Environmental Geomechanics
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Lecture No. 46
Thermal characterization-II

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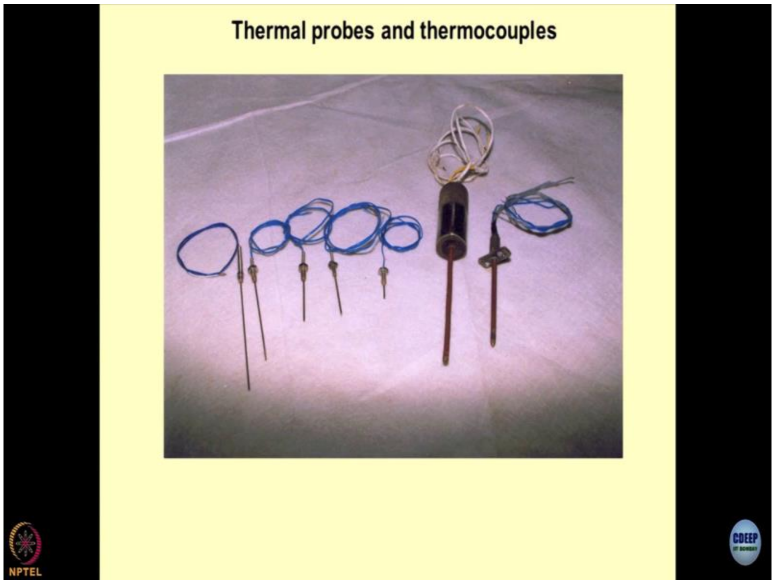

This is how they look like these are the thermal probes which we developed, and these are thermocouples which were used for measuring how heat migrates in the geomaterial at different distances and different times. This was the work which was done by my students Gangadhar Rao, David, Dr. Dali Naidu, who was a faculty member, IIT Chennai. And later on, Hanumantha Rao and Sreedeep and lot of people used these gadgets, they appear to be very simple, but when we were devising them, I am sure you must realize it was a tough time and we are not having much knowledge about how to fabricate these setups.

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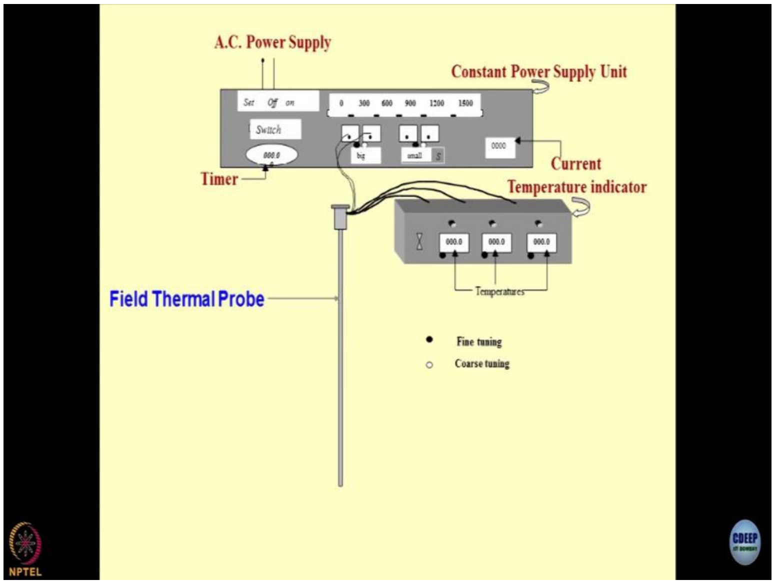

This is a set of which was developed by my student David. This is a field thermal probe which is 1 meter long, and this was the master as thesis and what we did is we divided the entire probe into 3 sections and these 3 sections, the temperature was monitored by using 3 thermocouples we call them as the top, middle and bottom. The beauty of this system is that you can do thermal profiling of the ground up to one meter. And if you want to go deeper, then you can cut a trench, and you can do first profiling one meter again you can do 1 meter.

And then you can keep on doing as long as the system permits. So, we apply a constant power through a constant power supply device; we heat up the nichrome wire, the concept remains same of the laboratory thermal probe and the field thermal probe. And when the heat when the heater emits the heat, and when the heat gets accumulated in the soil mass, we measure the temperatures by using 3 thermocouples. So, this becomes a thermal probe.

