Heat and Water Transport in Soil

Gaylon S. Campbell

Introduction

Heat and water transport in soil; the fundamental principles of science behind it probably is 150 to 200 years old. It's been known for a long time, and yet when Decagon built their first thermal properties instrument about 20 years ago, it was hard to find anybody who even would admit to needing a thing like that. They couldn't imagine what they would do with a thermal properties measurement. I think everybody thought that we just have a natural feeling for how heat flows in things. We should be able to look at something and know whether it will be thermally resistive or thermally conductive. The actual application in geotechnical engineering of this kind of science, science that has been around for many many years, is pretty new. It has been interesting to talk to some of you this morning, to hear about how that interest in those kinds of things, is increasing pretty rapidly. While one of the things that caused a lot of that interest recently is the one that Mike Beanland has talked about; the fact they put in some cables that burned up. So some people started thinking, well maybe we do need to engineer that a little bit better than we'd have been in the past.

Some Geotechnical Applications of Soil Thermal Properties

The kinds of things that the information that we will talk about here are applied in, are things like buried transmission lines for power transmission, a lot of interest now in data centers and other places where heat needs to be dissipated into the environment from things that are buried in the soil. When we run a current through a conductor we generate heat. The heat that is generated has to be dissipated to the environment with conductor temperatures that are low enough that we don't cause damage to the conductor. So, we need to know how fast the heat will be conducted away and that requires that we understand some things about heat flow and soil.

Another thing that has been mentioned, as we went around the room, is ground source heat pumps. The soil is increasingly being used as a reservoir for the heat. And we need to know how much heat can be stored and we need to know how rapidly the heat can be transferred to and from that reservoir. The last one, I kind of hesitated to even put that down. I wondered how many engineers in a room like this might actually be involved in storage of nuclear waste. I gave a talk a month or so ago in Iowa and at a group of geotechnical engineers and I was having some of the same thoughts there and wondering if that should even be mentioned but it turned out that the speaker just before me had worked on the Yucca Mountain project and spent a little bit of time in his talk talking about the storage of the high level waste. Have any of you been involved in any of that? Probably not storing it, but in the calculations and engineering of storage? Nobody here got involved?

Workshop Attendee: "Dr. Craig Benson and I worked for a consortium for the Department of Energy and we're working n long-term storage of low level nuclear waste but that repair the transfer still have to be considered long-term drying and desiccation of the cover systems."

Dr. Campbell: "So even in a low level waste you get enough keep reduction to that you need to do the calculations. Okay, I was not wrong again."

Thermal Properties of Soil Impact Wind Power Generation

This is a thing that is becoming more and more common in our surroundings one that Mike will talk about later today. About 10 years ago I was on a soils field trip, down along the Columbia River, the southern border of the state of Washington, and one of the things we saw on that trip was some of the early wind power plants that were put in. As they showed us around there, a number of those were stopped. Some were turning, and I asked, “Why are some of the stopped over here?” and they said “Well, it turns out the soils in this place are unusually poor conductors and we installed the cables in the soil and started it up and the cables burned out. So we’re needing to reinstall those things.” Well, I think was the start of a lot of the things that has driven the interest in this area now. A lot of people refer back to that experience and a lot of the engineering that is done, maybe even for data standards, but certainly for wind power installations. A lot of those now get a lot more attention paid to soil properties in the soil. Now, they felt that the problem was that those were loss soils and that they were all pretty poor conductors of heat, to some extent that was true I guess, but those are fairly typical of agricultural soils everywhere. The problem was with the expectation and not with the soil. They’d just didn’t plain measure it so they didn’t know what it was and did an engineer for that.

Outline

So the thing that we want to do this morning is to first of all talk about the fundamentally equations that on which all of this science is based that we will discuss for the next two days; Fourier’s first and second laws. The thermal properties that we will talk about measuring the end and how they’re defined. We will talk about the modeling and predicting thermal behavior of soils. Because soil moisture this such an important part of the overall picture we will talk a little bit about the water balance and what determines how dry or moist the soil is. We talked a little bit about linked transport and heat and water and soils, since that is the thing that determines whether the soil will dry out around some heated object. We will finish that discussion in this lecture, we will start the discussion and then I will try and bring that to a close later on today in the next discussion. As we go along today I hope that you will stop me when you want to. If you have questions or have comments, or if I have said something that you don’t think that is right let’s, stop and discuss it. I want this to be as two way as we can make it. It is a small group, so it will work fine for you to bring up points. If there are things that were not clear, let’s discuss that.

