Alison Berry: That's quite an introduction. Thanks, Emir. I'm glad to be here this morning; good morning everyone.

The purpose of this symposium is to talk about vegetation and levees. I think these two photographs depict sort of the key characteristics and the challenges of the levee systems of Central Valley California. On the one hand, levees afford important protection for our rapidly urbanizing neighborhoods adjacent to levees, and at the same time, the vegetation on the levees is a major riparian forest which provides rich habitat. And to say nothing, of course, of the central resources which is the water system itself. But there are concerns that vegetation on levees poses threats to the integrity of the levee, so I'm going to talk about particularly tree roots. I'm going to talk about some of the issues of tree roots as potential risk factors, and particularly I'm going to focus on how do tree roots grow and how do they grow in relation to levees.

So, the two key questions that I get out of the report, two of the most important factors that are of concern in terms of tree roots is whether they grow into the levees or under the levees and increase seepage or underseepage. So, that's one main issue. Another is windthrow; we saw some slides earlier of trees falling over and root systems uprooting, and those increasing surface erosion. Dr. Chris Peterson is going to be speaking about windthrow later this morning, so in the second part of my talk I'll just focus a little bit on the seepage question, where do roots grow in relation to levees, in relation to this question of seepage. The first part of the talk, though, I just want to have a "roots 101," how do tree root systems grow. And these are the major characteristics; I'll talk about each of these a little bit more in detail in the next few slides.

First of all, tree roots grow horizontally and they grow vertically, they are three-dimensional structures in the soil with a lot of variability and differences in pattern. Secondly, tree roots grow opportunistically. If soil conditions are permissive of tree root growth, trees will grow there -- in your sewer or whatever if they're very vigorous rooters. If soil conditions are prohibitive to root growth, roots won't grow there. So, that's another characteristic of tree root growth. And thirdly, tree roots grow biomechanically, so they grow in relation to the whole structure of the tree and to the stresses and the symmetries and the weights that are distributed and transmitted to the root system, the structural root system which is supposed to support the weight of the above-ground part of the tree. Then I'll talk a little bit about implications of some of these aspects for tree failures.

So, here's a current classic view of a tree root system shown in this diagram. First of all, you can see that the horizontal direction spread of this root system is enormous in relation to the vertical spread. It's quite common in many growth conditions for the horizontal spread of the root system to extend at least as far as the canopy, sometimes two and three times as far as the canopy. Now, I must say that the root diameter as you get out towards the edge of the canopy usually will decrease greatly, so we're talking about much smaller roots at the edges of the canopy than certainly you have in the center. But nevertheless, the horizontal growth of root systems in many conditions is very expensive. And surprisingly, you can see how shallow, in terms of depth, that tree root system is. It's down to about a meter in depth, so three to four feet is about the maximum extent of, say, 80 percent of the root system of many, many trees. That includes the fine root system, but it also includes those woody roots, so that's kind of a surprise also.

And you'll see there's no taproot in this drawing, and that's because the tap root is part of the juvenile growth of the tree, but usually, in most mature trees, with few exceptions, there is no major taproot. Instead, we have these sort of three different woody systems that make up the mature architecture of the root system. And all root systems are composed of these different systems in different proportions or combination. So, there are heart roots; you can see there the very thick buttress roots in the center of the diagram that support the main structure of that tree are called the heart roots. The horizontal woody roots that extend out exploring the soil volume, horizontal root system, and then you can see those vertical roots extending downwards, and those are called sinker roots. So, every tree root system has got some combination of these three systems of roots.

Now, let's go on to the second point: roots grow opportunistically. This is a diagram of a tree root system that was excavated painstakingly, cubic soil by cubic soil volume, showing how the root system is growing, where it's growing in the soil profile. So, tree roots are opportunistic. They need moisture, they need nutrients, and they need good aeration, so where they find those three conditions they will grow very well. And that's usually in the top foot or two of the soil. That's why a large fraction of roots are growing in that part of the soil. Mechanical impedance is also an important component of tree root growth; that is, high mechanical impedance will prevent roots from growing.

