2. I would like to talk about dams, For those of you not confronted by dams, the first thing to note is that dams are big, unreinforced concrete structures.
3. how they crack, how they age and how they shake in an earthquake.
4. Since I will make this presentation available to the organizers, here are some relevant publications.
5. So let us start with cracking of dams
6. And by cracks, I mean also joints, (horizontal and vertical) as well as unanticipated cracks.
7. Well, to understand cracks, you need to go to the laboratory and run a lot of tests, and since we are dealing with dams, tests must be big, must account for biaxial confinement, and cracks may even have to be subjected to internal pressures to model uplifts.
8. These are picture from other tests I did in which we looked at the characterization of joints subjected to cyclic loads, as in an earthquake.
9. Ok, so once we finsih tests, we go back to the office, and develop a constitutive model which related in this case normal and shear displacements to corresponding stresses.. In here we have a parabolic failure surface in terms of tensile strength, cohesion, and angle of friction. Please note that all my models are based on the one of Hillerborg.
10. For the joints subjected to cyclic load, there is a deterioration of the surface, and hence it must have a modified constitutive model. I will spare you the details.
11. Keeping in mind that joints are also used to model the rock/concrete interface, in here we check the element ability to automatically adjust for the uplift pressure during earthquake.
12. Once completed, the model is inserted in a finite element code (more about that later), and then we are ready to analyze a dam, such as this one in Japan. In this old buttress dam, the concern is a lateral excitation. Originally, they were going to spend $50 million dollars to strengthen it.
13. However, in tis old dam there was some reinforcement across the joints. So, we first performed laboratory tests to characterize those joints.
14. We also performed a finite element analysis of the model
15. And then performed a full 3D nonlinear dynamic anlaysis.
16. Here are some random pictures taken from the 3D finite element analysis. Well, the sponsor spent $100,000 on research, and we saved them $50 million dollars in unnecessary mitigation work.
17. This dam in the US, had a very complex geometry, and based on simple calculations which did not account for 3D, it failed to have an adequate factor of safety. So, I wa asked to perform a 3D nonlinear analysis. lease not the joints in the lower right image.
18. oK, let us move next to the aging of dams.
19. Aging of dams manifests itself through a reaction between the alkali of the cement paste, and the silica in the aggregates. This results in a gel which will cause expansion or swelling of the concrete, and as shown in this picture, there is a vertical and upstream deformation of the dam. This deformation may take over 20 years before it becomes noticeable. By the way, the only effective remedy, is, as shown in the picture to the right), to cut the dam, and allow the expansion to take place.

20. So what do we know? we know that the reaction ncreases with temperature and humidity, that expansion starts slowly, then accelerate, then slows down (a sigmoid curve), that if you constrain expansion in one direction, it will expand more in another. Those are the key points.
21. In our model, expansion is given by the volumetric expansion equation on the top, in terms of the maximum expansion epsilon infinity) which can be as high as 0.5% (or equivalent to a temperture increase of 500 degrees). The second equation is the kinetic of the reaction, that is how expansion occurs with time, it is in terms of two parameters, tau latency and tau critical.
22. If we have large tensile stresses cracks will be filled by the gel, and this will reduce the expansion
23. same thing under compression, micrr-cracks will be filled by the gel, and overall expansion is reduced.
24. Once we have the global volumetric expansion, we will redistribute this in the three principal directions,
25. as shown in here. The more confinement, hte more expansion in the other directions, It is that simple.
26. Unfortunately, accompanying this AAR reaction is a degradation in Young's modulus and tensile strength as shown in here.
27. So, let us look at this arch gravity dam in Switzerland, it suffers from AR
28. Before we can analyse it, we need to tabulate our input data. Keep track of all events affecting temperature or stress
29. We may even use a Matlab based program to perform a system identification
30. And then look at results and internal cracks
31. In this other application the foundation of an electric transmission line tower is affected by AAR and we
32. analyse it, and compare strains with those recorded in situ
33. Let us move on to shaking of dams
34. earthquakes do hit dams also
35. so let us examine a few key modeling issues
36. Briefly, we almost always need to perform a detailed transient thermal analysis of arch dams and account for all heat transfer mechanisms,
37. One important aspect often forgotten by structural engineers is deconvolution. That is if our seismograph records ground acceleration, and our model applies the excitation at the base of the rock, how do we determine that acceleration? i will not go into the details, but the key is the use of transfer functions in the frequency domain, and this operation is automated in our computer programs.
38. This is done by going from the time domain to the frequency domain, perform some operations, and come back through an inverse FFT.
39. as shown schematically in this slide.
40. This operation is fully automated in our program. Here you can see the nearly exact correlation of the input and deconvoluted signal.
41. Another important issue is the need to simulate construction, specially for arch dams so that we do not obtain artificially high tensile stresses i the middle top quarter.