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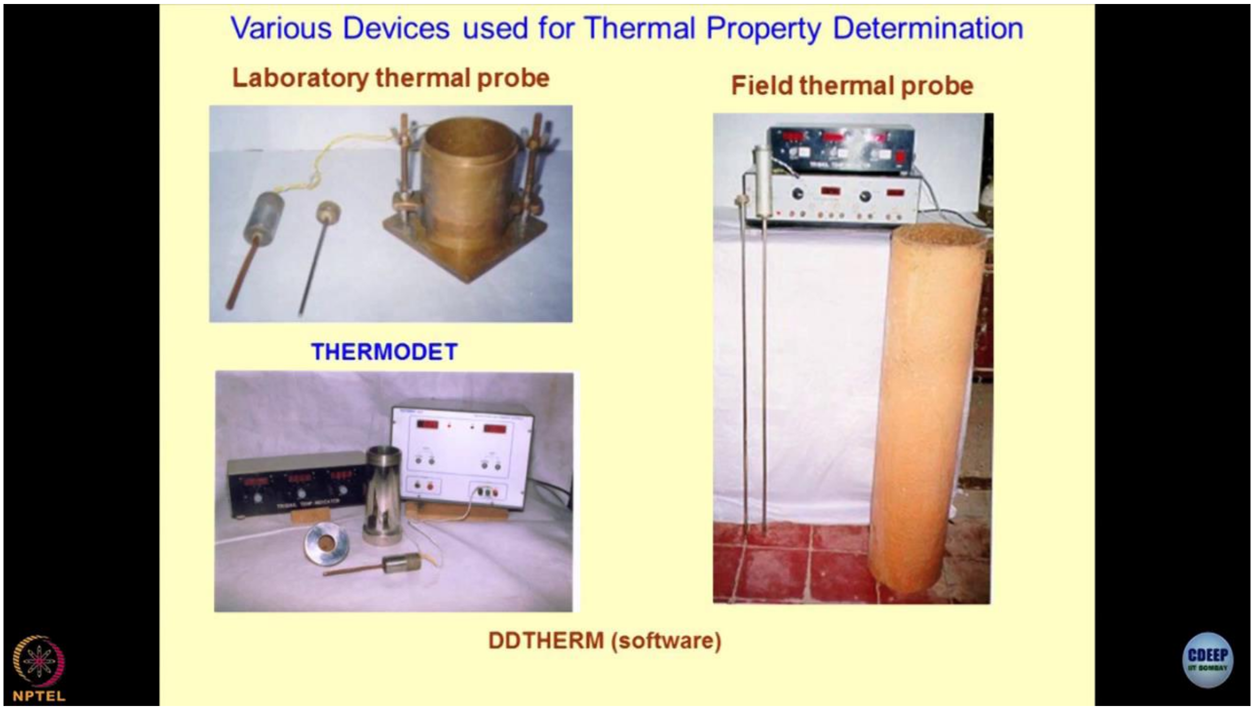

Now in the process, we also have developed different types of devices which have been used for determination of thermal property. This is all in house development. So, what you see here is the CBR mould or a proctor compaction mould and then the thermal probe which was developed can be inserted into the compacted soil mass with the help of a dummy rod. So, the diameter of the dummy rod is slightly less than the diameter of the thermal probe, and it is to ensure minimum disturbance which is the cost to the soil when you insert the thermal probe.

This is the field thermal probe which I was talking about. This is the setup constant power supply, which heats the Nichrome wire in the thermal probe, thermocouples reading are displayed on a temperature reader. And this is the mould which was used for creating the soil samples under control conditions and calibrating the thermal probe. It is a very interesting device which we developed those known as THERMODET, and the name came from thermal properties detector. All right, so we named it as THERMODET. And what you are observing is this is stainless steel, hollow cylindrical tube.

And there is a cap at the bottom, and there is a cap at the top which a hole and through this hole, the thermal probe can be fitted. After compacting the sample in this THERMODET device, we can put this collar or the cap at the top and then we can insert the thermal probe through it. Later on, this device can be either kept it in an oven, and I can find out how the heat migration takes place from the outer periphery to the inner benefit. After attaining a certain temperature, I can take out this device, and I can put in the water bath also and then I can observe how the cooling of the soil mass takes place so, in this way, the heating and cooling cycles of the geomaterials can be studied.

The results which we have obtained from these type of test utilized to create a software which is known as DDTHERM and I did a lot of consulting by using these tools as well as the software. And that became a big source of funding; there was a time when we used to supply these thermal probes to different Western countries also, particularly the power plants, those who are quite eager to know the thermal properties of the soil mass before the tensing of trenching operation takes place.

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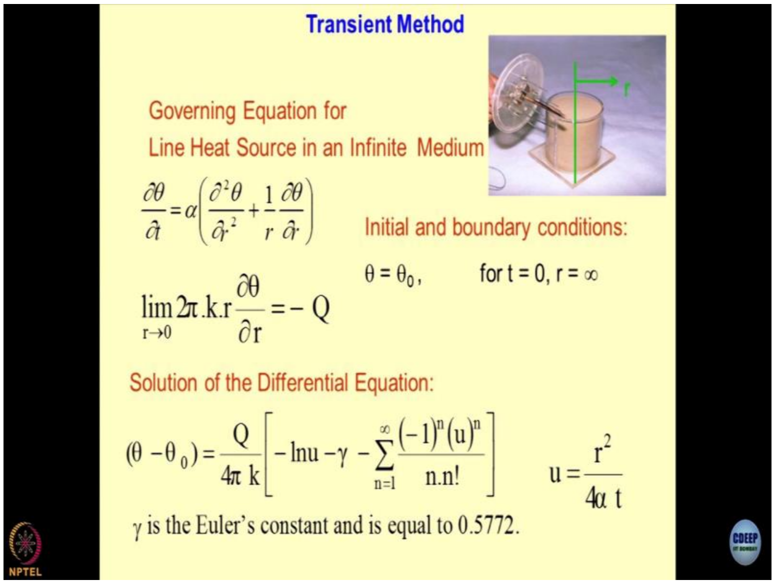