So, here's just a typical root system of many trees. You can see the central buttress roots there, the woody heart root system; you can see those lateral roots that are tapering in diameter as they go away from the base of the tree. And you note the marker there indicating 40 inches, so that's about three to four feet; most of the root system is located in that three to four feet. These are classic concepts. In the next part of the talk, we will see some differences on that, but this is just sort of basics that you want to know.

Now, I'm going to show a few examples of different kinds of root systems, so variations on these themes. And again, soil conditions are a major criteria determining whether and how root architecture is developed, as well as certain tree species characteristics. So, this is a group of cottonwoods from Cosumnes River, and you can see they've got some buttress roots there; very strong, extremely vigorous horizontal roots. Those are not decreasing in diameter as they go away from the tree.

And very strong sinker roots. So, this is a very aggressive root system -- exceptionally aggressive.

On the other hand, this is another example from along the rivers here in California. This was a Valley oak that was excavated by Don Gray and Doug Shields in their study about 15 years ago that has been referred to here, along a levee in the Sacramento River. Very sandy soils, this is a Valley oak, and look at that root system, it's going right down, and you can see the laterals are also very vertical in their orientation. It's unclear whether this could even be a taproot; it's more likely it's more than one root sort of twining around, so these sort of vertical center sinker roots. So, here we have a deep sandy soil; it provides very little mechanical support for a root system and it's probably very dry, droughty soil. So, the roots are growing downwards; they're probably growing along a moisture gradient and they're not spreading laterally due to biomechanical issues.

So, that's a contrasting kind of root system to the cottonwood; certainly not an aggressive root system at this level. Here's another very typical, this sort of root plate. We saw a few images of that earlier in other people's talks. These are usually because of shallow soils, you have a very shallow root system or there's some kind of clay pan or hard pan underneath, so you get this very broad, dense root system. It has very poor stability; it can be supported -- this was a Douglas-fir growing in a forest, they opened the forest to build houses and so the tree was much larger on the top than its root system could support, so in a storm it uprooted. So, that's a very flat root plate.

Here's another kind of a tree failure. This is a pine, very typical root structure of pines. They have often a very shallow surface plate, then they have some sinker roots, and they may have a deeper plate below. So, this one here had a very large canopy, asymmetric, so the above-ground part was heavy, it was growing into the gap, and when the soil became saturated it just seems to have hinged down. These roots look to me as if they fractured at the base rather than pulling the whole root system, so it's different from the root plate action.

The third point is that trees grow biomechanically, so roots respond to stresses and shifts in weight, bending stress and axial stresses can produce a reinforcement of the wood in areas where there is maximum stress. You can see I-beams or buttress roots and so on. In addition, the whole tree transmits stress to the root system which is supporting the above-ground part, and some asymmetrical force can cause compression on one side and tension on another. This could be wind or this could be other kinds of asymmetry, such as differences in the crown symmetry, sun exposure if the tree's growing on a slope, or if the soil itself is unstable. So, the whole tree has an affect on the architecture of the root system, which compensates to support the weight of the tree.

So, uprooting is a major concern near and on levees, and I just wanted to mention quickly, from the viewpoint of root architecture, there may be different damage levels due to uprooting based on different species, different conditions of soil, and different root architectural patterns. So, shallow root plates, as we've been discussing, might be one to two feet deep; they uproot, they're unstable, but they create rather a shallow divot. Aggressive root systems, however, can penetrate broadly, can penetrate deeply, and those systems can cause potentially severe damage, in my opinion. Steeply tapered roots like we saw in those buttress roots, those central heart roots, tend to fracture as they go over rather than pulling up the entire root system. So, there are different mechanisms of root system failure, and with different consequences.

