$Y = 0 + j\omega C$

Elements in series :

$$Z_{\text{equiv}} = \sum_i Z_i$$

Elements in parallel :

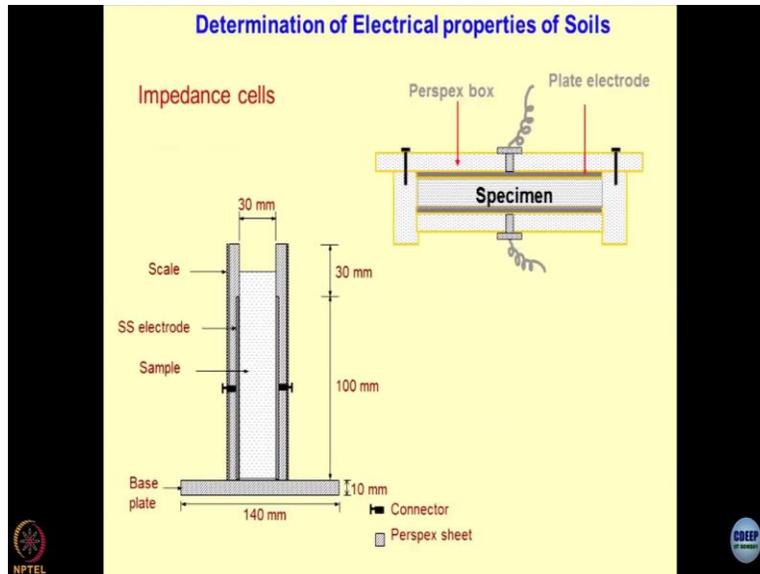
$$Y_{\text{equiv}} = \sum_i Y_i$$




In your engineering, soil can be represented as an RC material, a material which shows resistance and capacitance. So, this is the equivalence between the geomaterial or the soils and their electrical circuits. So, these are the components of resistance, inductance, and capacitance which can be utilized for defining their impedance, remember impedance is the resistance and admittances the conductance or inverse of the impedance.

So, you must have come across these terms; when you deal with the resistors, the impedance is R when you deal with the inductors, this is $j\omega L$. And when you really the capacitors this is $-1/(j\omega C)$. So, these components can be fitted to describe the state of the soils. And I hope you can realize that if I want to find out the total impedance, I can sum up the resistances and when I do for parallels then I have to sum up all the admittance of the material.

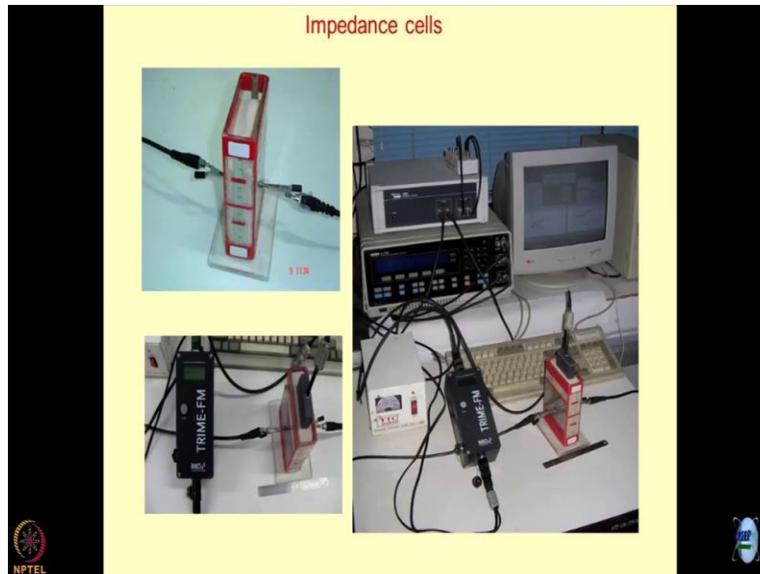
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So, one of mymaster's students started working in this complicated topic. His name is Azaz Masood Bhat, and he published two very impactful papers on electrical characterization of geomaterials, which have become landmark papers. He has created this impedance, and the concept is simple you take a small rectangular box, and this box is standing on a base plate, and there are two electrodes.

