Doug Shields: Well, my presentation today is basically going to be three presentations in one. The first thing I'm going to talk about is the levee study in the late '80's, then I'm going to follow that up with a little extension of that work that we've just done recently. I've done this with my colleagues at the sedimentation laboratory, where we've taken some of the information from that study and incorporated it in a computer model we have of bank stability, or slope stability. And then I'm going to come back and talk about another study we did in the late '80's out here on the Sacramento River revetments and the vegetation on the durability revetment.

Let me go back for just a second and say that, the 1980's studies are both documented in core technical reports and in the referee literature papers published in the Water Resources Bulletin, which is now the Journal of the AWRA, in 1991 and 1992. So, since the work has been published, I'm going to cover it rather rapidly and rather briefly, and I'll allow some time for your questions. But the work is documented in writing.

First of all, the levee study. This involved collection of field data in the summer of 1987; I was about 14 years old at that time. We looked at sites that were a rate along a 10 kilometer reach here near Sacramento, on the west side of the Sacramento River proper. We were looking at the effect of vegetation on the riverside levee embankment slopes, and within this 10 kilometer reach we identified six sites that were characterized by different types of vegetation. The veracious site had not been burned, it was covered primarily with California Rose and different kinds of [veges] and grasses, a dead oak stump and then a cluster of two rather large valley oaks, a stand of willows, some elderberry shrubs, because of their significance to endangered species, and black locus, and you see how they were arrayed there along the reach. Just right across the river from the Sacramento Airport.

At each one of these sites we excavated L-shaped trenches using the profile wall method that Allison discussed earlier. We dug down about four feet. The trenches ran parallel and perpendicular to the levee crest, and where we were working around woody species, we tried to dig the trenches where they coincided with the drip lines of the trees, thinking this was a more or less typical condition for a vegetative levee slope. However, at the elderberry site, to kind of max things out, we dug the perpendicular trench right through the center of the cluster of -- or the clump, of bushes.

And so this is what our field site looked like, one of our field sites. This is the perpendicular trench at the valley oak site. So, you see the two valley oaks there in the middle and the people are actually mapping roots on a clear acetate overlay with a grid there. Different colors were used to map different sizes of roots, different size classes were identified. So, basically, just a day at the beach there, they're having a good time. Ann McDonald, who's now with URS Corporation in Portland, led this effort, did a terrific job.

In addition to the botanic data, both above ground and below ground, we collected pretty standard information about the levee geometry and about soils. We used our bore hole sheer test device to get sheer strength parameters [unintelligible]. We found that the levees were overbuilt slightly on the riverside, they were not quite as steep as 3H on 1B. The levees were sandy, pretty uniform, medium sand, not very well compacted at all, and very little cohesion. We did see some inclusions of clay balls and just occasionally we'd find some [unintelligible] material, more about that later.

I'm not going to talk about the above ground botanical results because of time. But below ground we worked very carefully, we had to wet down the soil to get that trench space to hold a vertical slope, so it wouldn't just crumble off. And in addition to the root locations and sizes, we also mapped things like voids, [unintelligible], mineral inclusion and stratographic features.

We used the root information to compute root area ratios. If you're not conversant with this term, RAR, root area ratio, basically you get the cross-sectional area of the roots, the white spots here, and divide by the total area over which you're mapping. So, it's the white area divided by the brown area. The summation of the area roots divided by the total area, and we did this in 10 centimeter depth increments so that we could calculate the vertical distribution of root area ratio.

Again, I'm just going to let you kind of peruse the above ground results, but I'm going to talk about the below ground results. The root area ratios were pretty low numbers. Yes, that is three zeros one percent, to two percent, which is really kind of an out there, because our mean was only about .2%. Pretty large coefficient variation you see here. The root numbers declined exponentially with size, there were a lot more small roots than big roots, not much of a surprise there, and that's consistent with what Allison presented earlier.