Steady State Heat Flow: Fourier’s First Law

So, let’s start with Fourier’s First Law. It’s the relationship between heat flow and temperature gradient. We think of a slab of soil. In this case let’s say we have heat flowing in on one side and heat flowing out on the other. Let’s say this is steady flow so there is no storage if heat in the slab. T1 temperature on the one side and T2 on the other side. The heat flux density in the soil is equal to the thermal conductivity multiplied by the temperature gradient. Since the conductivity is constant through the slab. We can make that a difference equation of conductivity times the temperature difference divided by the finite thickness of the material. We can also write that as the temperature difference divided by the resistivity and then multiplied by the difference. So three terms that we need to, or two terms that we need to remember from this, is the thermal conductivity which is the ratio of the heat flux density to the temperature gradient and then the thermal resistivity which is their reciprocal of that.

Which is Best, Conductivity or Resistivity?

In these buried cable applications we tend to use resistivity. In most of the rest of the soil physics and engineering we tend to use thermal conductivity. Is one better than the other? I’m not quite sure why resistivity ended up being used in this area of buried cables, but I suspect that it is because that field was developed by electrical engineers who were familiar with the idea of a resistance and it was convenient to do. The resistance is nice in that if you have resistors in series you can add them together to get a total resistance. So I think some of those ideas appealed to the folks who started developing this area I suspect that's why resistivity was used rather than conductivity. It turns out it was a poor choice. For one thing, thermal conductivity is a property that is normally distributed. It is appropriate to make an average if you make a bunch of measurements of thermal conductivity. It's appropriate to do an average of those to get by and average conductivity. If you measure a bunch of the thermal resistivity, resistivity is not normally distributed. It is not appropriate to take an average of a bunch of thermal resistivities. The statistical properties are better. They're more correct for averaging. Thermal conductivity is more linear with water content so if you are wanting to interpolate between two points, you will come out better interpolating on the thermal conductivity graph then you will on the thermal resistivity graph. And finally, it gives you more correct perception of significance, we tend to look maybe at the dry end of resistivity curve and we see maybe a difference there of, let's say 100 degree centimeters per watt, and we look up at the wet end, and we see a difference of maybe 20 or something like that with all of that 100 is a really big deal. When you convert those two conductivity which conductivity is directly proportional to heat flow, we find that those differences are kind of the other way around. The thing that looks significant is not so significant. So for those reasons I prefer to use thermal conductivity.

Now, you will say, "But all of my customers want thermal resistivity. What do I do?" Well, you don't need to tell your customers what you did. You just need to provide the end numbers. So do your calculations in thermal conductivity and then take the reciprocal and provide the information to the customer that they want, but having done the calculations the proper way.

Workshop Attendee: "Gaylon, is then the next international conference on thermal conductivity then? (Laughter) You put thermal resistivity in the title."

Dr. Campbell: "We deal with thermal resistivity customers too." (Laughter) "We get you here by saying it's a resistivity conference and then we talk about conductivity."

An Extreme Example

This type of example illustrates that this is an extreme example you can kind of see how this would work. Let's say that you have two identical chunks of stuff here; one that has the thermal conductivity of 1, and one that has the thermal conductivity of zero. We want to know the total heat flow through both of those things. So the thermal resistivity, the reciprocal of 1 is 1 so the resistivity then of 1 is 1. The one that has zero conductivity, its resistivity is zero. Now if we average of the conductivity is, those two conductivities, the average of the two would be ½ and that would give us, if we multiplied that conductivity times the temperature, the difference that would give us the right value for the average heat flow. But if we took the average resistivity, the average of zero and infinity is infinity, so it would say that the heat flow is zero. Can you see where the problem comes in using resistivity? And for most problems, that difference is not so big that it won't matter. But you saw these bumper stickers that Mike Beanland put out here for you to take. For somebody that worries about things like $e^{i\pi}$ being equal to -1 they would also worry about whether they had correctly done the math on averaging their thermal conductivities. Am I right Mike?