So, a little bit about this transient method. So, basically, the probes which I have shown you act as a line heat source. There are like a pen, so, truly speaking this is a line heat source and the heat is getting emitted in the radial direction. So, we call them a line heat source. That means the heat source happens to be a line, and this is how it looks like. So, if you take some soil sample in the mould.

This is the thermal probe which is fitting at the centre and then I have fitted the thermocouples which I have shown at different radial distances and different z's of the sample. So, the basic idea is to measure the heat migration in the radial direction. So, this is a typical axisymmetric problem, where the symmetry of thermal regime is along this axis and what we want to do is we want to say, or we want to find out what is the temperature in the soil mass because of its heating as a function of r and t, radial distance and time.

So, this is the equation remember, do you remember, which is the second-order differential equation Fine. And this can be utilized for finding on the pore water pressure, 3-dimensional consolidation or the thermal diffusivity. So, theta is the temperature, rate of change of temperature with respect to time is thermal diffusivity, the second derivative of the rate of temperature change with radial distance $(1/r)\times(\eth\theta/\eth r)$ similar equations is for 3d consolidation also if you remember.

So, then we can substitute boundary conditions, and we can get this expression Q is the power supply which is $i^2\times R$. R is the resistance per unit length of the heater wire which has been fixed inside and then if you solve this expression this is the function which you get, I hope you remember this function is Euler's constant. So, ultimately this equation yields $\eth\theta/\eth t= Q/(4\Pi . K)$. k is the thermal conductivity inverse of thermal resistivity Can you recognize this term somewhere you have seen this in your conventional geomechanics.

What is time factor $C_v.t/D^2$ So, truly speaking this is $U= r^2/4t.\alpha$. So, this is sort of a function which is nothing but your time factor, which will be getting when you solve this expression. So, r is the distance of the heat front, t is the time, alpha is the thermal diffusivity. So, if I do these experiments and if I use this expression, I can easily obtain the thermal diffusivity, and by solving this equation, I can also get change in temperature, if I know the value of $Q=i^2\times R$ I can obtain thermal resistivity. So, out of the three parameters, I get two parameters by conducting these tests.

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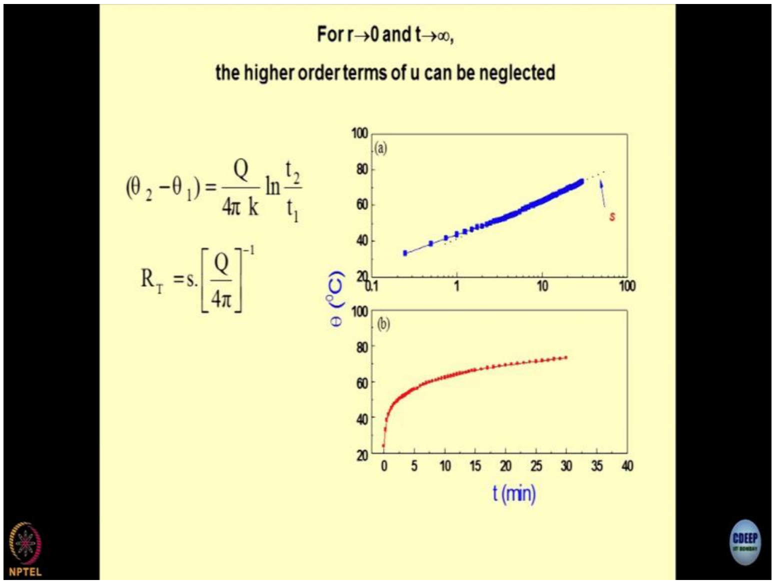

Now how would you interpret it the interpretation is like this, I can plot temperature versus time in 2 ways, one on a normal scale and second 1 is on the log of timescale. So, this is the equation which I have to solve. So, basically, this is $\eth\theta/\log(t_2/t_1)$, which is the slope of the line so having conducted the experiments if I plot the results and if I get the slope of the theta versus time profile or the graph.

I know the slope which I can substitute over here divided by $Q/(4\Pi)$, and you get thermal resistivity once you get thermal resistivity inverse of this will be thermal conductivity and wherever this line cuts the x-axis that t value becomes the t_0. And what I can do is I can substitute it over here R known, t is known, I cannot obtain the function U and hence I can obtain the alpha value.

