3D Nonlinear Transient Analysis of Concrete Dams

by

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ABSTRACT

Concrete dams, by virtue of the lack of reinforcement, and the potential for well predefined cracks (along lift joints and the rock/concrete interfaces, or in-between monoliths, not to mention within the solid concrete or rock mass) are indeed prime candidates for fracture mechanics. This paper will highlight laboratory tests, numerical models, validation experiments, and case studies. Numerous laboratory tests have been conducted to characterize fractured concrete under varying conditions (such as dynamic load, effect of water pressure inside the crack, cyclic loads) and will be reported. Other laboratory tests were conducted on a concrete dam model mounted on a shaking table inside a centrifuge to assess the accuracy of our numerical predictions. Finally, a numerical model (Merlin) for the nonlinear (implicit and explicit) 3D nonlinear transient analysis of concrete dams has been under continuous development for the past 15 years. The computational challenges encountered will be highlighted.

It will also be pointed out that, though nonlinear fracture mechanics has an important role to play in the seismic safety assessment of a concrete dam, it is only one major player amongst many other important ones whose participation is equally essential to the comprehensive analysis.

1 INTRODUCTION

Japan, which is geographically located on the intersection of three major faults, is one of the most seismically active regions in the world and as such has taken a leadership role in research and development to mitigate the destructive forces unleashed by a seismic tremor. Recognizing the computational power currently available, the advances in various related disciplines, the authors have developed a vision of what a modern analysis should entail. They seek not only to advance the State of the Art, but as importantly, to transform it into their State of the Practice, (Uchita, Noguchi and Saouma 2005).

Few organizations have previously embraced such a broad and challenging set of objectives. In the U.S., the Electric Power Research Institute (EPRI) has indeed funded for five years the third co-author to develop a fracture mechanics based methodology to assess dam safety. However, the impact of this research remained minimal. More recently, the European Community has funded a five years network program on the integrity assessment of large dam (NW-IALAD), but its objective was limited to the identification of the State of the Art/Practice as opposed to focused research.

Building on the American experience developed by the first author, and the seismic expertise and needs of the Japanese dam owners, an international collaboration was initiated seven years ago. Our approach is one which takes a holistic approach to a very complex and coupled multi-physics problem. First we identify the State of the Art, advance it need be, publish those results in the scientific literature to share it with others, develop a computational tool which can effectively and efficiently analyze the simplest and most complex structures, and last but not least assess the reliability of this tool through complex model testing.

This paper will share our collective experience in this adventure. However, before we proceed, it should be emphasized that a peculiarity of concrete dams is the simplicity or complexity with which they can be analyzed. In the simplest case, a spreadsheet is all what is needed, at the other end of the spec-

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trum a supercomputer (or massively parallel one) is essential. What causes this dichotomy is simple. As for most structures, design is limited to linear elastic analysis, generous safety factors, and simple calculations compounded by engineering common sense. Risk analysis on the other hand, is much more complex. The Federal Energy Regulatory Commission (FERC) for instance stipulates that a potential failure mode analysis (PFMA) must be undertaken. Hence, a nonlinear finite element analysis must be conducted to determine whether the dam can sustain a given flood, earthquake, blasting, aging of its concrete or a combination of the above. The stakes hinging on the outcome of such an evaluation are enormous.

Unfortunate recent events (Tsunami in the Far-East, and breakdown of levees in New Orleans) have shown the destructive nature of unleashed water. Our responsibility is to make sure that this does not occur through dam failure

2 TESTING

Nonlinear finite element analysis is much dependent on the constitutive models (stress-strain or stress-displacements) adopted. These must not only be rigorously derived, but must be based and validated by laboratory tests.

Material testing for dam much differs from "traditional" material testing for buildings. Major difference is in size of specimens, and in type of application specific tests. The resistance to crack growth of concrete, and concrete-rock joints in large specimens (5 by 5 ft and 3" MSA), Fig. 1 was first investigated, (Brühwiler, Broz and Saouma 1991). Also investigated was the relationship between crack opening and internal uplift pressures during both static and dynamic loads, (Slowik and Saouma 2000). Finally, prevailing ourselves of the existing testing capbilities, a large scale direct tension test was conducted on a 762 by 254 mm section, (Slowik, Saouma and Thompson 1996) and yielded an unexpectedly high fracture energy of 280 N/m, Fig. 2 3.

It is often desirable to extract directly in-situ key physical parameters of the concrete; this was attempted through the use of special probe which records radial displacements while it pressurizes a borehole. First, laboratory tests were conducted, then field tests performed, Figure 3.