Mike Beanland: "Absolutely."

So put this bumper sticker on your car and then do the calculations on thermal conductivity and then record it as resistivity.

Transient Heat Flow: Fourier's Second Law

Fourier's Second Law is for the case where you have storage so we have our chunk of soil here and we have a heat flow H_1 coming in one side and a heat flow H_2 coming out the other and we had some storage of heat in the block and so we can write that the heat capacity volumetric specific heat times the change temperature with time is equal to the change in heat flux with depth. We can substitute Fourier's First Law in for H to get this equation.

If we have a case where the thermal conductivity is constant with depth then we can take that outside of the derivative and we get this equation where we have a K over C outside of the derivative multiplied by the second partial of T with Z and that ratio of K over C will give the name diffusivity.

Transient Thermal Properties

We have now a couple more definitions that we need to remember. The volumetric specific heat; the amount of heat that we can store in a cubic meter of soil that will raise its temperature by 1° C or 1° K, and we can use C and K interchangeably here. The thermal diffusivity which is the measure of the greater propagation of thermal disturbances in the medium in the soil. And we can remember that this is the ratio of the conductivity to the volumetric specific heat.

Now let's work through a couple of applications of this. A simple application of these ideas of Fourier's first and second law. This is one that we can relate to pretty readily because it is one of the things that we see every day around us. Let's talk about the temperature of the soil when it's heated at the surface by the sun. We will simplify that by saying that the temperature, we will assume that the temperature at the soil surface overtime is the average temperature, the amplitude at the surface and then this is the angular frequency and the time and the time off set. If we make this assumption for that temperature at the surface and assume that the thermal properties of the soil were uniform with depth then by solving Fourie's Second Law we get this expression for the temperature at any depth or in any time, will be the average temperature, the amplitude of the surface. A term that has to do with the how the temperature wave is attenuated with depth and a term that oscillates but also shifts the maximum and time. The angular frequency is 2π over the period of the oscillation. D we call damping depth it is two times that diffusivity of the soil divided by the angular frequency.

Soil Temperature with Depth and Time

There are two periodic signals that applied to the soil surface, what are they? The ambient air temperature… I guess what I'm after is the periodic variations in the ambient condition that is applied up the soil surface. One of them happens through the day right? And the other is what happens through the year. So, we have two periods that we need to worry about here. One is the diurnal period and one is the annual one. This pattern will look the same for those two. This is the temperature at the soil surface, and then this shows how the temperature varies with depth over 24 hour period. So if this is noontime and if we follow one of those lines down we can see that the maximum changes depended on what the depth was over a period. There are other ways to think about that one. Interesting ways of thinking about it is historical information; that if we would dig down in the soil a ways we could find out things that had happened a while back. There is some history stored in the soil about the temperature fluctuations that have occurred. If we look down on that 3D graph that we just had, you can see their relationships here, this is the temperature at the soil surface and now if we go down. It is convenient for us to think in terms of damping depths. We have one damping depth in the soil the wave is attenuated to 37% of its value at the soil surface. At two damping depth it is about 14%. At three damping depths it's a little below 5%. So those are the depths that are shown here, this is the surface this is one damping depth, this is at two damping depth, and this is three damping depths. You can see by the time we've gone down to three damping depths that we're almost completely out of phase with the temperature signal at the soil surface.

So we can answer some questions with this: How deep would we need to dig in the soil?

How Deep in the Soil Do Diurnal and Annual Cycles Penetrate?

We will now here had deep would we need to go down in order for the temperature to not be influenced by the annual variation and temperature. If you want to be a purist and say influence means that there is absolutely no influence, in theory why you would have to say infinity right Mike? But if you are an engineer you would get as close as you need to for practical purposes and you would say, well I will go down as deep as I would need to not be able to measure it very well anymore. So that might be about three damping depths. So let's calculate the damping depths for the annual environmental cycle.