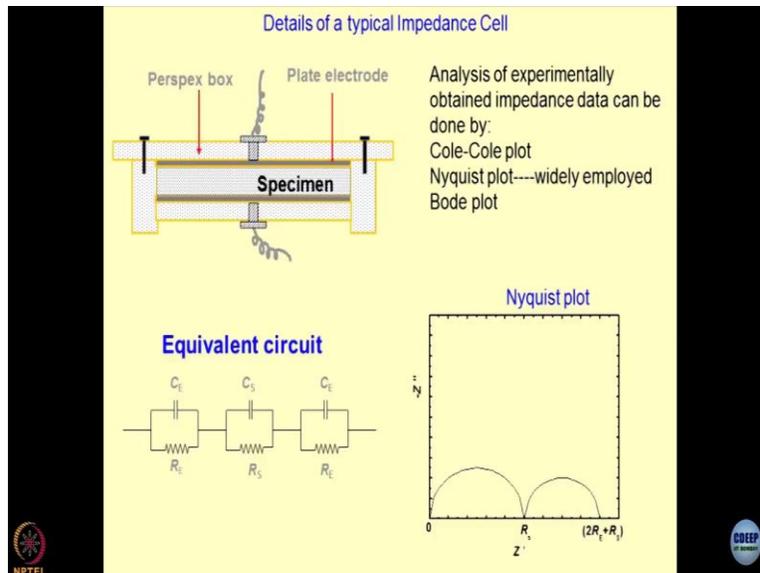
Which are plate electrodes which are fitted inside and this box can be used for finding out the impedance of the sands. And when you are dealing with the liquids, then you can use this type of a setup where the liquid can be contained in the cell, and there is a top cover, and there are two electrodes which are embedded inside the cell. So, both systems can be utilized.

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And this is how the setup looks like. What we are doing here is we measure the volumetric moisture content of the sample also along with its impedance. So, this is the impedance cell; we measure the impedance of the sand and the moisture content. This is the setup which is used for obtaining the impedance of the samples; this is what is known as impedance analyzer.

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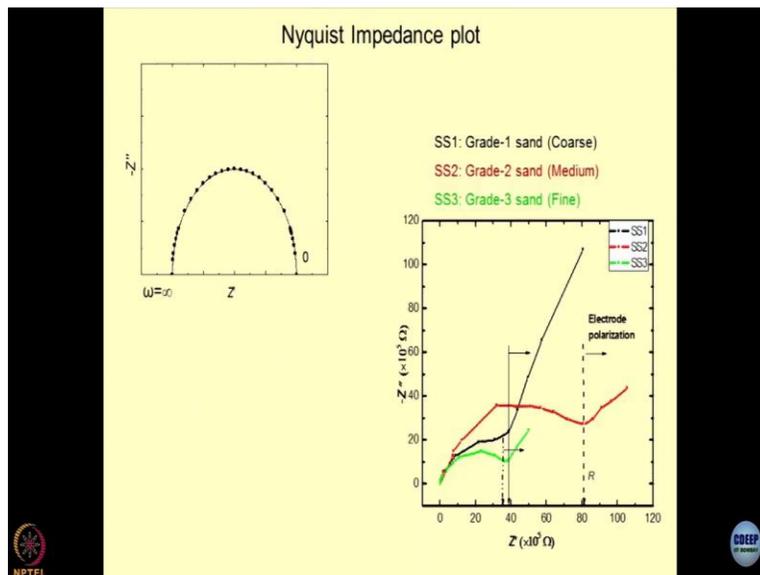


One interesting thing is that the sample itself can be modelled as a combination of RC. So, if I consider this specimen and these 2 electrodes, I can develop an equivalent circuit like this so, the central portion is of the specimen which is represented as a combination of capacitance and resistance and the two plates of the electrodes are represented as again RC circuit. If you plot them on a scale which is known as the Nyquist plot, there are different ways of plotting this data.

The complex electronic circuits. So, if you see here this is that ' is the real part of the resistance and this imaginary part of the resistance when you plot the results that you get from this, you can get circles and these circles describe the state of the material. So, as the frequency increases, it tends to infinity very high gigahertz values if you are using the resistance offered by the sample would be less.

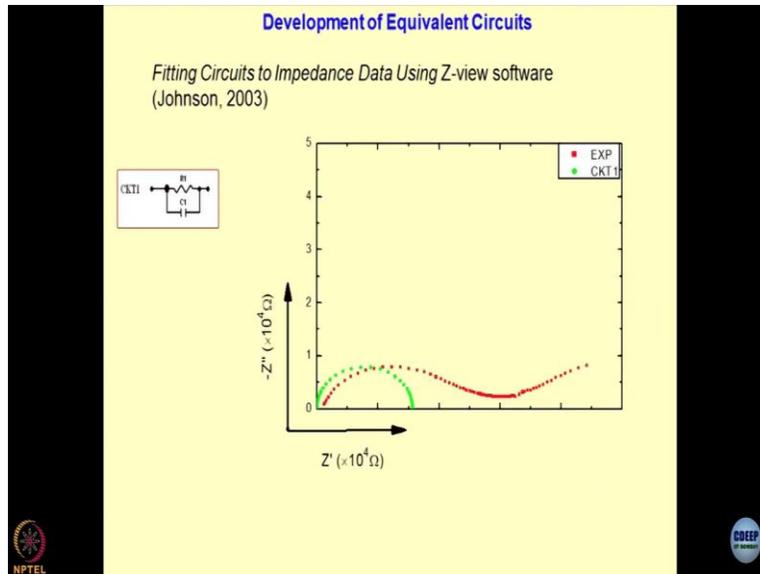
So, this is the very state of the art thing which we are doing right now. And we are trying to capture the response of geomaterials and the mechanisms which happened in them by capturing these type of results and showing how the phases are getting formed and disappear.

