Underground Cable Crossing

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3D Case Study – Underground Cable Crossing

I'm kind of going to go through this quickly because there's actually a bunch of slides in here that are really nothing but fine print and are probably not going to be very interesting for most people anyway. This is really a follow-on of a special application of finite element modeling that is if you will is kind of taking it into a new dimension and that is primarily because the other modeling that I was showing you was two-dimensional modeling. Which, you know if you have a nice simple plane you have a relatively low density of modeling points and as soon as you move everything up into a three dimensional case, two things happen as you obviously you really dramatically increase the complexity of your modeling and the calculations involved and you've also severely limited your available software applications because there's just not much available.

Background

I had a case presented to me where, this was back in the Stateline Wind Project, we had some existing cables that were heavily loaded, and because of expansion of the project we actually needed to cross those cables with some new cables. So we had a problem where we were already at a thermal design point where there really was no extra capacity for dissipating heat available. However we had to find a way to make a work.

Cable Crossing Needed

I actually looked at, well here's a brief, there was additional thermal capacity, we knew we were getting after some kind of fluidized thermal backfill or enhanced thermal backfill, but we had no real idea of how much would be necessary. The other part about it is in a case like this instead of a simple two-dimensional model where you're dealing with axial heat dissipation you now actually are also going to have heat dissipation along the length of the conductor. Especially aluminum, aluminum being an excellent thermal conductor. So we kind of had a notion of what we were going to need that we were basically need a cruciform in the shape of a small "x" if you will, at the location where the cables crossed some kind of the enhanced thermal backfill but we wanted to get a better understanding of what that would be.

Cable Crossing

We actually came up with some engineering designs but in this case as we were only looking at 18 inches of separation between our cables because we had to maintain a minimum depth. Our existing cables were up already at the minimum depth allowed, we actually had to go underneath those with the new cables. and then that they actually make things worse because the new cables if placed at the greater death would have overheated anyway, even without the presence of the old cables. So we knew we were going to be dealing with a problem because those were already running at their maximum rating, those were the worse thermal environment because of the added depth we were going to have to come up with some kind of a creative solution.

2D Model – No Diagonal Heat Flow

The problem with conventional two-dimensional methods is the fact that it really can't consider heat flow in all different directions. That if you have a pair of cables crossing, or roughly crossing, well there's heat flowing out of diagonals and a two-dimensional model can't consider that at all. A two-dimensional model will also not consider heat flow along the conductors themselves that we found out to be quite significant. However as a part of setting part, lets see what we can do. We have existing software, I have two-dimensional model capability, let me see what I can do and the answer was I couldn't come up with a good salute approach because there were too many other problems. And essentially that the software we are using is a two-dimensional only and then I started looking at some three-dimensional software.

3D Finite Element Analysis

I ended up, the software I ended up working with is a program called FlexPDE it's actually flexed partial differential equations. It's a finite element modeling package developed by some very high-level mathematical thinkers from Lawrence Livermore Lab. It's all basically a partial differential equation solver. Forget it, it's all over my head.

Cable Crossing Model

A totally different way of working things, just an example, rather than building a physical model with circles and arcs and building up a physical model on a visual interface, FlexPDE has a totally different way of looking at things you actually define everything mathematically and you define equations. So you need cylinder, you have to define that cylinder as having an axis along the Z axis and a x square plus square root of x squared plus y squared is equal to the constant. And you have to define the equation for what that cylinders look like. Somehow in the software the software is intelligent enough to take that equation that I give it and actually turn it into a three-dimensional model. That is magic as far as I'm concerned. I have no idea what they how they make that work but it does work. This was that this was a conceptual drawing of what we thought we were going to end up needing to model. Just so we had some idea of how to build up the model.

Script – Problem Definition

Now this is the stuff we're going to go through really quickly because this is the esoteric equations but these are all of the different little things that had to be put together to define, you know, what the heat dissipation was going to be mathematically in all of the X and Y coordinates, Z. coordinates of this model.

Script – Heat Sources

So FlexPDE uses this mass descripting language and there's all these interesting things like a use step function meaning the heat flows inside not out. So I can actually define a cylinder and give it a heat production inside the cylinder and I can basically say it's zero on outside and it's whatever that number is on the inside. but I have to define everything I do in terms of all three dimensions for the entire size of the model. So it gets the mathematics of it. It probably took me four weeks of effort, just to work my way through the math to be able but do this. There's also that the complexities of building the physical space and applying all of the boundary conditions. So you can just pretend that was the esoteric stuff will go through really fast.