The periods for the diurnal cycle and the annual cycle are shown here and then we have chosen diffusivity 4 x 10-7 m/s, that is the diffusivity kind of typical for a moist soil. And so we get a diurnal damping depth of about 10 cm and an annual depth of about 2 meters.

Attenuation Depths For Soil Temperature

If we put a temperature sensor at a depth of about 30 cm, three damping depth, we would expect the variation in temperature at that point in soil to be pretty much independent of what was going on at the soil surface of this moist soil. If we were to a temperature sensor down at about 6 m depth than we would expect the temperature to be pretty much been independent of the annual variation. So if for some reason you happen to know what the average annual temperature was at that location how could you find that out?

Workshop Attenddee: "Measure the temperature 6 m down."

Dr. Campbell: "Yeah, go out with the auger and dig a 6 m deep hole and put a thermal coupler down the hole, and the temperature you measure would be pretty much the annual temperature."

Workshop Attendee: "Gayon? I have a couple of questions. How would I get an average temperature if I can only measure down to 1m in the soil? You can estimate the air temperature at zero meters. How would you do it?"

Dr. Campbell: "Actually Mike is going to talk a little about that a little bit later on and maybe after he covers what he's going to cover then if there are still questions we will go into that in more detail. But we have, you know that we have modeled that a lot that we have computer models that do that kind of stuff, and you have too, so we can do it. Usually if there are plants growing on the surface, temperature isn't so much different from the air temperature and you just use air temperature. If it were a dry bare surface all the time, then that would be a really poor approximation, you would have to do something better."

Workshop Attendee: "So the damping depths are independent from the soil properties, is that because it is the same calculation of the long-term study states?"

Dr. Campbell: "Well the soil properties are represented through the diffusivity. OK it turns out that we will see that that is a pretty conservative number. So it doesn't vary as much as conductivity or specific heat. It varies by a factor of two or something
like that."

Workshop Attendee: "So this is probably where in some discussions with electrical engineers about how they pick the depth of burying these cables is around five or six feet is that's the optimal depth that's just to see that you have a consistent soil temperature environmentally outside of the heat source of the cables. They might have come up with it that way but..."

Dr. Campbell: "But I don't think so, but again Mike will go through a lot of that stuff in a lot of detail, so if I can defer to him for all of that. "

Mike Beanland: "The quick answer is that it's econmoic trade offs, it's not just a physics problem."

Dr. Campbell: "Okay thank you."

Other Applications of Fourier's Second Law

So other applications of Fourier's Second Law well really everything that we will talk about in the course is in applications of Fourier's Second Law the Neher-McGrath calculations that Mike will talk about in the next lecture are analytical solutions up of Fourier's Second Law the 2D and 3D numerical models that he will talk about later today and tomorrow our applications Fourier's Second Law, and even the measurements I will talk about later on and that Doug will take you through, all of those are applications of Fourier's Second Law so that really is the important part of all that will be presented in the course.

Water Content Strongly Affects Thermal Properties

Now is you saw that there are thermal properties of soils that we need to know in order to apply Fourier's Laws and the range of variation in those properties are shown here. Conductivity for mineral soils tends to range from 0.2 W/(m K) to maybe 2.0 W/(m K). Certainly you can have values outside of this range for a loose soil or for a soil high in organic matter. You can get values have that have value 0.1, as Doug pointed out if you go to Mars you can get even lower ones than that. You can get conductivities certainly above 2 in dense quartz , of a high quartz material. Volumetric specific heat ranges from about 1.0-3.0 (MJ/(m3 K) and you can get values outside of this but that's a pretty conservative property of soil. Diffusivity depends tends to range from 0.2 to 0.7 mm2/s.