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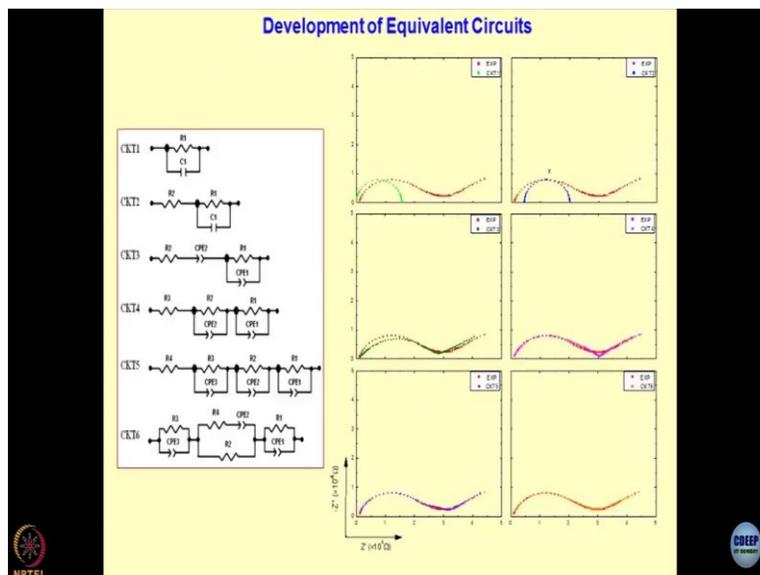
We did a lot of experiments on soils of a different type is sands. And just to show you how the results vary the real part versus the imaginary part. I am not going into the details of how the analysis of the results is done. Just my intention is to show you how these results can be utilized for characterizing the geomaterials.

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We use Z-view software. And the best way to analyze a soil mass would be to create a simple RC circuit. So, what it shows here is, if I include the response of theoretical models, on the experimental results, these are the experimentally obtained results of the soil sample which we were analyzing. And if I fit an equivalence circuit to this. A simple RC will give you a lot of deviation from the experimental results. That means you need to refine your circuits.

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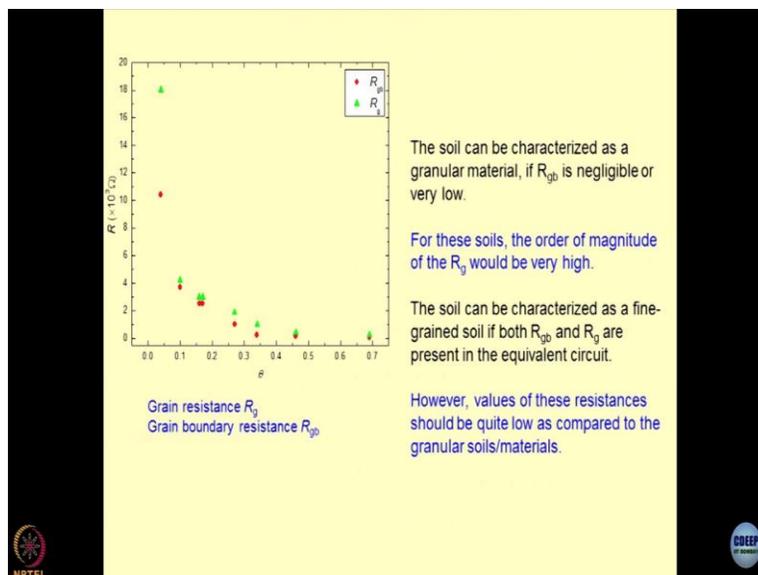
I hope you will find it very useful. And this is a very complicated process where you keep on generating the equivalent circuits of the soils and the materials and keep on mapping them over here. So starting from a simple RC circuit what we have done is we have added resistance to the

RC circuit and with this, what has happened is the results are at least bound by the experimental results.