The root frequency and the root area ratio declined with depth, and so here, this is depth below surface, up here at zero is the surface of the ground, and we're showing our data down about a meter, and that's about as far as we were able to go down. And, you know, based on what Allison showed this morning, the question is, well, did you miss some roots because you didn't go deep enough? And I'd have to say, well, probably so, because we didn't go all the way to -- we didn't get all the way to the zero with the root area ratio down here.

This is the average, or the control, or the veracious site, right here, and this is the average with the wooden grip line sites right here. So, you see, we're pretty much in that .2 to 0 range. Important point though, is we found no significant difference in root area ratio at depths greater than 20 centimeters. Above 20 centimeters, a lot of veracious roots up there. Below 20 centimeters, based upon analysis of variants, and one reason we were unable to detect a significantly significant difference, is because of the wide range of variants from site to site.

However, if we take those data and we plot a cumulative frequency distribution, like a grain site curve here, on the vertical axis, of course we have the depth of the soil surface, and here the percent of roots above a given depth. So, the dark green is the woody sites and we can see that about half of the roots, about half the root area ratio, is above 25 centimeters. This is depth below the soil surface in centimeters, not meters. But anyway, you see the curves lie pretty close to each other, we got more herbaceous roots at shallow depths and then more woody roots at what I'll call the mid-range depths, and then they kind of come here together close to a meter.

These results are consistent with findings about others -- no, well, Bill Gates is trying to ruin my life again. Up here, bound curves from Jackson, et al 1996, this publication right here that appeared in the Ecologia, they reviewed 250 studies of roots from all over the world and plotted these kinds of curves for different species and different biomes. And what we found is that temperate grass land is up here, it has its roots concentrated near the surface, a desert is back here. So, our herbaceous site is close to -- kind of close to desert, the woody sites hit the temperate deciduous biome right on top of the money.

So, we may have missed a few roots at depth, but I think all in all, we're very consistent with the findings that have been published in the literature about the vertical distribution of roots. That's the takeaway message that I'm trying to show on this slide.

Okay. A few qualitative observations and then we'll go to the data. I think Dr. Gray talked about seeing these [tubules] that were filled with different kinds of sand. We didn't see very many voids, the density of voids greater than 5 millimeters in diameter range from only 0 to 10 per square meter, and average 1.65 per square meter. Not many holes in the levee. Also, I think Allison, or Dr. Barry, showed a picture of our -- Allison showed a picture of our dead oak stump and we see these lateral roots in a non-orthodox, non-classical way. Instead of radiating outward, it actually angled downward and we interpreted this as an adaptation to our extremely [unintelligible] site.

Okay, so those are qualitative observations, and I'll slow down here long enough to say this is the only thing I have to tell you about root induced findings. There's nothing else in this study that really gives us much information about root inducing findings in these qualitative observation.

We did do some analysis on seepage, but instead of looking at root induced piping and its effect on seepage, here we were looking at the modification of surface permeability's due to vegetation. Normally we expect vegetation to increase the surface permeability of the soil, but what we did is kind of a sensitivity analysis where we look at the existing permeability and then we increase that by a factor of 10 and decreased it by a factor of 10. And the idea is under steady state extreme hydraulic loading, where you've got a water surface elevation that's, like, 90 percent of the levee height on the riverside, and if the surface foot of the levee has a change in permeability, what are the implications for seepage? And so here are findings. This is the flow net that we got with a phonic difference relaxation technique for a homogenous levee. The flow net for a levee with more permeable skin, what we'd expect from the vegetation, really isn't affected very much. A less permeable skin, say the vegetation possibly may be trapped some vines or something, and that's kind of hard to conceive of, but it's a kind of a what-if analysis here, elevates the discharge point, and so it increases the discharge area here on the land side of the levee. So, a negative indication as far as the effect of vegetation permeability, if it makes the skin less permeable.

The main analysis we did, though, was a slope stability analysis. We did two kinds of slope stability analysis, and I refer you to a publication for the details. We did a infinite slope analysis, which is appropriate for sandy soils subject to shallow sluffing, and we also did a circular arc analysis, and really, the findings of these two were confirmatory or complimentary.