Now, we get to the question that was brought up. Do dead roots pose threats? What about root turnover and the formation of channels? I think we need a lot more information on the persistence patterns of dead woody roots, large roots, and their turnover patterns. It has been reported in the literature that large diameter Douglas-fir roots - that is, two-inch diameter roots - persist for 50 years or more. Hardwood roots are more susceptible to decay; they may have a different trajectory - 20 years, 30 years, something like that. In either case, as decay takes place, you get deposition of organic material; it makes a nice channel for roots to grow in. If there are other roots around, they'll be opportunistic and they'll grow in those channels very nicely. But on the other hand, if there are no other roots around, if there's large-scale tree removal, then it's been shown that indeed these lots of killing of the root systems will result in soil destabilization.

Okay, so that's the first part, the primer on root growth. I want to now get into, where do roots grow in relation to levees? Do large roots grow into or under levees and cause increased seepage? I think excavation trench profile method, as has been done in the past, is still the best way to find out essential information. And we're only just starting this project; we have a trench profile project at Mayhew levee here in Sacramento. We've done just an initial look, and so this is one location and three trees that we've excavated. So, this is an overview of the Mayhew levee; it was constructed in the 1970s as part of establishing this residential neighborhood here adjacent to the levee. You can see the levee road, you can see the 300-foot berm there, running along the American River. There's quite a wide berm before you get to the levee itself. So, the levee is scheduled to be re-graded, so this provided a really good opportunity for us to come see these trees along the slope there, along the berm itself and the toe of levee, provide good opportunity to do some excavations and see where tree roots are growing.

Ones we look at, really, are mature oaks; we just looked at three mature oak trees. You can see here, this is one of them, and this is the one I'll mainly talk about today; the others were very similar results, however. This is 14 feet from the toe of the levee; they ranged from 14 to 30 feet from the levee toe. We did use the trench profile method, so you excavate a backhoe trench, you climb into the trench and you use some acetate sheets, marking grids, to mark where the roots are and what sizes they are. So, the trenches were four feet deep; by contract, we had that restriction, and they were running parallel to the levee, just at the toe of the levee.

The length of this tree crown, from dripline to dripline, is 56 feet, so we have a trench of 48 feet along the length of the tree. So, here's our backhoe excavating the trench. You can see the levee toe there and the tree. It was a big project and it involved a lot of people, a lot of help; SAFCA sponsored the project, Army Corps was there with a lot of help, and a number of people, scientists were there. We had a lot of help from consultants and other organizations, and we had a great research crew from UC Davis and Sac State who helped us with the excavation.

So, here are some data; that's our full profile of the one tree. You can see the roots look like pepper on that profile. The tree trunk is towards us and the levee toe would be away from us, into the screen. Here's just a chunk of that 12-foot length of what we found. And as I said, we found essentially the same results in all three trees. So, here's our four feet profile. Roots 10 millimeters or less in diameter are black dots, and roots 10 to 19 millimeters are red dots. The black dots, I should say, are most roots below 5 millimeters, so 1 to 2 millimeter roots. We were just recording every root, so most of the root system that you see in the top four feet, 14 feet from the trunk of this tree, were tiny 1 to 2 millimeter roots. The red dots are 10 to 19 millimeters; that's less than an inch diameter, so we had a smattering of those. And essentially we had one root in the entire profile that was over an inch in diameter.

So, very different from the classic concept. Where are the roots? We're down to four feet -- oh, and we're well within the canopy here, and we're well within the dripline. I wanted to show bulk density over there on the far right; we did some bulk density measurements. You can also see there's a zone with almost no roots in it, that's a two to three foot zone, and it was highly compacted, very uniform. It looked like we may have grazed the toe of the levee and there was a compaction zone there. And you can see that's reflected in bulk densities, which increased significantly in the middle of the trench. So, bulk density for this trench at that depth was 1.63, and the critical bulk density for root growth in this soil type is 1.65. So, I just wanted to have that illustration to show you roots growing in a sandy loam soil at these different bulk densities, 1.6 and above. Basically, we found that roots do not grow in that compacted zone; it was a successful mitigation effort.