So, which is the thermal diffusivity so that means we have obtained R_T and thermal diffusivity and then you can obtain the C_P value is this part okay?. So, when I started my experiments on the thermal properties of soils, I never realized that what will be the scope of application of these type of studies. But in today's world, I realize that these properties and these type of experiments have become so important and their application are so diverse, that sky is the limit.

One of my students, Dr Krishnaiah, applied all these concepts to determine the quality of the food grains, rice, wheat, sugar, and how to stop the germination. Because germination of the grains is a function of temperature and humidity, and he was the guy who extended all these concepts to find out the condition of the packed meat and the fish. Because as these items rot, they disintegrate and their thermal properties change.

So that is what I am saying the sky is the limit to think about the application of these parameters. So Dr. Krishnaiah did a lot of work in this area. And we also extended these concepts to determine the thermal properties of concrete and different type of composites.

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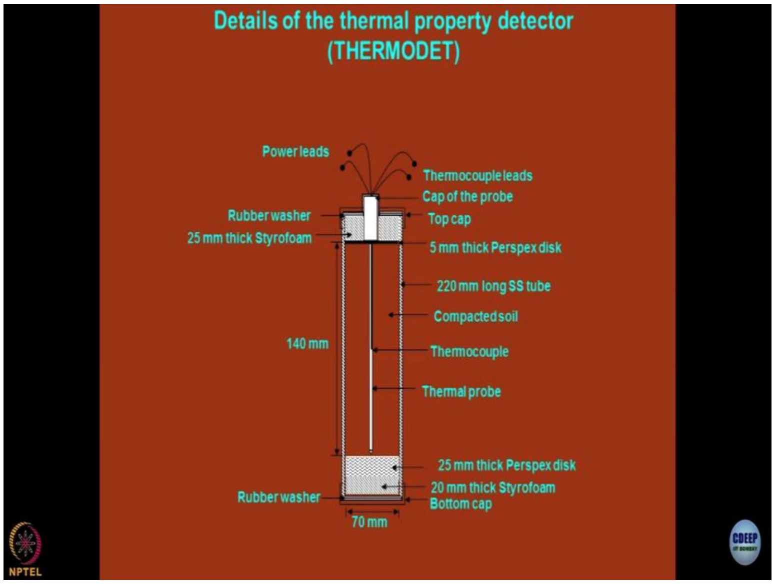

So these are the details of the THERMODET, which was designed by my student David. I explained this. Also, this is a hollow tube in which you can fill up the geomaterial, and the bottom portion is an insulator, the top cap is also an insulator and through which the thermal probe can be inserted into the geomaterial and then I can do heating and cooling experiments.

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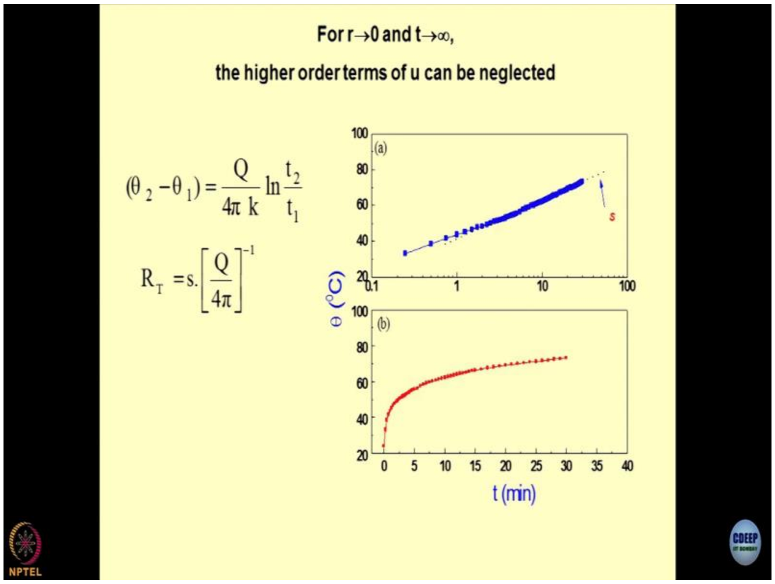

All this is published work so, you can find it out on the literature, and there is nothing new for that matter, but now, these tools have become very very useful for solving various problems which geotechnical engineers are facing. Typical cooling curve, I hope you can realize that the temperature is dropping down as the time increases, the previous one was the heating curve. So, here if you see, as the time increases the temperature of the soil mass increases.