The way we treated the vegetation, and this is the only link, really, between all that digging in the field in 1987 and the stability analysis, was we assumed a relationship between soil cohesion and the root area ratio. And I say we assumed this, this was actually based upon the experimental work that Dr. Gray did. He showed you a picture of it, where they isolated a soil block, root permeated sand, and did a direct sheer test on it. They did tests with field samples and with lab samples and this relationship is an empirical relationship here. .233 times the root area ratio for the additional cohesion, due to roots, is based upon that work. He showed a slide that had the -- in different units, 3.2 instead of .23, but it's the change of units to PSI to get the 3.2.

Well, what's the effect on soil cohesion? Very conservative, based on measurements published by others. This increased our soil cohesion only about 50%, using the mean value of root area ratio and the mean value of soil cohesion we measured in the field. But it had a major effect on factor of safety. Now, here I've plotted three curves where we have the factor of safety on the Y axis and root area ratio in a log scale on the X axis. The different curves represent the different depths to the failure surface.

As to the one that appears to be most critical is this one down here at 40 centimeters, and you see a major increase in factor of safety as we move from minimal root area ratio up to a higher value, decreasing the factor of safety from an unstable to a pretty stable value. To get this kind of relationship we're looking at a very steep slope, this is one that was -- I assumed it was measured from the land side slope, very low friction angle, zero cohesion in the soil, and the seepage angle is equal to the slope angle. So, we're really pushing things here to be conservative. We assumed a constant root area ratio that was not varied with depth for this particular analysis.

How does this root area ratio, this X axis, play out in terms of what we observed? The green line that just suddenly appeared here, is the mean for the herbaceous sites, and the box represents plus or minus a standard deviation. This burnt green is the mean that was observed for the woody drip line sites, plus or minus a standard deviation, and so, you can see that the vegetation is having a significant positive impact on slopes that go up with these assumed conditions.

Okay, so we're ready for the key findings of this particular study. The roots were concentrated near the surface, the large lateral roots that we observed from the stump angled downward, the vegetation made an important contribution to slope stability. Apparently roots did not create void, we found no evidence and we found evidence to the contrary. The voids we did see were associated with animal activity, both insects and rodent. We concluded that maintenance standards should favor woody shrubs and small trees.

There are several limitations here and I want to just stress these. There was no quantitative analysis of piping potential, root induced piping, one way or another. There was no analysis of wind throw issues, obviously no analysis of conveyance flood site or inspection, either.   That's what we found out on that study.

So, let's shift gears. If you were listening closely here -- let me go back to this, if you were listening closely, I was able to show that vegetation is good for slope stability. I did not show what kind of vegetation is good for slope stability. I showed you that we found no significant difference in the average root area ratio deeper than 20 centimeters in the soil under a herbaceous site, or under a woody drip line site. No significant difference. So, vegetation is good, but what kind of vegetation we really weren't able to show that.

Shifting gears, up to the present date, from 1987 up to today, we -- I got one of my colleagues in the sedimentation lab, Dr. Natasha Collin, who works with Andrew Simon, to spend a great deal of time looking at the effect of vegetation on screen bank stability, on bank stability. Andrew, with a lot of folks that work with him, have come up with a numerical model called the ARS Bank Stability Model, and it is intended to model screen banks, it simulates a wedge type slope failure. You can have five different soil layers with different soil property. You give it the phreatic surface within your screen bank, it is based upon static 2D conditions, this is the input screen for the model, and it is a free download.

But what I got Natasha to do was to modify the model so it considers vegetation along the bank slopes, or bank base. The one that you can download for free just considers vegetation at the top of the bank. In addition, the latest version of the model incorporates certain advances over that .23 times the root area ratio that Natasha has made. First of all, we think that approach may have overestimated the contribution of vegetation because it assumes that all the plant roots break simultaneously. That when you load the root permeated soil, the root saturated soil, that all of the roots contribute to resisting the load that's been placed on the soil at the same time.