Another example of tests particularly relevant to concrete dams is the response of joints subjected to reverse cyclic loads, Figure 4. As the earthquake shakes the rock/concrete interfaces, there is a degradation of the interface resistance to crack formation/propagation. These tests are essential prior to the development of a constitutive joint model to be used in strong earthquakes.

3 MATHEMATICAL MODELING

Mathematical modeling of a double curvature arch dam subjected to a strong earthquake is indeed one of the most challenging civil engineering problems. It is a tightly coupled multi-physics problem. One must understand the 1) thermally induced initial stresses in the arch dam, 2) nonlinear mechanical response of joints and cracks, 3) hydrodynamic forces exerted on the dam, 4) staged construction and residual stresses, 5) dynamic flow of water inside a crack, 6) Wave propagation from the epicenter to the dam, 7) "Soil-Structure" interaction, 8) Structural model, and last but not least 9) the dynamic structural response of this massive concrete structures.

Whereas a thermal transient analysis may not be particularly challenging, determination of the thermally induced thermal stresses, simulation of the construction process, and of the joint grouting is a delicate computational task which may not be easily accomplished with commercial codes.

Joints and cracks do constitute the primary, if not the only source of nonlinearity in the stress analysis of a dam. Whereas most commercial codes, as well as researchers, focused on the so-called smeared crack model, we felt all along that the discrete crack model should be one adopted. In the smeared model, the mesh is fixed, and Gauss points constitutive models are modified to reflect the presence of a crack. A major limitation of this model, and despite years of research, is the difficulty to capture the localization of the crack. In the discrete crack model, the mesh topology reflects the presence of the crack/joint and a special interface element is inserted along the crack. In the context of dam, where few cracks/joints exist, and which location is known a priori, there is little doubt that the discrete crack model should be adopted. Hence, much of our effort dwelt on improving this model. When used along the concrete/rock discontinuity in a dynamic analysis, this model indeed captures the nonlinear response of the joint through crack opening and normal stress distributions which account for possible (small) cohesive tensile stresses, Figure 5.

Our focus on discrete crack may have started with (Saouma 1980), really took roots in modern plasticity approach through the model developed in (Cervenka, Chandra and Saouma 1998) which was extensively used for actual nonlinear dam analysis, and culminated most recently with the extension of our previous model to account for reverse cyclic loads, (Puntel, Bolzon and Saouma 2006).

During an earthquake, joints open and cracks may form. Currently, there is much controversy as to whether water can flow into the newly formed crack, and what the dynamic uplift is. There is some strong experimental evidence that during crack opening and closure, we have respectively a decrease or an increase of uplift pressure. Hence during crack propagation, not only is the new crack surface subjected to an internal uplift pressure, but the magnitude of the pressure is a function of the rate of crack opening displacements (as a first approximation), Fig. 6.

Earthquake records (accelerograms) are usually measured or determined at the surface. Yet the analysis requires modeling the rock foundation (and its mass), at the base of which accelerations are applied. Again, in simpler analyses the surface acceleration is simply applied at the base; however a more rigorous approach would require deconvolution of the signal under the assumption of a linear elastic rock foundation. This is done by first applying the (surface) recorded signal at the base, through a preliminary finite element analysis compute the induced acceleration on the surface, transfer those two accelerations from the time to the frequency domain, and compute the transfer function. In the general three dimensional case, there will be 9 transfer functions which constitute the convolution matrix. The inverse of that matrix times the input accelerations will give the deconvoluted one. Hence, we the deconvoluted one is applied at the base of the foundation, the induced acceleration at the surface will be nearly identical to the one recorded, Fig. 7.

Whereas many simpler analyses ignore the foundation mass, this must be accounted for in a rigorous nonlinear analysis. A major complication becomes modeling of the so-called free-field as the seismic wave will artificially and numerically be reflected by the lateral edges of the model. This problem was long recognized. In the context of a finite element (as opposed to boundary element) analysis, this problem is most efficiently addressed through application of boundary conditions which would absorb these waves (thus we often talk of “Silent” boundary conditions, or of radial damping). The classical (and partial) solution to this problem is the application of Lysmer dashpots. However, in this model, the free field is assumed to be rigid. A more rigorous model, developed by Miura and Okinaka (1989) consists in a separate analysis of each of the free fields (2 in 2D and 4 in 3D) for each of the 3 components of the earthquake record. The determined velocities are then applied as initial boundary conditions to the dam which must also have the traditional lysmer support, Figure 8.