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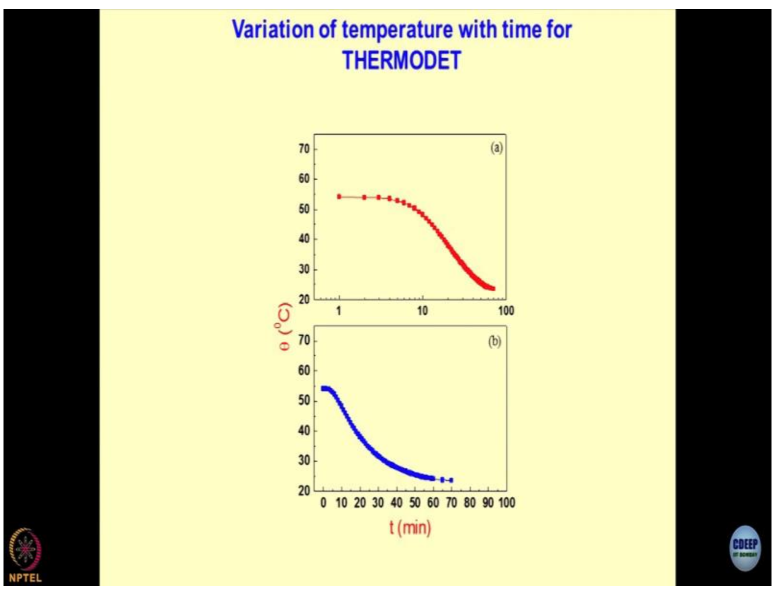

So, this is a typical cooling curve where after heating the sample in the oven, you take it out and put it in a water bath. So, I can get the properties of geomaterial, the thermal properties of geomaterials both under heating and cooling cycles, and then I can use them for various industrial applications.

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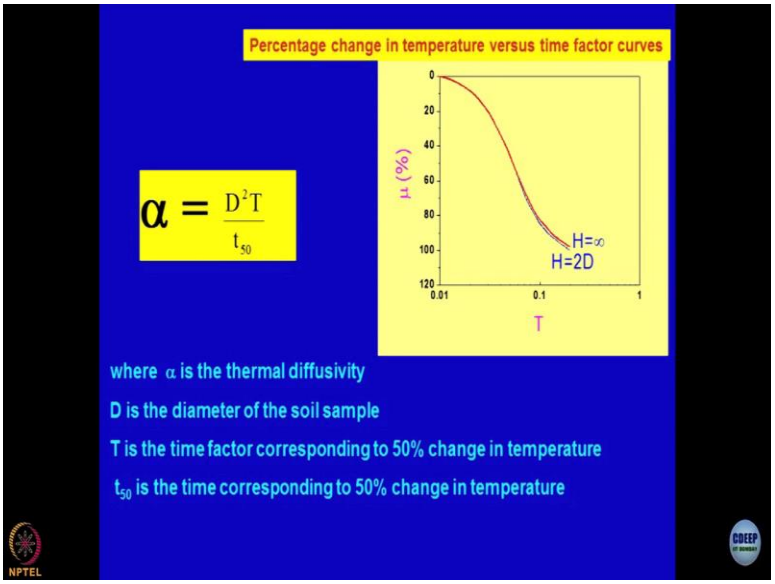

Some more similarities between the consolidation studies which you do and the heat experiments that we are doing, if I define a term as a percentage increase in temperature of the soil mass and this is a time factor t, which corresponds to 50% change in the temperature. So, this equation is well known to you. So, corresponding to $T_{50\%}$ change is somewhere here. So, if I go in the horizontal direction wherever this cuts these graphs.

These graphs are nothing but the solutions of the Euler's equation which I showed you. The time series for different geometries of the mould when the height is quite long. The second solution is when the height is two times the diameter of the mould so for 50% mu value you can get T you can substitute over here, and you can get diffusivity. I mean these devices are now quite commonly used, and you can read about them in the published literature.

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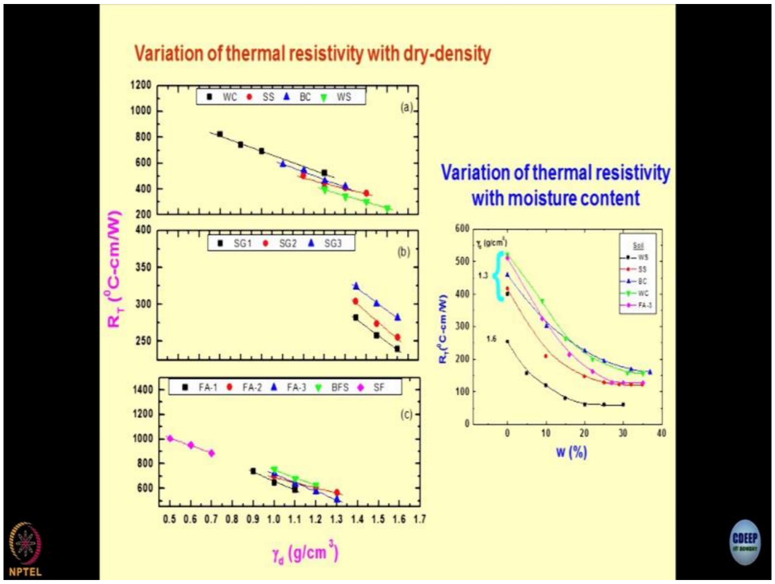

These results show you the effect of different soils which are listed like WC, SS like block cotton soils and weathered soil as a function of density and R_T. So, the first thing which I wanted to show you is that thermal resistivity is inversely proportional to γ_d and the logic I gave you the better contact between the grains for better γ_d the resistivities are going to be less so because higher γ_d corresponds to lesser air content in the voids.