We were not very happy with that. So, we have included one constant phase element; I do not know whether you remember or not in your electronics course, they must have talked about the CPEs constant phase elements, which maintain the phase of the system constant. So, by introducing a constant phase element, we realized that the results are quite matchable. And then we did further manipulation to come out with an equivalent circuit for the soils which looks like this.

So this is the electrode; this is the electrode in which the sample is encased. So, that means the soil sample has been represented by two resistances and one capacitor of what is known as CPE constant phase element. Now you can reply or get the answers to the type of question that you have been asking any process which happens in the soil mass will get reflected, if I measure R_2 , R_4 and CP2.

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And that is how I can say that what is changing over a period of time. So, all the properties of the soils have been now imbibed with time. And that is the art, so, here we have shown how the resistance of the soils changes as far as the grain resistance is concerned, the grain boundary two grains sitting next to each other, there is a boundary getting created and two grains sitting

together will also create a sort of a capacitance effect because of the pore solution inside. So, we did this type of modelling a lot.

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Basic Models to Depict Flow Paths of AC in Dry Geomaterials

AC flow through a dry soil may occur due to:

- (i) a-a (the surface of the soil grains, which is mainly due to the presence of surface charge carriers/ions)
- (ii) b-b (the soil cluster, wherein soil grains are in contact with each other and current may flow through the interconnected grains)
- (iii) c-c (partly through the soil grains and partly through the air present in the voids, which is a least likely path due to its very high resistance, unless the air is contaminated with fumes of water or chemicals)

Legend:
■ : Electrodes — : Conduction path
☁ : Soil grains □ : Air

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And then we came out with the analogy of how current flows through the geomaterials all this done by my students, Azaz and Dr Hanumantha Rao. So, you can read their papers which have been published. Now if you look at the possibilities of current, which is passing through the dry materials, there are three possibilities. In dry soil, so voids have only air, one of the possibilities is that from grain to air to grain to air, this is one of the possibilities. The second possibility is of the current passing is grain to grain, grain to air, grain to grain to grain, and so on.

And the third one would be through the voids only, I hope you can realize that deciphering this information from mathematical models is not going to be easy, but we are into it, and we are trying to develop models which will help you in defining the state of contamination of the soils, we would also try to develop models where you can differentiate between the fine-grained soils and coarse-grained soils including their shapes is quite intricate R&D differentiating between the saturated state of the material and the unsaturated state of the material is very easy that you can do very quickly by doing this type of modelling. So, this is the micromechanics of how the current flows through the porous media. So, A to A is the surface of the soil again which is

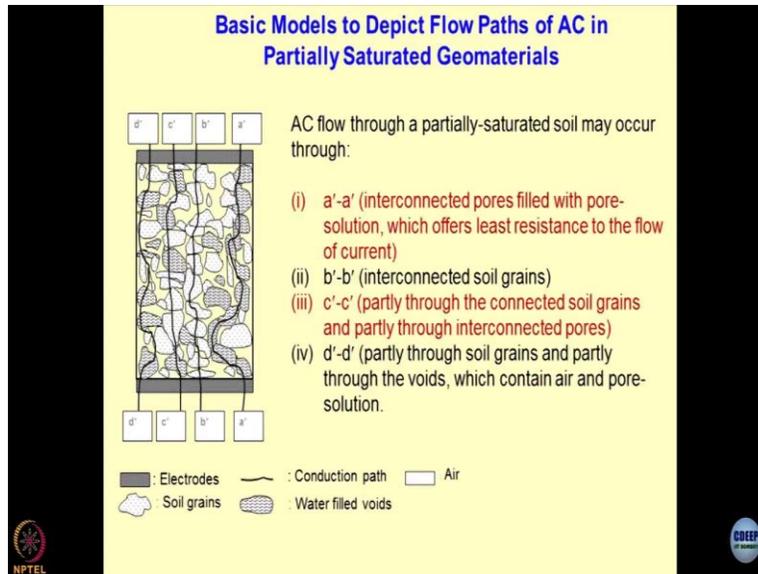
mainly due to the presence of surface charges. If you remember, we were talking about what is the difference between the coarse-grained particles and the fine-grained particles. Coarse-grained particles do not have surface charges; Fine-grained particles have a surface charge.

So, this is one of the differences. And we can utilize this concept in differentiating the material without any sieve analysis because the sieve analysis and the hydrometer analysis has its own limitations and the problems. The BB part is the soil cluster, wherein the soil grains are in contact with each other, and the current may flow through the interconnected grains, this type of possibilities are going to be more in case of fine-grained materials as compared to coarse-grained materials.