And, in fact, the roots rip, they break one or two at a time, and this is found -- this is represented by a fiber bundle type model, and it's more realistic. Also, the root contributions to soil strength are very based upon the vegetation species that age the soil type and the moisture content. A much more sophisticated look at the vegetation and this is in the bank stability model, what they call the rip root algorithm.

So, the conditions that we assumed for our simulation exercise, basically we just pulled the conditions from our field study back in the late ‘80’s and fed them into the model, and we -- the bank stability model makes you assume a horizontal phreatic surface, definitely a worse case condition as far as a levee. And so we kept that at 80% of the levee height, and so she looked at a lot of different scenarios, in the interest of time, I’m just going to present a few here. I am going to show three different kinds of vegetation and you see that the rooting depth assumed there and their contribution to soil cohesion.

We’re just going to look at the impact of vegetation on a one on three -- one horizontal, three vertical river side slope, and we’re going to look at a condition where we have a low river state, like a rapid drawdown, 80% of the levee height, but a high phreatic surface, up here at 80% of the levee height, so kind of a worse case condition as far as the hydrologic loading’s concerned.

So, here’s what we found out. The red dash line at the bottom of the bar chart, the factor of safety of one, the vertical axis is factor of safety, and so you see the vegetation free bank, or vegetation free levee is -- factor of safety of only .54, unstable without root reinforcement. Bunch grass comes up here pretty good, mature -- young trees not quite so good, small trees and immature trees are best of all. So, positive impact.

So, quickly, key findings under worst case assumptions of riverside slope is unstable without vegetation, and as far as factor of safety goes, mature trees are better than bunch grass, are better than young trees. Maintenance standards should favor bunch grass or trees based upon this little study here. [Unintelligible] large trees because this has nothing to do with wind throw. So, I’m not going to say large trees, but bunch grass or trees.

Several important limitations. We only analyzed wedge type slope failure, the effect of vegetation on soil permeability and the seepage was not considered, wind throw not considered, piping potential not considered, and it’s a minor point, but since we’re talking about physics, I will mention that the surcharge, the additional weight of the vegetation on the river slope is not considered in this modified model. It is considered in the downloadable bank stability model, [unintelligible] vegetation [unintelligible].

Well, let’s go back in time, back to 1989, and now we’re in the third phase of my presentation, we’re going to talk about the revetment study. The reason to talk about revetment is, and you folks that live out here know this, but I preface my remarks by saying the revetments coincide with the river [unintelligible] or the river slope of the levee in some cases. In other cases they’re very approximate to the levee, the revetments are key as far as protecting the levees go. They may be within that 15 foot vegetation free zone that the white paper is talking about, so that is one reason for the interest in this work.

This study in comparison, I’ve already presented, is purely empirical. We simply took one reach of the Sacramento River and we said, how did woody vegetation affect the durability of revetment during the project flood -- not project flood, the flood of record, during the flood of record. So, we calculated damage rates for vegetated and unvegetated revetment, allowing for the type of stone and construction date and bank curvature, and then compared these with past [unintelligible] statistics.

First of all, the study reach was from Sacramento River mile 84.5 to river mile 119, this is between the Freemont [unintelligible] and the [unintelligible]. There are no major inflows or outflows in this group. These are annual peak discharges that I just downloaded the USGS for the [Gage] and [Wilkins] slew, and when we did the work in 1989, the 1986 flood was the flood of record, and apparently it still is, and there’s an interesting positive trend here which [unintelligible] you that.

What we did was, we said, okay, what revetments were damaged during the flood, and were they vegetated before the flood? We found only five instances of revetment damage that resulted from the flood and we got these from request under the [PL849]. Only five cases, none of them supported vegetation before or after the flood. So, well that makes for a very short research project, so we said, why don't we do this? Why don't we look at inspection records and aerial photographs, and just find out where the vegetation was before and after the flood, and then let's get in a boat and go out and see where the vegetation is today, because it had only been two or three years since the flood.

