Modeling Soil Thermal Properties: Compaction, Moisture, Temperature, Composition and Stability

Gaylon S. Campbell

This afternoon we want to start just by looking in more detail at the thermal properties of the soil and how to model those of the factors that are important in doing that and then the tomorrow morning we'll talk about the measurement of thermal properties.

Outline

And so, further discussion here will talk about first of all the thermal properties at soil constituents and how to put those together in such a way that then can model specifics to key volumetric specific heat of the soil, the thermal conductivity and finally the thermal diffusivity, which should be pretty easy if we can be up to two of diffusivity is just the ratio. And then we talked this morning a little bit about the general ideas behind it and a model for thermal stability in soil, we'll finish up that discussion this afternoon.

Modeling Soil Thermal Properties

Soil is a mixture the solids of the soil minerals, organic matter, liquid which is mostly water, and that and gases. The thermal properties of the soil will depend on how much of each of those things we have and to some extent how they're mixed together, what the geometry of the shape factors are that are concerned with those.

Thermal Properties of "Pure" Soil Constituents

The soil constituents and their thermal properties are listed here. You see some things that kind of jump out at you. The thermal conductivity of air is an awful lot lower than that of the thermal conductivity of anything else here but so the more air we have in the soil the poorer conductor it'll be. The thermal conductivity or organic matter is also pretty low but for soil that's high in organic matter will have a low thermal conductivity or a high resistivity. Water is a little bit higher but not nearly as high as the minerals and finally the highest of all was the quartz and so soil that is high in quartz we would expect to be a good conductor of heat. As far as specific heat goes we can see that a lot of things work on a similar here but water has the extra high specific heat and air, of course, has a very low specific heat.

Volumetric Specific Heat

To model the specific heat of the soil is pretty straightforward. The volumetric specific heat is just the weighted sum of each of the constituent so these x's are the volume fractions of each of the constituents of the minerals, the water and the air and then the c is the volumetric specific heat of each of those constituents off of that table that we had before in the volume fractions have to add up to one. Well that makes it pretty simple to model it and that the relationship between it the water content and specific heat is going to be linear. You can see for this kind of magenta line a sort of typical mid texture soil that the specific heat will be about one for dry soil and it will be about three for wet soil. That makes it pretty easy to know how to predict that. In fact, it's probably, in most cases, easier and more accurate to predict than to try to measure it. Predicted meaning to measure the water content than the density of the soil and then calculate it from that.

Calculation of Volumetric Specific Heat

So just to go through a quick example here; have a 50% pore space in the soil, 50% soil minerals, 25% air, let's say, and 25% water. So kind of like that field capacity soil we talked about this morning and we just go through and put down each of those and we'd get a number like 2.2 MJ per cubic meter. You can see that it wouldn't have made any significant difference to this calculation to have left the air part out of that, we just need those two, but it's interesting that this part, since the specific heat of water is so much higher than other things that might be there that the water has a pretty big effect. Makes it so that you can actually measure the water content of soil reasonably well with a device that measures the specific heat and you can do that measurement with heated needles that we'll talk about tomorrow.

Volumetric Specific Heat Range

So to do this we need to know the volume fraction of the water and the minerals in the soil. We think about the various possibilities that we might encounter, a low volume might be somewhere around one, a high value might be somewhere around three for soil. If we had some really dense material like a compact concrete, that has pretty low void space that might range from 1.9 to 2.6, and then granite, that would have even lower pore space, kind of around 2. So if somebody walked up to you and asked, "What's the specific heat of this soil?" What would you tell them?" (Audience Discussion) It's pretty easy to predict what the specific heat of the soil will be 2 MJ/(m^3K). You might be wrong, it might have been dry soil and it would have been 1 but you wouldn't be very far wrong, it might have been saturated soil it and would be 3. But it will be somewhere around 2. If someone came up to you and asked what is the specific heat of this rock, what would you tell them? You would tell them 2. Okay, so the answer is two, whatever they ask.

Mike talked about those situations where you're trying to model the transient behavior of the systems with the cables and so on where you're getting heating of materials may be diurnally or over whatever the load cycle is, and so the heat storage is important in those situations the heat capacity is important and pretty easy to model and pretty easy to predict, that is fairly straightforward.