And hence the resistivities are going to be less. Another way of interpreting this will be if you plot RT with respect to moisture. So, this is how the peculiar curves look like they all tend to converge at a certain point. So, if you keep on adding moisture to the soil, say about, more than 40 or 50% what is going to happen all of them will converge to a point which will be the thermal resistivity of the water.

So, this type of analysis shows that thermal resistivity of the water is less as compared to thermal resistivity of the soils and the air and this is where you can see the influence of γ_d also, the lesser density shows more resistivity as compared to higher density. So, higher density indicates lesser resistivity and more moisture indicates less resistivity. So, these things are quite easily understandable, and they can be used for designing various thermo active structures.

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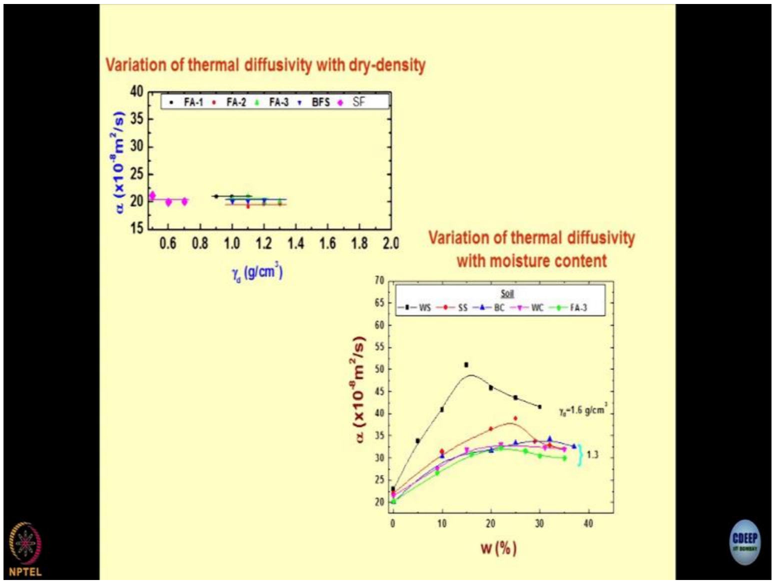

Now, if you plot the thermal diffusivity as a function of γ_d, what we observed is that this remains unaltered, there is no influence of unit weight on the thermal diffusivity. Similarly, if you plot thermal diffusivity with respect to moisture content, we observed some changes, and this is where the effect of γ_d gets translated, a denser system will show higher diffusivity as compared to a lighter system.

This is quite understandable later on my students like Dr Padma Kumar and Somenath Mondal and Sayyam Dangayach they all did the modeling of heat migration through the continuum, where you have used this concept of how diffusivity and resistivity parameters can be linked with discrete elements or finite elements to show the migration of the heat in the continuum which is geomaterials.

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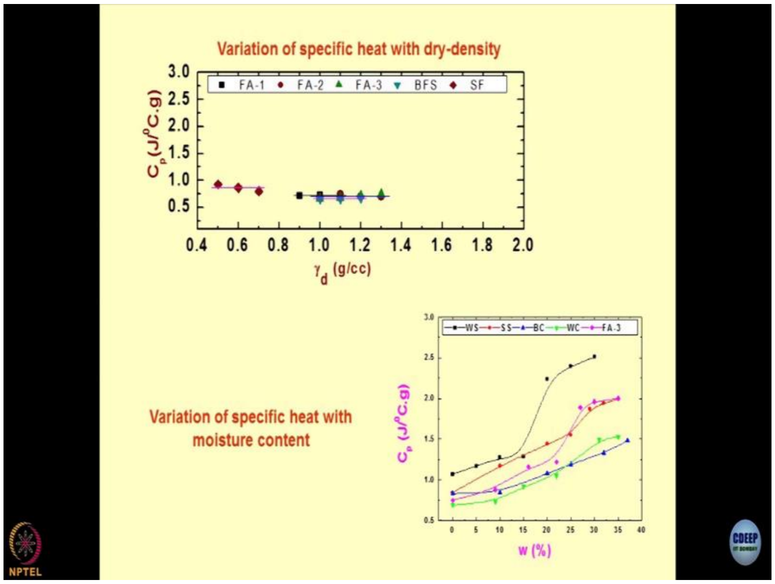

Of course, the last parameter is the C_P, and that is a specific heat when you plot it with respect to γ_d. Again, there is no variation. But, when C_P is plotted with respect to the moisture content, there are few trends which are appreciable. That as the moisture content increases, the specific heat of the material increases and that again is because of the water because water has a very high specific heat capacity. So, these type of studies were done; intensive experiments were done based on the gadgets which I showed you.