Wire Frame

The bottom line is that somehow through magic, as the software is able to take the mathematical description that I've given it and turn it into a physical model. Because we were dealing with a crossing, there is two directions on this because anything on this side is the same as that side and anything on this site is the same as that side because I had a nice neat right angle cross. So the only thing I had to do is model a quarter of my field and I chose so my origin happened a bit the vertical axis in right through the middle of the project. I ended up building the model 12 m x 12 m and going down 12 m in order to get what I thought was a sample that was large enough that I would be outside the zone of influence of one cable on the other.

Surface Mesh

This was the wireframe model that the software builds and then the model the software then actually goes through a process internally for developing its own finite element grid based upon you can define the mesh density in various on various axes or on surfaces or at various points. Then the software will go through and develop and optimize a mesh and is it are fascinating process to watch the software basically grind through a three-dimensional mesh. Because you're talking about millions of other data points and millions of mesh elements and the software has to kind of make a stab at it and it actually goes through several iterations to refine its own mesh.

Solid Elements

It builds the mesh for each individual item. This was a mathematically defined point where the cable was actually bending and that was the cylinder of the cable. Now because of it the size limitations of the modeling because I've mentioned before the problem of having a very large physical universe and a very small object in it, there was no practical way to model the individual conductors very well so we ended up having to do is say now I have to do take this model down as small as I can, but I'm going to have to assume I just have a homogenous heat source of some kind in here because what I will study that small model more carefully but I have to look at the larger case. So I'm trying to basically get myself out into a model outside of even basically taking an entire conductor as a heat source and then working for that. So that was one of my conductors.

BackFill

I also had it to define various portions of the enhanced thermal backfill at the corner where those two conductors crossed. You can kind of see here, you can see the dip here for one conductor, there's actually there a quarter round here where I'm getting a half a portion of another conductor and here's the other conductors where actually the modeling is this is the model for. This is what I find fascinating is the software was actually able to layer things and be able to say, "Ah ha! Here is a cable so I will remove the cable from the model for the thermal backfill and so I will cut this model based upon the presence of the other models."

Solid

Eventually it builds up a solid model showing all of the different portions. Then having built this model with all of the mesh, and I don't know if you can see very well, but there you can see a few little dots in there and that's basically all the node points. So if you imagine this cube that has been built now instead of a simple two-dimensional plane, is now I have this two-dimensional plane with the increased complexity of a by, if you will, or more to basically build a three-dimensional modeling. so there are those of those were typically multi-million point models in order to do this. I remember early on in this game I try to build a complete model before I started thinking about the symmetry and basically the software was at the grind and grind and grind building the model and I realized that I had to simplify the model as much as it could. I had had to do mesh control and reduce the number of data points to get the point where I could actually calculate in a reasonable period of time. I didn't have a supercomputer available so I had to do this on a PC so I had to make do.

Results – Temperatures at Top Cable

What we were able to find, I was able to get some very interesting data out of this. Again, I was working with the goal of trying to keep the conductors not exceeding 90° C. One of the things I used to validate the modeling is that I knew I can see from this temperature profile, lets see, I'm trying to remember exactly what all of this is, at the top of the cable, so were the top cable goes straight across this was existing cable. By looking at the temperature profile in the area that was far enough away from the new cable and validating that and knowing that okay if I come up with a 90° C conductor temperature at that point then I know my model, fundamentally that my model is working pretty well. And if I know that I got a 90° C temperature over here, I know my model is also working pretty. Then I'm going to find out what happens in the middle.

Results – Temperatures Vertical Slice

Again there's cut through, looking at the model, looking at the new cable being installed underneath the existing cables and the thermodynamics involved. I have some close-ups and here's some of the close-ups and this is where it modeling and looking at the thermal conductivity along the aluminum conductors in the cables became important because there's actually the temperature gradients change simply because I have heat moving out of the hot zone along the aluminum conductors and then dissipating and fact is the hottest point of the cables actually becomes the interface between the thermal backfill and the native soil because I basically that's heat traveling down that line and there becomes a shifts the hot point.

Results – Temperature Probe at Crossing

These are some various, sorry that the lines are fine, this is a temperature along the vertical axis, top to bottom, or actually bottom to top, so I'm at 12 ft below grade my ambients were quite high because of the modeling, the location we were dealing with. My surface temperatures were 25. But then we did see that as did go to depth we did get the higher temperatures. I was able to work this design keep the temperatures below 90.

Results – Heat Flux Bottom Cable

Here's some information about the heat flux. I showed yesterday about some of the heat transfer and actually the interesting part, the heat flow from here is actually back into this and this is the enhanced fluid backfill so the heat is produced to the cable here actually instead of dissipating up actually flows back along the conductor into the thermal block.