Specific Heat Take-Home

So the take-home I would say are these things:
1) 2 (±1) MJ $m^{-3}K^{-1.}$
2) It varies linearly with water content
3) It makes it easy to interpolate it and extrapolate and can be computed. Usually it's easier to get a water content measurement than the density measurement than it was to measure and calculate it is to measure directly, although Decagon does have a device that measures it if you really want a measurement of it.

Volume Fractions of Solids and Water

Now some relationships at lunch some of the talk around our table was that some of us are soil scientists, some of us are engineers, and some geologists. But everybody wants to measure this stuff differently and have a little bit different name for it, so all of these are some of the definitions that a soil scientist uses for the volume fraction of solids; it's the ratio of the bulk density of the soil of the particle density of soil. Depending on whether you're a geologist or a soil scientist, choose a little different for our standard density of solids, but a soil scientist always uses 2.65 Mg/m^3 as the solid density. And then the conversion from volume fraction from mass basis water content for the mass of water per mass of dry soil to convert that to a volumetric water content you multiplied by the ratio of the bulk density of the soil to the density of water.

Conductivity can't be predicted from xs by itself

Now we'll look at the modeling the thermal conductivity of soil, it's a little bit harder problem than the modeling of specific heat. We can illustrate the reason for that more difficult problem in this kind of simple way. Let's say that we had some volumes of air and mineral that we want to put together, air and solid mineral, and let's say we ran the heat flow through this way so that those two paths were in parallel with each other. We can easily calculate the thermal conductivity of that thing. So that would take a half times the conductivity of the mineral, half times the conductivity of the air we get 1.26 for the thermal conductivity. Now we'll just lay this on it's side and have those two in series and when we do that again we can do the calculation, we just take the harmonic mean of those two things and when we do that, we get a value .05. So we get this enormous difference in average conductivity, depending on which way the heat flows.

Thermal Conductivity: Hypothetical Water Dependence

How does it flow in soil? Well I've just done this calculation here, this shows the conductivity of the mineral fraction,this the conductivity of the water, this the conductivity of the air, and if I trace out now the thermal conductivity versus water content for those things in parallel it will look like this. By tracing out for the things in series that looks like this, if I take a real soil, now you'll see a little bit later on, the vapor flow in the soil has an important effect on the thermal conductivity, but if I eliminate that and just look at the conduction part through the solids this is it the relationship between the two. You can see that it's somewhere between the parallel on the series arrangement and so what we need is some mathematics will somehow take into account that not only the fact that we have certain fraction of mineral, certain fraction water, and a certain fraction of air but also how those things are put together.

Modeling Soil Thermal Conductivity

Those are the equations that are here that make up that model and it's in a sense like the specific heat model that we just talked about and that we have volume fraction of mineral multiplied by conductivity of mineral, volume fraction of water multiplied by conductivity of water and volume fraction of the gas phase multiplied by the conductivity of the gas phase. But in addition to those things we have got these C components, that are weighting factors, and those waiting factors we calculate down here. They have to do with ratios of the gas to fluid conductivity, the water to fluid conductivity, and mineral to fluid conductivity. When I say fluid conductivity, what that means is that the kind of a composite of air and water or gas and water conductivity that I'll show you how we calculate in a minute. The stuff on the bottom is just to take out those weighting factor affects. So it turns out that all the other things here these GA and GC are shape factors that take into account what the shape of the particles that are in the soil. (Workshop attendee asks question) Yeah, I've given a couple references at the end that I think show up on the last slide. There are two references right on the last slide of the presentation that you can see in your book, there. Some of you may be familiar with de Vries's model for thermal properties of soil, a fairly old model, this is a more modern version of that, that we did a few years ago when we were modeling effects of forest fires on soil temperature.

Thermal Conductivity of the Air Spaces

Ok, so that gas phase, the thermal conductivity has two components to start up here, the conductivity of the air and then a component that has to do with the distillation of water within soil pores that when water evaporates at one point and condenses at another point, it carries the latent heat of vaporization with it, and you'd think, "Oh that cant be any big thing," but it turns out it can be a pretty big thing, in fact it's responsible for almost all of the temperature dependents of the thermal conductivity of soil. That is the gas phase conductivity, it's the air conductivity up and in this term that has to do with the diffusion of moisture within the pores.