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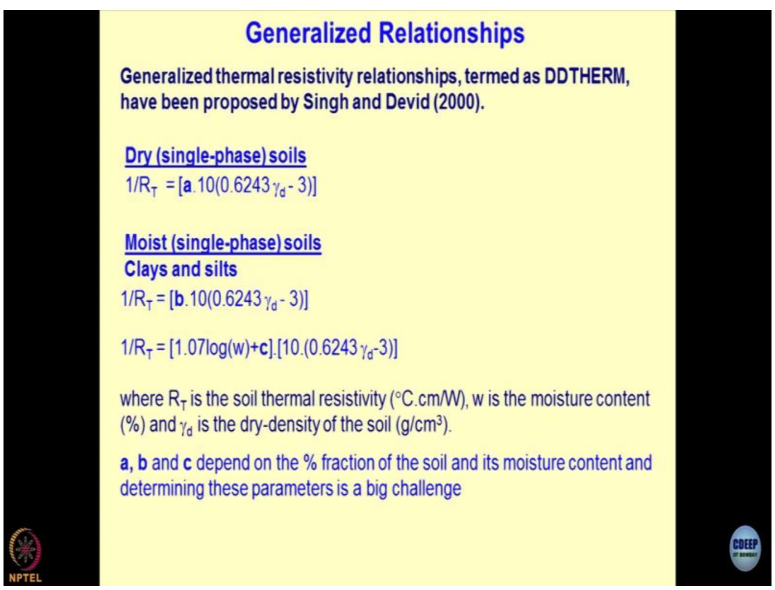

And then what we did is we created generalized relationships for professionals to use them. These generalized relationships were known as DDTHERM which I said, and they were developed and proposed by my student David for single phase system for moist soils, and we have different coefficients which are coming over here you need not write it down all this is published work you can check it from the net.

So, these are the coefficients a, b and c, which would depend upon the type of the soil which is being used that is the matrix or what we call it as the text. So you have to do the particle size analysis first. And then a, b, and c will depend upon how much clay fraction, silt fraction, fine silt, coarse silt, sand, gravel the soil has, and then you can superimpose all these things over here.

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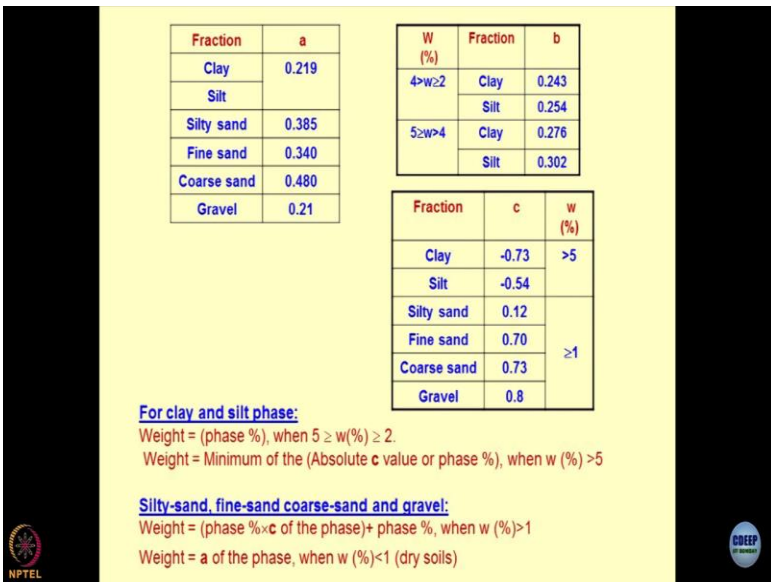

Fraction	a
Clay	0.219
Silt	
Silty sand	0.385
Fine sand	0.340
Coarse sand	0.480
Gravel	0.21

W (%)	Fraction	b
4>w≥2	Clay	0.243
	Silt	0.254
5≥w>4	Clay	0.276
	Silt	0.302

Fraction	c	w (%)
Clay	-0.73	>5
Silt	-0.54	
Silty sand	0.12	≥1
Fine sand	0.70	
Coarse sand	0.73	
Gravel	0.8	

And then we came up with some guidelines also how to obtain a, b, and c parameters depending upon the moisture content and type of the soil. So, as you can observe the parameter, a depends upon the fraction of the particle size b largely depends upon the moisture content as well as the particle size and c parameters again depend upon the moisture content and the particle size. So, put together all these things, you can use them, and this software is already there, using this software.