The third possibility is partly through the soils grains and partly through the air, which is present in the voids, which is the least likely partly due to his high resistance which is offered by the air. So, once you enter into the micromechanisms of this type, it becomes quite complicated. Presently what we are trying to do is we are trying to model the gaseous phases into the soil mass and the bacterial activity into the soil mass.

So, for us, the bacteria itself becomes a particle and gas molecules would be present into the pores. And if I apply pressure and temperature conditions, what is going to happen? Either the gases which are present in the voids would get dissolved in the pore solution, or there could be the crystallization of the water in the form of the ice. So, this becomes a very complicated matrix.

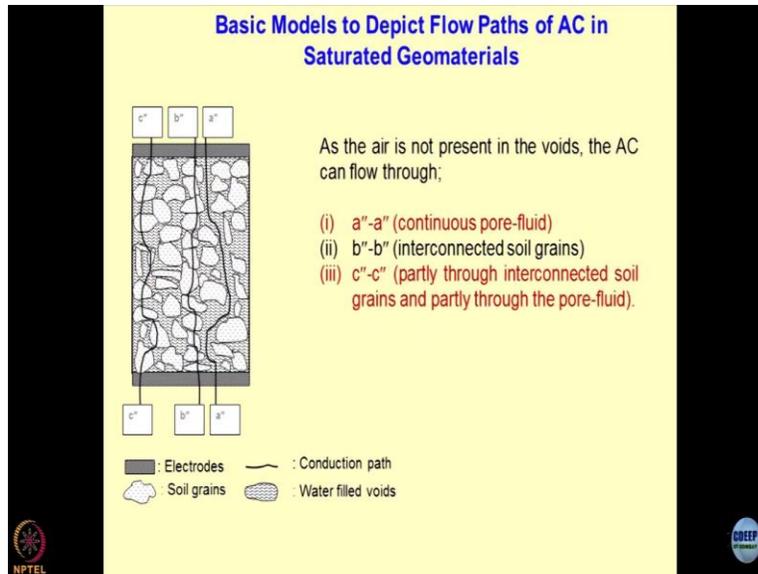
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The second possibility is when we deal with the partially saturated soils. So, the concepts remain the same only thing is we have created a void which is water-filled. So, you have the grains of the soils in between there is a void which is full of water. To me, It appears like several capacitors which are arranged within the soil mass either in the parallel or series. So, once I do the impedance analysis, I come out with equivalent circuits, and they are in equivalent circuits. Then again I have a model what type of combinations of the resistances, the capacitance can be possible which would give you the response of a material. So, there are the possibilities of current passing through this A', interconnected pores, these are all interconnected pores, the easiest way for conduction of the current. Particularly, if the ionic solution is present in the pores.

The B is interconnected soil grains only then C' is the part through the connected soil grains and sometimes through the interconnected pores and DD is the grain through the voids, which might contain air and the pore solution.

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The third possibility would be when we have saturated soils. So, I hope you realize now we are trying to attempt characterization of geomaterials based on their saturation which is the genesis of unsaturated soils. So, one of the possibilities is the pore solution continuous pore solution which is present in the soils. The easiest way for current to pass through, no resistance is being offered much. 'A' is continuous pore-fluid, 'B' is interconnected soil grains provided the soil grains have good conductivity like fine-grained materials.

The third is the sandwich of the two, we have the interconnected soil grains and partly through the pore fluid. So, these type of micro-mechanisms have to be studied, and they should be developed in the future **"Professor - student conversation starts"** Sir, microorganisms like when they are present you said the current passing capacity would decrease drastically. Say it again. The microorganism is if present in any phase around the soil grains, then the organic matter will hinder the process at that time I was about to ask that. Very complicated situation.

The aim is to use these models to determine how degradation in the material is going on. And not only the degradation, but up-gradation also. If we need to find the impedance of the fine-grained soils or the properties of fine-grained soils, then what we will do. He employed for sands impedance of sands he found. So, if we need to found the impedance of clays or fine-grained soils, so, what change will occur. What change will occur?. How will we do interference will

come. A quick answer to your question is nothing of this sort is going to happen. Measurements can be done.

It is like generating a lot of ECGs, but if the doctor or the person does not know how to decode the ECGs, what is ECGs are going to do. I hope you can understand my point. So, the measurement of the properties is not an issue. You can just pack the sample in the cell and then you can measure something. The million-dollar question is how to create a mechanism out of it and how to decipher the results so that these results can be utilized by people who are in the field of monitoring instrumentation and micromechanisms. **"Professor - student conversation ends."**