42. Next we examine the various dynamic interactions, fluid-structure, fluid-fracture, and rock-structure
43. As mentioned earlier, it is very important, specially for gravity dams, to automatically adjust the uplift pressure when the rock/concrete crack propagates. This should also account for drain effectiveness.
44. During an earthquake, the uplift dynamically change, when the crack opens it drops, and when it closes it increases drastically.
45. You note here how the dynamic uplift increases with time
46. Ok, next topic: One of the most important issue is foundation rock interaction. Because the finite element mesh is finite, waves will reflect at the boundary and get magnified if the mass is modeled.
47. this would be the case in such model if mass is different from zero.
48. This is the so-called Lysmer model where we place appropriately fine-tuned dashpots at the end, it works but this is not enough
49. Let me say a few word about our model. It is not a very complicated one to understand. Basically, we have to model the free field (that is the rock mass outside the foundaiton) as a shear beam, determine the velocities and displacements, and then transfer those as nodal equivalent forces in a second analysis of the dam foundaiton.
50. as it is schematized in here for 2D and 3D
51. This is an important slide, the foundation is subjected to a harmonic excitation at the base. If we do nothing special, notice the erratic response for sigma x and sigma y in the top. Things get better in the middle with Lysmer, and much much better with our new model.
52. This is also true for the 3D validation problems.
53. Next, the modeling of the boundary conditions in dynamic analysis are very important. What is important to mention, is that we must first perform a static analysis for the foundation supported. Then we remove the supports, replace them by nodal forces, and do a restart to perform a dynamic analysis. Only this way we can avoid so-called rocking problem in a dynamic analysis.
54. Finally, we performed an extensive parametric study, considered various effects, and all those results will soon be published.
55. One of the most important conclusions is that proper modeling of the rock-structure interaction is equivalent to about 15% of Rayleigh damping (as opposed to the usual 5%). Clearly by accounting for this, we reduce artificially high stresses.
56. Finally tools. For nine years I was funded by the Tokyo Electric Power Company (over a million dollars) to develop a unique finite element code for the AAR and seimic analysis of dams. Also for a pre and post processors.
57. I will not go in details about each one manuals can be downloaded from my web page.
58. here are a few examples from the windows based graphical postprocessor. It is very user friendly and was written by my group.
59. Another example of 3D plots generated, such as crack stresses or uplift pressures,
60. Let us move next with validation. Japanese are very demanding, they wanted to make sure that Merlin makes good predictions.

61. So they built a model of a Japanese dam, mounted it on a shake table, and itself was mounted inside a centrifuge.
62. Here is a closeup of the dam, and instrumentation. You note how Buckingham law's of similitude, stipulates that at 100g, the duration of a 10 seconds excitation is reduced to 0.1 second.
63. We ramped up the acceleration
64. and looked at various transfer functions to detect first occurrence of crack
65. They were happy to note that Merlin's prediction and experimental observations were not too far, and now they use routinely this finite element code.
66. With this slide, i would like to conclude my talk. It is a reminder that we can not ignore the integrity of our dams.
67. Thank you for your attention.