Cable Ampacity vs. Thermal Resistiviy

Now to get down to the heart of what I think most of you care about. This is a diagram from a Bush paper, that came out quite a long time ago that I think makes some important points, but I think Jim was mentioning a little bit ago. This is the carrying capacity that the conductor current can have in a buried cable has a function of the thermal resistivity of the soil. It shows dry soil and wet soil. The point is, is that in wet soil you can transmit maybe twice the amount of current that I could in the dry soil without dangers of the cable. So, you say well why don't we just always have the soil be wet and then we can use more electricity through the cable? Obviously, it matters whether it is going to be wet or dry. I think Mike would tell you that good engineering practice has to take into account the fact that it might get dry at some point, but if you could somehow guarantee that it would not, it would have enormous advantage and I will talk a little bit about some of that stuff.

Soil Moisture Concepts and Definitions

I wanted to spend a little bit of time talking about water content in soil. When we talk about water content, we measure that as the mass of water in the soil divided by the dry mass of the soil. We will standardize that as, or what we will call our gravimetric water content measurement. We will also talk about volumetric water content. They cubic meters of water in a cubic meter of soil. I will spend just a few minutes talking about how to convert back and forth between those. If you were to go out and step in some mud someplace, you might say, "Oh that soil was saturated with water!" But saturation has a specific meaning when we're talking about and that means that the pore space is filled with water. That probably would not be the case with that soil where you stepped in the mud. With normal well drained soil, within two or three days of the time that it is saturated by heavy rain or to irrigation, the water will have drained out of under the influence of gravity to the point that the soil reaches what we call field capacity. And field capacity is not a specific water content, it depends pretty heavily on the texture of the soil but for a typical, we will say mid texture soil. When the soil reaches field capacity of about half of the airspace will be filled, or about half of the pore space will be filled with air, about half of that filled with water, and in the pore space makes up about half of the total of the volume of the soil. One's the soil reaches that field capacity again in theory the soil could dry out all of the way by the water running out of it by the gravitational pull but that would take some millions of years for that to happen. So over that time span that are of interest to ous, the time span between rains or whatever, the soil really doesn't try out a appreciably below that field capacity value by any other process then water uptake by plants and evaporation of water through soil surface. Evaporation and typically doesn't reach the fact if evaporation more than 18 cm into the soil, so if the soil is going to try below that field capacity value it will have to be because plants to go up the water.

Now the water content of the soil profile where these cables are being buried, or rather things are being buried, it is determined by the water bonds. When we do a water balance it is just like your checkbook. We have certain amount water coming in and we have some water going out and we have some water stored hopefully with their checkbook that is a positive number.

At the input precipitation in irrigation typically we have some losses from runoff and the water goes into storage here. Some runs off the bottom. Some that evaporates out of the top and some is taken up by the plants that are growing there. When the plants have taken up all of the water that they can take up out of the soil, some of the water will be held so tightly by the soil particles in such a low energy state that the plants cannot get that water out. How much water remains at that point? Well about half of the total amount of water that it had when it reached field capacity. I don't know if that's surprises any of you, but if, the volumetric water content that field capacity were 26% by the top time the plant reaches what we called permanent wilting, 13% of the water would still remain in the soil.

We call this part the Plant Available Water and this part of the water is unavailable. When we take a soil sample and dry it out in the oven and measure its water content, or measure its thermal properties at that point it's thermal conductivity or thermal resistivity, that the condition that would likely not normally occur in nature.

Example: Soil Volumetric Water Content

This is a picture of a series of irrigation water content over time where irrigation of rain occurred. Decagon has some probes that we monitor water content in soil so we can make this kind of diagram pretty easily. And you can see each time when there's a rain you get the water content going up and this is in Florida so most of Florida is made of sand. This pretty course textured material, you can see that the water content drops down pretty rapidly to field capacity which would be somewhere in this range and in this more linear decrees is due to the water being taken out by plants. If you take shallow measurement the blue one, those things responding pretty readily to the irrigation and if you pick good deep location 3 feet down, the red one, you can see that there is a dual A in the time the water gets to that depth and the amplitude of the variation is a lot smaller. If we go to a deeper depth still, we would see that the water content stayed pretty constant. As the water content changed at the soil surface and it would only be the big rains or that big you radiations that ever said to water down that far into the soil.

Workshop Attendee: "Is it safe to assume then that 90 cm you could come up with approximate average of the water content?"