The denominator of this is the atmospheric pressure minus the vapor pressure of water. Now Mike was talking about cables getting up toward 100°C this morning and he talked about the fact that that's the boiling temperature of water. What is the vapor pressure of water at the boiling point? (Audience answers). Yes, which is what the atmospheric pressure is right. So when I subtract the vapor pressure at the boiling point from the atmospheric pressure what will I get in the denominator of this? (Audience answers). You get zero, that's right. And what happens when you divide something by zero? (Audience answers) It becomes infinite. And so, in theory at least, this gas conductivity becomes infinite at the boiling point. Now that's a pretty high thermal conductivity, right? Now you have trouble getting there, course, because the water's all gone out of the soil before you get to that point. This f_w function I show here, this relates to that liquid return flow that we talked about this morning, that as the soil gets drier, the water can't move back in the liquid phase to reevaporate, so that f_w goes to zero. That goes to zero at the same time that's going to infinity and so you end up not having a perfect conductor anymore. But those are things to remember as we model this, that it has to do not just with heat flowing but also with water flowing in the soil.

Liquid Return Flow: Soil as a Heat Pipe

So just to try to illustrate that a little bit, the way the soil works as a heat pipe, this bottom line again plotting thermal conductivity versus water content, this bottom line is this situation that it we would have if there were no vapor flow in the soil. So pretty uninteresting relationship, but this top line is the line we would get in the soil at 90°C, little bit below the boiling point, and we actually get, when the soil is wet enough for some of that liquid return flow to occur, we get a jump up in thermal conductivity that actually decreases as we increase the water content of the soil. If you think about a soil pore, you have, if this is the hot end of the pore, you have evaporation occurring and the water goes across it condenses on this side, moves back through the liquid for phase to the point where it's evaporated and goes across again.

Now this is just like the heat pipe like when you buy to cook your turkey, right? Have any of you used a heat pipe? Nobody? Maybe some of you have one in your computer to keep your CPU cool. It's a neat idea, you get enormous thermal conductivities that way to show, a while ago somebody was selling heat pipes for cooling CPUs on computers and they had a chunk of copper, probably eighth inch diameter copper wire and they had a heat pipe of the same diameter and they wanted you to put the copper wire in the hot coffee and then put the heat pipe in the hot coffee and see which one burned you the quickest and it was the heat pipe. It was a pretty effective conductor of heat and soil is too when you can get this return flow occurring, but it only occurs to a point.

Temperature Dependence of Soil Thermal Conductivity

So let's talk now about the effect of temperature on thermal properties of soil. This bottom line is that same no vapor flow line that's roughly what you would get if you had the soil pretty close to freezing, not frozen, but the vapor transfer within the cold soil is pretty low and you wouldn't get much effective temperature. But now for a 25°C room temperature soil, you see this jump occurring jump and this jump is the result of that vapor flow in the soil. If we heat up the soil we increase that, and this 65°C line is kind of a magic line where it doesn't matter whether you have the water or you have the vapor, they're equally good conductors. So the vapor flow in the pore space is as good as the water is as conducting heat at 0.6, but only down to the point where you can resupply the water, if you get down at this point you can't resupply the water when those go down. And then you can see as you get up to really high temperatures, adding water actually decreases the thermal conductivity of the soil.

Ok, so now I've given you all the information you need to perfectly model temperature dependence of thermal conductivity in soil. How many in here have ever taken that into account in any design that you ever did? I won't raise my hand either, because I have never done it either. We know this, we understand it, and then we pretty much ignore it right? There are situations where we probably shouldn't, we happily make our measurements at room temperature and publish those results for our clients, but really that cable is probably running, in most cases, hotter than those measurements were made at and so to the thermal conductivity, likely is somewhat higher. (Audience comments)

There's another place that it matters, too, and this will probably come in when you talk to them tomorrow, Jim, that sometimes we want to make these measurements in a pressure plate, add pressure to move water out of the soil. When we do that, pressure suppresses this thermal component and so we did a pretty big study, a number of years ago, where we were wanting to measure that vapor component and we can bring any of these curves right down to that one just by making the measurement under high pressure conditions, well not all the way down to it but close to it. (Audience comments)