Free field modeling require that there is no vertical support below the foundation (to avoid the vertical reflection of waves), hence in our analysis we first perform a static analysis with gravity load, and then the program can automatically replace the vertical reactions by equal nodal forces for the restart in the Dynamic analysis.

While conceptually simple, this can be a potentially “labor intensive” task as velocities must be extracted for each time steps from many different files and then inserted in the main analysis input file.

Amongst the many “fine-grain” issues in the structural model (and not previously discussed), we list the need to have an initial static analysis, followed by a Restart (and resetting of displacements to zero) of the dynamic analysis with dynamic elastic properties. In the dynamic analysis, one needs to avoid the effect of “rocking” (reflection of the elastic waves with the vertical supports of the gravity load) by replacing static reactions with point loads in the dynamic analysis. Concrete and rock should also have different Rayleigh damping coefficients. Different joint models should be used if we expect a pure mode I (simpler) or mixed mode crack propagation. Highly fissured and fragmented rock (as is the case in Japan) should have a nonlinear model, and major rock joints should be modeled.

Whereas until fairly recently, transient analysis was considered to be computationally impossible (and hence most analyses were linear and performed in the frequency domain) , this is clearly no longer the case. With modern computers, time history analysis of even small dams is becoming the norm. Time integration can be either implicit or explicit. Dynamic crack opening and closures can induce numerical problems, and integration schemes may have to be refined. In Fig. 9 it is apparent that the both the Newmark β and Hughes α methods yield identical results as long as the discrete crack is not activated, when it is Hughes time integration method is more suited to dissipate the high frequency content of the response. More recently, we have modified our code to accommodate explicit (which being conditionally stable requires very small time steps) method. A major advantage of the explicit time integration is that the global structural stiffness matrix need not be assembled, and hence the code can be relatively easily parallelized to run on multiple CPU's. This was done through the MPI library, whereas we used METIS for domain decomposition. It is our strong expectation that complex 3D nonlinear analysis of dam-foundation-reservoir system can most effectively be analyzed in parallel on a network of computers connected by 1 GB Ethernet network. A special purpose 2D-3D finite element mesh generator, Kumo-no-su, for concrete dams with the capability of supporting all the above features was developed, (Saouma 2007).

4 ANALYSIS

The kernel of our computational tools is the finite element code. It is a 3D nonlinear dynamic finite element code which has been under continuous development for over 12 years. Being (as all other programs) developed "in-house" we do have the source code and the flexibility to easily modify it to address new needs of the Dam Engineering profession. Merlin, (Saouma, Červenka and Reich 2006) has a library of over 25 constitutive models, 30 element types, different algorithms for nonlinear analysis (including indirect control/Line Search). In addition to stress analysis, it can also solve transient heat transfer analysis (to determine temperature field for AAR analysis), and steady state seepage analysis (to determine initial uplift pressure in complex geological formation). Implemented in Merlin are all the desirable features previously discussed, and others (such as a comprehensive model for AAR largely based on the experimental work undertaken at the Laboratoire Central des Ponts et Chausss in France).

Whereas much of the earlier emphasis was on discrete crack models, Merlin can combine localized failure (discrete cracks) with distributed failures (smeared cracks).

Not surprisingly, computational time on a Pentium IV of a 3D nonlinear analysis with dam reservoir can take well over two weeks. Hence, to address this severe constraint, an explicit version of the program was developed, and the parallelized using the MPI library (http://www-unix.mcs.anl.gov/mpi/). Hence, not only seismic analysis of a dam with reservoir could be performed in a matter of hours, but also analysis of dams subjected to impact or explosives could be possible. In turn, the preprocessor can perform domain decomposition using METIS (http://www-users.cs.umn.edu/ karypis/metis).

5 IMPORTANCE of POSTPROCESSING

Whether running a simple or complex analysis, Engineers no longer limit themselves to scrutinizing pages of output data file. Not only graphical postprocessors are essential, but those must be "jazzed-up" to satisfy the wishes of a new generation grown with electronic games. Last but not least, the Engineer should be able to "data-mine" the information needed to prepare analysis reports. This was accomplished in our case with our in-house program Spider, (Haussman and Saouma 2006). As this tool was developed by Engineers for Engineers, it truly responds to all our needs. Hence, Spider accepts input data from:

Eigenvalue analysis: display and animation of mode shapes. User selects the mode shape, and spider will display it in static mode, or through an animation. Animation can then be saved into an .AVI file.