I did a lot of consulting work for Boeing, Hyundai, different types of thermal power plants and different types of solar ponds which are being constructed in the country, foundations for the furnaces and the forging units. So, these are the applications, where thermal properties are being used and of course, the cable laying process where most of the industries which are dealing with the cabling laying operations would like to obtain the thermal properties. So that they can design the configuration of the cable. So, if in a furnace sir the temperature at the surface like the concrete floor goes very high, then if there are underlying fine-grained soils then there are like large chances of settlement because of the dragging out of the water first of all cracking itself. Cracking of the floor will take place if the underlying water content gets lost in the fine-grained soils. So, like how would you prevent it, you treat it or like. You have to design thermal barriers.

So, if you are so eager to know about this, you should read the papers published by Dr Kolay where we have designed FTBs fluidized thermal beds. So, these FTBs are laid in the foundation of the trenches fluidized thermal beds so, these type of systems are designed, and they are provided in the foundations of the structures so, that the heat which is generated from the structures gets easily dissipated in the soil mass.

So, this is the engineering of the soil mass that you have to do based on the thermal property augmentation. Are you getting this point? Yes. That is the question since you are like allowing the heat to go into the soil mass if it is a fine-grained soil must let us say then like your horse lab, the downward potion can sink the soil below your concrete floor if it is not a slab simple, then if it is not a raft then it there might be cracks in the floor itself.

Correct. You are right. So, your questions are interlinked. What heat flux does it change the moisture content in the soil was fine. It initiates the drying process. This is what is known as a coupled process that is the heat front is moving in the system, and along with it, it is taking all the moisture also along with it. So, this becomes a coupled phenomena, migration of heat and migration of moisture; subsequently, we will observe that once the migration of moisture takes place from the soil, the tensile strength mobilizes.

And if the tensile strength is lesser than the thermal stresses, the material will crack. Fine. This is number one number two fine-grained soils with active minerals where their tendency is to absorb and desorb moisture. We call them as drying, sorry swelling and shrinking phenomena. So, this type of action might get actuated because of thermal flux migrating through the soil mass. So, where there is engineering. The engineering creates the barriers in such a manner that this transition becomes as less as possible as less abrupt as possible.

So, what I have done $\eth\theta/L$, which was extremely high, I can design a filter in such a manner that $\eth\theta/L$ can be negotiated to become a very small number. That is it. And that would depend upon the properties of the material which I have used in the filter bed, thermal filter bed, or thermal dissipater. So, this acts like a shock absorber, thermal shock absorber. So, that is what has to be designed. Hope you realize the intricacies associated with this.

So, next time whenever you see any trenching operation where the cabling is to be done, just stand by the side for some time and see how do they do it. So, there is a special procedure, which is to be adopted for laying the pipeline. So sorry for laying the thermo activate pipelines and the power cables. You cannot just lay them on the ground. The second implication of all this discussion could be because of thermal heat migration; there could be an expansion in the pore fluids.

Because we are talking about thermal expansion coefficient of the fluids, which is air and the water, so, imagine a system which is control volume, and you are applying thermal flux, what is going to happen pore water pressures might develop. So thermal consolidation is the term which comes handy in defining the system is the ability to not to create or develop the porewater pressures inside this because of thermal loading. So, now the whole context gets changed rather than mechanical consolidation.

We talk about thermal consolidation, do you realize how things change. And this is the work which was done by Rakshit and all of you attended his PhD defence, he was talking about thermal consolidation if you remember and before that one of my Master's student, Punith, he did some experiments on thermal consolidation of geomaterials, and he has filed a patent also for his setup, which he has developed himself to study the thermal consolidation in fine-grained materials, **"Professor - student conversation starts"** like what I have got is if there are fine-grained soils above that I have to use some special type of geomaterial in which I can like to use them to diffuse the large temperature variations. Rather doing all these things the best thing would be when you go to cold climates what do you do cold climates? Yes, wrap your body with an insulator. Here, what we have to do we have to wrap the entire utility with a conductor. The moment you wrap it with an insulator what is going to happen, the temperatures will build up inside it's a reverse philosophy.

So, there you wanted to protect yourself so that the outside temperature and your body temperature do not intermix. Here what you want to do is you want to have a sheet of a layer on the structure, which will allow easy conducting of the conduction of the heat. **"Professor - student conversation ends"** So heat dissipation has to be enhanced. So, the design has to be dealing with the social aspects also. Environmental aspects also. Then comes the legal aspects.

Do you remember my old discussion which I had with all of you then comes the technical issues? And once you have done this series of issues, then comes the financial issues. Now, the fact of the situation is that we are finding to handle physics much more difficult as compared to chemistry. It is not easy to perform temperatures can temperature-controlled experiments in the laboratory at very high pressures; we are dealing with pure physics.

Now, what is extremely difficult that the chemistry because chemistry happens at the molecular level slowly without telling you. You need not make any efforts, then the biosciences or the life sciences, in the soil, all these mechanisms already occurring. You need not do much. But when you deal with 25 MPa pressure, 35 MPa pressure, 2-degree temperature, the cost of experimentation is extremely high. And you have to take safety as a prime measure.