The thermal conductivity of things other than that vapor transport, tend to be fairly constant with temperature so if you see strong temperature dependence it usually is because there's some moisture involved. (Audience comments.) Well the conservative case is this one, of course, where the soil is dry and you're not counting on any of that. But if you have soil outside and its that wet, this will be its thermal conductivity at this temperature. I mean this is just for one density but…
(Audience comments)

I think any time the soil gets like that, it's going to be pretty hard to keep that both wet and hot, I think and especially as you approach the boiling point it probably will be essentially impossible to do that, you just can't conduct water through soil that fast. And then I think, maybe Mike, you have some experience with this or some of the rest of you, but I think it's possible to dry out the soil around cables that are running underwater, that even with that much water around that you can heat them up enough so that they'll still produce a dry layer around them. Is that true? (Audience comments). And It probably, those are conditions where you probably don't have the best hydraulic properties of those materials, you probably don't have the chance to come back and redo it to engineer the stuff that goes through.
(Audience comments.)

I have made measurements up to 70°C, I think, it's not easy to do but it's possible. (Audience comments.)Audience discusses). That's the model that I just presented, (Audience comments.) Yeah, the model is tested against measurement. Well, those references are secondary ones, those reference the primary references.(Audience comments.). Yeah, that's a really good point so you really are not getting super high temperatures out at the interface of the soil and the duct bank. I think that's an important thing to remember that the conductor temperature that Mike talked about is not the temperature of the soil that you're dealing with.

(Audience comments.) Mike's point, from this morning, that I guess this applies mainly in a direct burial situation but that radial geometry that you deal with in a cable, makes it so that a very thin layer of dry soil just outside the cable gives you essentially the same overall resistivity that you would get if the whole soil were that value, but that was just a property of that radial geometry. That wouldn't be the case with the duck bank or something that didn't have that kind of geometry but it really is the interface between cable and surroundings that end up controlling pretty much the whole heat flow situation.

Temperature Dependence of Thermal Resistivity

So if we plot this as resistivity instead of conductivity, take the reciprocal and multiply it by 100, you can see it's the kind of numbers we get and this is for, again, something that you might find in an agricultural field but not necessarily something that you would find at the construction site. And it's a place where we need to be a little careful when soil scientists are talking to geotechnical engineers, that we expect to grow crops on the soil that we talk about and then the geotechnical engineer wouldn't necessarily expect their crop to grow once they were through with the soil they were dealing with. So, where Mike talks about these kinds of numbers as being extremely high numbers for resistivity to me those don't seem high at all, that's what I expect to see for a soil. But not a soil that has been compacted to maximum density, certainly.

Response to Thermal Conductivity of Solids

Look now at the composition of the soil. The middle line here is the one we were talking about before, kind of a midrange loam type soil with the bulk density around 1.35 or something, and I wish I had in my head what that converts to in pounds per cubic foot, but I don't, it'd make more sense to you. If we compare that now to a quartz sand that have somewhat higher density but sands tend to compact to a higher density than that in the mid range textured soils you can see a couple of things; that this jump occurs at a lower water content, that we get higher thermal conductivity all the way through that are our maximum conductivity is quite a bit higher in fact about twice as high as the highest for the loam soil. And so, one way if we needed higher thermal conductivity, would be to look around for quartz sand but not necessarily something that you can do outside the laboratory. On the other hand, if we compare it to an organic soil, you can see that that's a horrible conductor, much lower over the whole range of water contents and we'd expect that because organic material has a much lower thermal conductivity.

Resistivity Response to Solids Properties

Comparing on the resistivity scale, if Geotherm were surprised at how high the resistivity of that loess soil; you should have sent them some peat moss or something.

Response to Compaction

Anyway, the other thing that and this is from an engineering point of view of a much more important point, and that's the effective compaction, this is something that you have a lot of control over as an engineer. This is our curve from before, and if we fluff the soil up a little bit why we get this kind of a curve that drops it pretty significantly. If we compact the soil we get a much, much higher thermal conductivity without changing the material at all. My guess is that the problems that Mike talked about this morning had an awful lot to do with just the lack of compaction, you can't compact dry soil, you've got to wet it up a bit in order to get it to compact, and so even though I suspect that hauling a little water would've been cheaper than replacing the cable, the Snake River was not that far away from where they installed that. (Audience discusses). Well you're replacing air and water by a solid so those low thermal conductivity things you're replacing by high thermal conductivity things and you also are improving other things, as far as the models concerned, and it has mainly to do with replacing low conductivity things with high conductivity.