And so, we built a series of overlays, clear material, about three by five, that could be overlaid on base map. This was back in the day before everybody had a GIS and a GPS, so that's how we did, and so, we were able to look at the relationship between revetment damage and these other variables. To have a database that we could actually analyze, we divided the revetments into 30 meter long segments, and for each segment we recorded in the database, this suite of information, bank curvature, construction date, revetment material, usually your cobble or rip rap, and then the vegetation conditions from different sources, and whether or not the revetment was actually damaged or not when we inspected it in 1989.

We did a very simple classification as far as vegetation types go. One was bare rocker soil, or just a little grass or herbaceous material. Type two was this sort of vegetation here, woody vegetation less than 12 feet high, and then if you had more than that, that was a type three. An important point here is, to be very conservative; we did our classification based on the largest individual plants growing on each segment. So, this right here's a type three revetment, even though there's only one tree in that 30 meter segment.

What were our results? Well, about two-thirds of the bank line of our reach was revetted, a lot of rock out there. Only about 10% of the revetment supported some type that is two or three, of woody vegetation. The state inspection records underreported revetment vegetation by 80%, relative to aerial photos. I’ve already mentioned that only five sites were reported as damaged, during that ’86 flood event. We classified about 3% of the revetted bank line as damaged in the September ’89 visual inspection, and this was right on top of what Mike Harvey and his associates did, when they did the same thing just before we did. Mike Harvey was retained by the Sacramento District to do a series of geomorphic studies.

And most of the damage was what Mike called threading, here. This is an old cobble revetment and there’s been a vertical displacement at this point, exposing its cohesive bank, and the reason he called threading, is these failures appear periodically down the bank, and was able to relate this to the alluvial [unintelligible] of an area and selective removal of fine material.

So, what we did is, we took our database and we said, well, let’s just calculate the damage rate based upon, you know, all these segments for vegetated versus unvegetated, and use [Chi-square] statistics to see if they’re significantly different. And so this is what we found for vegetation, about 3% of the unvegetated segments were damaged, 5% of the vegetated, but that was not significant, according to chi-square, bank curvature almost exactly the same damage rate, based upon spray convex, or concave. The material, again, about the same damage rate for cobble and rip rap, but we did find a very significant difference. The older revetment tended to show more damage and, again, most of the damage was that threading on the cobble revetment, not as much tow protection or special tow trench design on that cobble revetment, and perhaps that’s why it slid down the way it did.

However, when we lump all the data like this, we were concerned that we might’ve been comparing apples with oranges. So, we did another analysis where we split things into some smaller categories. First of all, based upon the construction date, three different dates you see here across the X-axis, and then for each construction date, we looked at bank curvature, straight, concave and convex. This led to some categories that had only a very few revetments, for example, it stands out kind of like a sore thumb, we've got a 60% damage rate for vegetated revetment recently constructed on convex banks, but this represented 3 out 5 revetments. At any rate, if you look at all of them, the damage rates were higher for unvegetated in 6 out of -- 6 categories, only 3 categories were vegetated [unintelligible].

We look at rip rap revetments, previous was cobble revetment, we had several categories where there were no revetment segments found. But when we count up the score, the damage rates were higher for unvegetated revetments in three categories; only one category was the vegetated damage rates higher. There were two times where both rates were zero.

Okay, and I'm trying to get through here where you can have a chance to talk a little bit. The damage rates for revetments supporting woody vegetation tended to be lower than unvegetated revetments, when you compared apples with apples. The Chi-square test indicated that older revetments were more likely to show damage. During the 1986 flood, vegetation did not adversely impact revetment ability. This is an empirical study, any time you have an empirical finding, to transfer those findings elsewhere must be done with great care. Very low damage rates, and that's why we had to do our statistics the way we did, and, again, there's no assessment here of vegetation impacts on flood [unintelligible] or inspection.

Okay, somebody else can talk.