All right. So, where are the roots? So, we said, let's just do one scoop of the backhoe below four feet. And so here's the trench floor right across from the trunk, and sure enough, we hit roots. Not very many, but some. You can see it's a two-inch diameter root; there's a couple of one-inch and so forth in that scoop. So, amazingly enough, although there's no roots in the top four feet, we were finding roots at the toe of the levee here at two-inch diameter. We wanted to corroborate that. We are also experimenting with ground-penetrating radar as a way of non-destructively analyzing root systems in soil. In fact, John Lichter shown here has really been a leader in this field, developing a GPR or trying to apply it and other tools, too, to look at root systems of trees.

So, here he's running a scan line; we set up an experiment with five scan lines, shown in this diagram. The tree itself is on the left and you can see the levee slope there, so one, two, three, four, five scan lines running parallel, again to the toe of the levee. The one in the middle corresponds with where we excavated, where our trench profile was. So, five transects three feet apart, two of them on the slope, two of them on the berm. And we did this for the three trees. Again, I'm just going to show briefly one set of data here, and this is very preliminary. It's almost raw data. There are some calibrations that we need to go out there and do in the field; these are just the early glimmerings, and there's a lot of chatter, a lot of artifact, which you can see as these sort of vertical lines in this tree.

I'm not going to go into detail on this. I'll be happy to talk about methods with you if you like, but essentially, the take home is that those red dots, except where you see the vertical lines, can be interpreted as roots. The antenna we used detects roots only one inch in diameter and greater, so we're not picking up any of those small roots that we saw in the trench. It can penetrate eight to ten feet. Essentially, the GPR data indicated that any large roots present were between four feet and six feet in depth, which is just where we actually did see them in that single scoop that we did. So, if we take a sort of overhead view of the transect, and again, you've got the tree and then the five transects - you can see the two on the levee slope there - the X's mark what can be interpreted as roots. Or they could be rocks. But that's the beauty of the transect method; if you have parallel lines and you can see the roots going from one to another, then that suggests it may be a root rather than a rock. In fact, we found very few rocks in these soils anyway. And the squares are artifacts, probably due to the way we were rolling the cart or something like that.

These are things we have to sort out, so I'm almost hesitant to present these, but it confirmed our data so nicely that I just thought it gives you a hint, and it has some promise as a methodology, I think. Again, this is the depth range between four feet and six feet; 41 inches to 72 inches. And if you squint and use your imagination, you can sort of trace some roots, potentially, from one transect to another. I think we need to repeat this with a slightly more dense array, but it looks as though there are quite a few roots close to the tree, or some roots, and this is the entire scan. This is the entire 50 feet of the canopy, so we're scanning from one end to the other; this is the sum and substance of the roots in this tree. But you can see some do extend - maybe - this is what we call "virtual trenching," so we have to call these "virtual roots." But we'd like to go back and confirm it. But it's potentially possible that there's a root or two in this zone, 41 inches to 72 inches that might be getting into this part of the toe of the levee. Now, they're not into the compacted zone so they're probably going underneath the levee.

So, take-home messages to wind it up. First of all, some roots, anyway, could be growing under the Mayhew levee from nearby trees. However, the roots avoided well-compacted fill. They were not growing into that toe region of the levee. So, that suggest that some mitigation measures such as keyhole trenches or the slurry walls or deep protection trenches may be effective in coping with these root systems. Again, they are opportunistic; they can only grow where they are able to grow. However, there are many unanswered questions raised by just this much data. Where are those roots in the top four feet of soil? Is it because it was an oak species, it had some particular characteristics of this species? Is it because of California Mediterranean climate, we have a droughty soil? Is it because of that relatively high berm? These are some very good questions that I think we need to get at. Are their species differences, are there differences in rooting patterns in different soils or regions in the country? We need more information combining trench excavation and other methods such as GPR, if we can get it standardized, to determine the real picture of roots and levees.

Now, just as a final point, as I was preparing the biomechanical part of roots 101 and thinking about rootshoot consideration, it occurred that crown asymmetry is a high risk factor, and also crown size. Pruning, while it may be a very expensive route, could reduce risk of root damage considerably, both from blowovers and reducing the overall vigor of the tree. With that, I'll conclude and turn it over.