Compaction Effects on Thermal Resistivity

When we look at it in terms of resistivity, then we can see the enormous fact that compaction has on that.

Take-Home

As we try to measure or model thermal conductivity, what we want to remember is that thermal conductivity of soil depends on a bunch of things not just water content. We do our dry out curves and send that to our client, but that's not the only thing that it affects that it depends on the composition, on the temperature, on the density and on the water content. And when we're supplying information to the clients, we need to control those things which I think most of you have considered it in more detail than I have considered it in and that you do take care to do that. It's not like the specific heat, if I came up to you and said, "What is the thermal resistivity of this soil?" What would you say to me? (Audience answers). You need to measure that, that's the right thing to say in my opinion. We work with a German company; their little tagline is “”Measure to know,” and that's what you do with thermal conductivity.

U.S. National Electrical Code: Annex B (2005)

Now Mike made reference to this, if you lookup in the US National Electrical Code Appendix B, they will give you information about thermal resistivity. So you don't need to measure to know, right? They say, in fact, that 90% of the soils in the United States of America have a thermal resistivity of 90, so now you know. Concrete is 55, damp soil is 60, and very dry soil is 120. So there's everything you need to know about thermal resistivity all in one table.

Representative Resistivities for Agricultural Soils - Not 90

So if we take this, what I consider to be to be a fairly representative US soil, 90 is right across there and you can see that as long as the soil is wet enough, it might be somewhere around 90, but certainly not 90% of the soils in the US. 120 is here, you can see that that's not anything like any resistivity that you would have for dry material. And of course nothing like anything you would have for organic material, so I would say that, that table is worse than useless, that it not only is not right but it's wrong enough that it can lead to some serious problems. But when you go to your clients and the number that you hand them is not 90 and they're upset at you for that, at least you know where that's coming from. That certainly is an experience we've had quite often, is that when we furnished information or when we furnished an instrument that they've used to gather information they make the measurements and the numbers don't come out 90 and they say there's something wrong here, this is not coming out to the 90.

(Audience comments). That's my guess too, is that there are that comes out of that draft that's at the end of the IEEE standard and if you look at that graph you will see that there's not a soil in it. None of the materials there are what I would call soils, they're all engineered materials, and so I think you're exactly right that that no one ever looked at any data from soils. (Audience comments). Well and in those situations you are dealing with engineered materials where you've contacted them to an optimum density and you really do come true about these numbers. (Audience comments). I agree with you on that and the places you get into trouble are these ones like Mike talked about that morning where somebody takes those numbers and applies them in a situation where they don't have the ability to do the insulation. (Audience discusses).

More Take-Home

So a few things, I guess in most cases, are obvious if we want to create low resistivity, high conductivity, we want compact, it if it were possible, high quartz moist soil.

Thermal Diffusivity: D = k/C

Diffusivity is a kind of binary property, it's the ratio of the conductivity to the capacity, you can see that in some cases it starts out low in dry soil, some cases it has a maximum at an intermediate water content and actually decreases at higher water content. A little bit of decrease here too. In essence, it's either low or it's high, all of the soils have a diffusivity around 0.2 when they're dry, and then depending on what they're made out of them how dense they may be 0.4 or higher when they're wet, and those are square millimeters per second.

(Refers back to slide: Response to Thermal Conductivity of Solids) There was one point I wanted to make back here that I think is important, this is the quartz, the comparison of the quartz, the loam soil again, you can see down here that when it's dry that even though the quartz has a thermal conductivity above 8 and other soil minerals have a conductivity between two and three, that they both have the same, the soil has the same dry conductivity. Why is that? (Answer: "Prosody.") What you mean by prosody? (Audience discusses.)Well these are just, since they can do this in a model, we're comparing the same density, but I think you're getting at the right idea of that, what is it that's controlling the heat flow in the soil, is it the mineral or is it the air that's controlling it? (Audience answers.) That's right, it's the air. And so it doesn't matter how conductive the mineral is, they both come out to be about the same. (Audience discusses). If you're designing, as Mike has talked about, designing for dry soil conditions or dry backfill conditions, then you're kind of wasting your time to be looking for high conductivity versus low conductivity that is going to a quartz material or something that has a high, thermal conductivity won't help in the case.