Results - Heat Flux Top Cable

Same issue with the existing cable, which is just passing straight forward through here and using this technique of a three-dimensional finite element model allowed me to go in and tweak the size of the cruciform. Do I go? How far away from the crossing point do I have to move the thermal backfill out? And would probably have to spend a lot more time engineering this it would have to pour a lot more thermal backfill that we thought we would need. When we approached this problem there was no software available that would give us a clue as to what it the thermal conditions would be at a cable crossing. So without doing some kind of modeling and analysis we would make me just making a guess because it there was no information available. By doing the modeling even if the modeling had approximations and simplifications, that I have to treat an entire conductor, which consists of a heat source in the middle and then plastic insulation around it, I have to treat that as a uniform homogenized material, is at least it was a tool that allowed me to go in and make some good approximations and come up with an engineering judgment and be able to make a recommendation to the field to be able to say, "Ok, well you need to go 10 feet or 9 m out from the crossing point in both directions and by the time you get out that far with your enhancer and backfill, you're in a good position. You'll be able to maintain the cables below that 90° threshold, even at the point of crossing, and how close to the surface do I have to be, I can vary that because that's a critical function because the heat, obviously, there's a significant temperature gradient which means significant heat flux through the top, immediately above the thermal backfill (Refering back to slide: Results - Temperatures Close Up Vertical Slice.) So, again, that was how high do I want to bring the thermal backfill to be able to get a good design? If I could bing it all to the surface, that's wonderful, we actually had a constraint due to the land use that we had to have native soils for the top, I think it was 6 or 12 inches because this was dry wheat farming and basically no matter what you did down below you had to return the topsoil to the upper area and that had to be undisturbed wherever the cables were.

Review

So, I'm making it really quick, the point that I think I want to make is that if you're doing any kind of thermal modeling for underground cables, it's really nice if you have a long linear section, you can take the cross-section two-dimensional modeling. It's fast, it's simple it's very flexible and basically, it fundamentally can do the same thing that other Neher-McGrath based software can do. However, as soon as you jump into something that is three-dimensional, Neher-McGrath is not based on three-dimensional modeling. There is nothing available that I'm aware that can address that and if you want to do any kind of design work you're forced to go into something of the nature of 3-D finite element modeling. (Audience comments)

I could find nothing in the literature, so if there are standards for designing a cable crossing I could find nothing written and so I think there may be experience by a transmission engineers. Now in the distribution low-voltage level nobody really worries about it. Everything is so massively overbuilt that thermal issues are really not a concern. And in transmission lines you don't have cable crossings, you've dedicated corridors and lines run along and I don't know of any cases where you have crossings. There are cases where you have a cable crossing, lets say, an oil pipe line or gas pipe line and those always operated elevated temperatures so there are design issues on that. In some cases you have to go under those also because of the constraints of the right away leases.

Again, in my research I could not find any standardized recommendations on that and so I think what happened is people just did it seat-of-the-pants, they said "Well, if I've got to go down that deep I'm just going to put in a whole bunch of fluidized thermal backfill and just bring it all up and we're going to put a block that's 10 feet by 100 feet and cross our fingers", and the engineer goes, "I think it'll be okay", and so he signs off on paperwork and you go, "My God, that's $1 million worth of thermal backfill you're putting in here."

The fact is, to do the modeling is not something people want to do; there are no guidelines or standards and in this case I found a way to make it work. (Audience comments) I'm sure people have come up with things like that it and when I was doing, simply, 2-D modeling and trying to come up with a way of doing it without really knowing the details, I mean I could say, "Well gosh, do you rate the cables by 70% because that will reduce the heat output from each cable by 50% and now might then heat at that crossing point" is exactly what it would be, otherwise there's my degrading factor and that would work, that fundamental, but that means that you're entire cable is operating at 70% rating and when you're running 5 miles this way and 5 miles that way. That's a lot of cable to waste and you know the national electrical has the same thing. You want as many electrical conductors and the conduits you have to rate by this percent, you know it's the sane basis. But the cost impacts of doing that, I think, are different. I think there are rules of thumb that we can use, I know in that case ,"Hey, drop the current to 70%, I'm fine", or I could put a wire in and that is twice as big. I could put a couple splice boxes in on either side and double the number of conductors I've got and cut the current in half or cut the resistance in half, or whatever it takes to do it and I could put a bigger piece of wire in there and do the same thing, so this is a way of trying to solve it without doing that.

(Audience comments.) I don't remember the exact specification; it was a locally developed segmentation mix of fly ash, sand, gravel, Portland cement, low strength PSI. And we were basically relying on the sand, the fly ash, and the Portland cement to provide a thermal conductivity. I think it was actually three quarter minus because of the volume we were actually going to go as much as three quarter on the gravel, I don't remember the exact mix that we specified in that, I actually have a library of specified mixes and they are all very comparable.

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