Dr. Campbell: "It might not be at 90 cm, but there is a depth somewhere down there where the irrigation and the plant uptake are not affecting the water, there's just a constant drainage of water down due to the gravitational pull and it will stay pretty steady at that point. If you know the hydraulic conductivity of the soil, you can predict the rate of drainage out of the bottom. "

Water Balance Take-Home

So out of the water balance discussion we can say that I think that soils within them below the route to its own will have water contents typically between field capacity and permanent wilt point and that they will not get dryer then the per minute wilting point. And that the plants can't dry soil below that perminant wilting point and other then than the surface layer we shouldn't get water contents below whatever that value is.

Can the Soil Around a Buried Cable Ever Be Dry?

Then the question comes can the soil dry around....can the soil around a buried cable ever be very drying? You think about the possibilities. We know that it can't by natural causes. And natural meaning plants uptake and evaporation. It could dry out if you could make a trench and put the soil out on the surface and then let it dry out and put dry soil back in that trench. It could be dry from that. But the other possibility is that it can dry out by the heat but is coming from the cable that is going through it.

Moisture Migration Under Temperature

I want to talk about a little bit about thermal induced water flow now and these are some data that was published back in 1954 by Taylor and Cavazza. Sterling Taylor was the person who got me into soil physics lots of years ago. A professor at Utah State university, he died at a pretty young age but was had an intense interest in these linked transport problems and particularly water flow and soil and I think his interest was from this early work that was done by Cavazza. Luigi Cavazza is a professor, or was a professor, at University of Bologna in Italy, and I think he is still active. He is pretty old now but I think he comes in to the office on occasion and still does some research.

He set up these soil columns and he didn't have any way to monitor the water content In Situ in the columns and each one of these lines that you see represents a different experiment or where he would take a soil, then set it up, put a temperature gradient on, and then let the heat flow through for a little bit, and then tear apart the column and measure the water content of the soil in the column. So you can see it has that is starts off I think one day, no six hours, twelve hours, one day, two days, and then four and seven days. This is the hot end, other column, and this is the cold end of the column. It started out an uniform water content, but you can see how the water moved out of this part of the column and condensed over in this part of the column. An interesting thing is that it is drying front that is moving through the soil it is not just getting a general gradient that we get the drying front that is moving. This was a column that he called loose soil.

This is a column that would be called compact soil. Subject to the same temperature gradient that he had with the loose soil, but now you can see that that behavior is quite different. That now we get some change and water content here and some change here. But we don't get drying at the wet end. Now why don't we get drying at the wet end? Well as the water moisture gradient develops there movement away from hot and toward the cold end, all right in the vapor phase but there's also a movement back from the cold end and a hot end in the liquid phase. Liquid water will move from wet soil to dry soil and so it is moving back that way and keeping this wet.

There was a question back here?

Workshop Attendee: "The Y-column, is that moisture gradient?"

Dr. Campbell: "This is water content. I should have been clear about that. This is distance along the column and this is moisture content. So all he did was to take apart the column section and measure the water content at different places along the column. And he just plotted what he measured here."

Workshop Attendee: "You could see they heat sources on that right side..."

Dr. Campbell: “Yep, so the heat is flowing this way, but the water is flowing back and then in the loose soil the water couldn’t flow back fast enough to regenerate itself, but in the compact soil it could. So it didn’t dry out. Now this also...”

Workshop Attendee asks a question.

Dr. Campbell: “In the loose soil the hydraulic conductivity is too low for the water to flow back fast enough to replace the water that is being evaporated.”

Thermal Drying Around a Cable After 40 hrs.

Now this is the same thing that happens around buried cables that have current running through them and are generating heat. This data is out of that same paper that it talked about a few minutes ago. Bush Black and Martin took a short section of cable and put it in a box in the laboratory and made some measurements there where they had heat generation and then took it apart and sampled the soil around the cable to get the water content. You can see that again drying front moving out from the cable, this is after 40 hours of heating that rates would be typical of a buried cable. I think the material they called it a Georgia red clay, which is not maybe soil science expression but something that you can relate to. These guys were at Georgia Tech. Now, you might wonder why don’t we see that and moisture out here like we did in Taylor and Cavazza’s experiment. But this is a different geometry, this is a cylindrical geometry, their’s was a planar geometry and so the amount of water that has to move out from this region around the cable is pretty small compared to the amount of water that can be stored in the soil around it so you don’t see much change out here in this region away from the cable but you get the same behavior near the cable that Taylor and Cavazza saw.