Diffusivity Conclusions

So with diffusivity, again, if somebody walked up to you and wanted to know what that diffusivity was, you can hazard a guess, probably you come up with something like 0.4 mm^2/s or something. Think of it as a kind of a binary property. (Audience discusses).

Critical Moisture

So now let's finish up that discussion on critical moisture and link transport of heat and water. I think we've heard of deluded to hear that, the idea that critical moisture content, the point at which the liquid return flow can keep up with the vapor transport. I've heard people talk about this inflection point here as a critical moisture content and there's some justification for that, I think, in that we know that this inflection is due to the soils not being able to supply the water for the microscale circulation of water, and so we could say well if the soil is below that water content we would get dry out and if it were above that we wouldn't. But the problem is not as simple as that, I think, that there will be cases where we would always get dry out and I'm not sure that, there may not be any cases once the soil got that dry where you wouldn't get dry out if you had a temperature gradient but I'm sure that you can get it up in here even if you're above that point. So I'm not sure that that's the criterion we should be looking for.

Model For Critical Moisture

We talked about some of the basis for a simple model this morning, and the return flow to the cable being all in the liquid phase, the water flow away from the cable, being driven by the temperature gradient, and so if we can say that the flow to the cable is in the liquid phase and it's limited by the unsaturated hydraulic conductivity of the soil. Then if we know the unsaturated conductivity, which depends on the moisture content or the suction, or the water in the soil, then we can calculate that value. The flow away from the cable is in the vapor phase and we can calculate that value if we know the temperature gradient in the pore space in the soil and then the critical moisture will be the value of which those two match.

Limiting Liquid Flow to the Cable - Same as Flow to a Root

So I went through and did that calculation, then the liquid flow to the cable is a problem that has been worked out quite a while ago in the soil's literature in calculating the water flow to a plant root. Now one of the things about water flow in soil that isn't all that obvious, but gives soil a lot of interesting characteristics is that hydraulic conductivity, the ability of the soil to conduct water, is strongly dependent on its water content or its or suction, in fact so strongly dependent on it that if you were to try to increase the water flow in the soil by doubling the gradient, the driving force on water flow, you might actually decrease the water flow rather than increase it. And so it means that the plant, if it wants to take up more water, it can try to suck harder but when it tries to suck harder it might actually decrease the amount of water that can take up rather than increase it, and it turns out there's a limiting rate at which the plant can take up water and that limiting rate is the same as the limiting rate at which water can be resupplied to that hot cable and then its given by this equation. So this K here, and I've unfortunately used the same symbol for hydraulic conductivity that I used a little earlier for thermal conductivity, I apologize. That's the hydraulic conductivity of the soil. This Psi is the suction; this is the soil suction, this is the air entry suction, this is radius out to the bulk soil, this is the radius of the conductor and so from that pretty simple equation we can calculate the limiting the rate at which water could be liquid water resupplied to the cable.

Vapor Flow From the Cable

Now we can do, we can also calculate the rate at which the vapor moves away from the cable that is controlled by the temperature gradient. The temperature gradient is controlled by the thermal conductivity of the soil. That limiting rate at which the vapor moves away from the cable, has in it the slope of the saturation vapor pressure function, the diffusivity for water vapor in air, some things that have to do with the porosity of the soil, and the dissipation rate for heat from the cable and in the bottom, this now I'm calling thermal conductivity, I should have switched those around, maintained the same symbols.

Comparison of Limiting Liquid and Vapor Fluxes

So we can do this calculation for different soils if we have information on the hydraulic properties. And here I just show for a sand and clay, that limiting rate of liquid flow, that all of the other textures fall between those but most of them fall pretty close to the clay line. The sand as the main one that's out separate. These lines across here or for the vapor flow and these are numbers, again, from Bill Black and some of his students at Georgia Tech. This is a higher rate, I think he said, that the dissipation rates from the cables,. do you have, can you give us a feeling for that Mike? (Audience discusses). Okay so let's look at the 20 now, it will give you a little bit more background, we talked about permanent wilting point and field capacity this morning and those values vary a lot depending on soil texture when you do them in terms of water content but they don't very so much when you do them in terms of soil suction, and that's one advantage of doing the calculation in the way that I've done here, is that field capacity is in this range from about 10 to 30 J per kilogram soil suction and permanent wilting point is that 1500 J per kilogram when we do it in suction, and that's pretty much independent of both the texture soil we're dealing with. So immediately when we look at that and put a point out here at permanent wilting point, we should be able to immediately conclude something about thermal runaway in soils that can be accessed by roots and could have the moisture drawn down to permanent wilting point. What can we conclude? We would always have thermal instability in those conditions, right? That at permanent wilting point, the soils will always dry far enough, especially in the sand that we would have thermal instability but even in finer textured soils, it probably also would be thermally unstable or might be thermally unstable. Now this is just for a particular set of conditions that are particular dense and so on. (Audience comments). So we can say that finer textured soils will be better than sands and I think that you said that some folks here that have done these kinds of things and have observed this. We would say though I think, that even with sands, if we could keep the soil close to the field capacity, pretty good chance that it would always be thermally stable.

Critical Moisture Conclusion

Well what are some of the factors that would influence that? Let's go back and look at this a little bit, this is the rate of vapor flow. (Refers back to slide: Vapor Flow From the Cable.) If we can increase the thermal conductivity that's in the denominator, so that'll reduce the rate of vapor flow. The higher the thermal conductivity we can get to, the more thermally stable the soil will be. If we compact the soil, this term fee is the porosity, if we compact the soil that reduces that number, again, that makes the soil more thermally stable. But s, that's the slope of the vapor pressure curve with temperature, that roughly doubles with every 10 °C increase in temperature and so the higher the temperature is, the higher the vapor flow will be. And then Q_h, is the heat dissipation rate from the cable, and again the more heat being dissipated from the cable the more unstable the soil will be.

So the conclusions that I come to from this are that if there are plants growing in the soil, there's always the potential to drive the soil to the point that the soil will become thermally unstable and I think that's pretty clear even though these are pretty rough calculations that you won't have a condition where a soil could be thermally stable when the plant could withdrawal the water that's its able to. At field capacity, I would say that soils, especially finer textured ones, but probably all soils, would be thermally stable. And that as long as you could maintain the soil that wet, maybe there's a high water table or some other condition where you are pretty sure that it's not ever going to dry out, seems to me like you could be pretty confident that the soil would stay moist and that you would have higher thermal conductivities and then the points on compaction that those decrease the philosophy and increase the conductivity.

Conclusions

Any questions about that thermal stability calculation? That's something that I haven't seen done before, I worked in this area of link transport and one of the first things that I ever did in soil physics, my masters degree was on link transport of heat and water and plant tissue and I was getting ready to put together this talk, I was thinking how unhappy I was at standing up your time after time and saying, "Well thermal stability means that the cable dries up, but I can't tell you what it relates to," and I thought I should be able to do a better job of that and so I went back and did some of these calculations and it turned out it was that it's not that difficult. There are number of things in the literature up on this, they're a little bit old papers, they're back in the 80's, as Mike said these guys are all retired now, so a lot of the work has never gotten into circulation for some reason in this area but these kinds of things are consistent with the things that they taught in those papers.

(Audience discusses). (Refers back to slide: Vapor Flow From the Cable.) It's not temperature that determines it, the temperature comes into this term here, that's the one that is most temperature sensitive, but it's the temperature gradient that matters, not the temperature.

(Audience discusses). We'll cover that tomorrow morning, we'll talk about using one of the ways of using a thermal probe, to make that measurement, or to determine whether the material is thermal stable or unstable. (Audience Discusses). It isn't a function of temperature so much, as it is heat input, he was saying that you have to put in quite a bit of heat and when you do that you can dry out the soil around it and you'll get that change in resistivity and you'll to be able to identify the point at which that occurs.

Okay so we've talked, I think, enough about being able to estimate specific heat, thermal conductivity, we've talked about the fact that that is a function of the number of variables, only one of which is water content. We've talked about diffusivity, a fairly conservative property for a lot of purposes. That has to do with how rapidly thermal disturbances can propagate in soil and so it's a useful thing for that and thermal stability depending on the hydraulic as well as the thermal properties of the soil.

References For Modeling Soil Thermal Properties

Then I mentioned a couple of references; these refer back to the original papers, any other discussion on this stuff? Ok, thank you.

Printed in USA

14538-01