Thermal Dry Out Model

So we can do a model for this fairly straightforward model. We can say that the water moves from hot to cold mostly in the vapor phase. The water movement is mainly the temperature induced vapor pressure gradient or they have the temperature gradient, the soil is wet, the humidity in the soil when it’s even moist is very close to 100%. When the soil is as dry as it can get and still support plant growth its relative humidity in the soil is 99%, so we can assume that the soil is essentially a saturated system where we are the temperature gradient and it will have the vapor pressure gradient that we can calculate that gradient pretty readily. Now there can be some thermally driven liquid flow but that usually is when the soil is pretty wet and it’s not typically enough to worry about four are this application. We can say then but the water moves back from cold back too hot when we get a gradient in the amount of water but is there. That that moves in the liquid phase. Thermal drying depends on the size of the temperature gradient. And along the unsaturated conductivity of the soil. If the unsaturated conductivity is high, then we don’t get very much drying. If it is low then we can get drying around the cable.

Some Consequences of Thermally Induced Water Flow

So we will spend more time in the next lecture talking about that model and some of the consequences of it. But what is this thermally induced flow have to do with the stuff that we are wanting to talk about in today and tomorrow? Well one of the things that has to do with is that you cannot use steady state methods to measure thermal properties of unsaturated soil because the temperature gradient will induce moisture movement. When moisture moves that will change the thermal properties of the thing that you are trying to measure and you can’t do it. The methods that we will talk about mostly for soil will be transient methods, ones that can be used in these situations where we get thermally induced flow and another thing of course is the soil will tend to dry out around cables. This thermal runaway condition that is probably something that many of you understand a lot better than I understand it, but if we talk about thermally stable and unstable soils, a thermally stable soil is one where that liquid return flow is fast enough to meet the demands of the evaporation that occurs due to the temperature gradient. Thermal unstable soil is one where the return flow it is not fast enough. So the soil tens to dry out around the cable. When it starts to dry out the thermal conductivity of that drying soil decreases the resistivity increases. When the conductivity decreases the temperature gradient gets bigger. When the temperature gets bigger that drives even more moisture out. When the additional moisture comes out then the temperature gradient get even bigger and you get a thermal runaway condition, where the soil will dry out completely.

Workshop Attendee: "How do we tell if the soil is going to be stable or unstable?"

Dr. Campbell: "We will talk about that more and the next lecture and I'll get to a model of that. This is well…we will get to it in the next lecture."

Workshop Attendee: "I just wanted to point out that another application that we are working with is another implication is highway substrate systems where we have a pavement in Texas can get up to 120 or 130°F, that impacting the moisture flow on the pavement system and then the effects the surface system of the pavements so in addition to what we have here is geomechanics impacts the coupling moisture flow."

Dr. Campbell: "That coupling is even stronger when you start to get freezing. You can get enormous driving forces for moisture flow when you get freezing. Those of you who live in northern climates know about frost heave where some of the energy that is available in these link transports systems."

Conclusions

So just to conclude the solutions to Fourier's Laws, that basis for the model laying that we will talk about and the applications that we will talk about for the rest of the workshop. But in we need a knowledge of thermal properties to solve those equations for the practical cases we will hear about here. Remember that a substantial amount of water remains in the soil even after plants have taken an out all of the water that they can. The water around a cable will be, and therefore, the thermal properties of the soil around will be determined by how much water is applied to it by the surroundings. How fast water can move back against the temperature gradient and how fast the water moves out because of the eve evaporation. I think it is significant that the drying error is occurring as the drying front not a gradual thing but a step function almost and that the water content of the soil outside of that region, that is drying right around the cable, is minimally affected. Okay, I think that is all.

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