Time History analysis: real time display of displacements and accelerations while the (very long) numerical simulation is under way. User can select in real time node and degree of freedom for which accelerations are to be displayed (histogram at the bottom, bar chart and numerical values on the top), through a graphical user interface. Furthermore, the user can select two accelerograms and seek the evaluation of the transfer function between the two signals (FFT and transfer function all being internally computed), or plot accelerations and FFT's, Fig. 11.

.AVI files showing the animation of the dam's response are also possible. Finally, Spider is also setup to read various analysis results and automatically determine the deconvoluted earthquake accelerogram which should be applied.

Nonlinear finite element analysis: Provides practically all the major and (minor) features we found in other finite element postprocessors. Aside from the usual displays of meshes, contour lines, contour surfaces, carpet plots, vector plots and principal plots, Spider provides a number of other features. Display of individual groups, possibility to slice the structure; provide different types of displays for a sliced structure, and many more options, Fig. 12. Of particular relevance to dam engineering, Spider can display contour lines for the factors of safety, surface plots of the joint stresses, displacements and uplift pressures.

It should be noted that Spider is in no way "hard-wired" to Merlin, and that it can be used as a stand-alone post-processor to other finite element codes. User has to supply a .pst file, .rtv or .eig (standard post-processor, real time view, or eigenvalue) file

6 VALIDATION

Society can no longer afford the failure of a major infrastructure before it revises its mathematical predictive models. This is particularly true for dams where increased sophistication in modeling and narrowing factors of safety (economic hardship) imposes upon us to verify the accuracy of the mathematical models through controlled laboratory testing. All model testing must satisfy Buckingham's laws of similitude; for most ordinary structures, this is seldom a concern however for dams it is. Hence, for a dam model n times smaller than the corresponding prototype, we must increase the gravitational forces by a factor of n. Furthermore, a 10 seconds earthquake hitting the prototype should be modeled by a 10/n model excitation (hence if n. is 100, that 10 sec. earthquake must be applied in 0.1 sec!).

Whereas we do not, yet, advocate the use of centrifuges to assess the safety of an actual dam, we certainly recognize the values of such a test to validate numerical models. Indeed, this may very well constitute the only safe and reliable way to verify the accuracy of a numerical code for dam engineering. Preliminary centrifuge tests of dams were performed in Boulder in the early 90's through our EPRI project. Most recently, we have examined first the development of uplift pressure beneath the dam, and assessed the accuracy of our models, Fig. 15, (Gillan, Saouma and Shimpo 2004).

Building on the experience gained from the previous test, a new test program was initiated to dynamically excite and crack impounded dams inside a centrifuge, (Uchita, Shimpo and Saouma 2005). Hence, the facility of the centrifuge facility of the Obayashi Corporation was used. A model, representative of Japanese gravity dams, was cast with a very shallow foundation, Fig. 16.

Beside strain gages, the dam was instrumented with crack gages, laser based displacement transducers, and accelerometers. Whereas no attempt was made to model uplift, the impounded dam was to be excited by a series of harmonic excitations (five cycles each), with increasing magnitudes. Following each excitation, a "white-noise" excitation is applied, and through the determination of the transfer function between base and crest, damage (cracks) was detected.

Again, the objective was not to test a particular dam, but rather to test a generic and representative geometry which could be used to assess our computer program Merlin. As with the uplift investigation, numerical prediction of crack propagation, and crest acceleration was very satisfactory, Fig. 17

7 CONCLUSIONS

Historically, Dam Engineering has constituted some of the most complex and challenging engineering problems. Hence, solutions initially developed for dams were subsequently extended to other Engineering disciplines. Furthermore, given what is at stake, we no longer can satisfy ourselves with simple engineering approaches, instead we must take advantage of the latest developments and lead the way in Civil Engineering research and development.

Nonlinear fracture mechanics plays a crucial role in the seismic safety assessment of concrete dams, it is by far the largest source of nonlinearity. Joints are present between monoliths, between the rock and the concrete and potentially in the rock foundation as joints or in the dam as cracks. Nevertheless, it should be made clear that as important as fracture mechanics is, it is only one "player" amongst many others which should also be accounted for.

8 ACKNOWLEDGMENTS

The research reported in this paper could not have been possible without the precious assistance of numerous collaborators: Prof. Brühwiler, Prof. Slowik, Dr. Puntel, and particularly Dr. Ćervenka. Their contributions is gratefully acknowledged. The extensive software development was made possible through the invaluable assistance of Mr. Takashi Shimpo and Mr. Yoshinori Yagome. Financial support for the research was made possible orginally by the Electric Power Research Institute (EPRI), and for the past seven years by the Tokyo Electric Power Company (TEPCO) through the Tokyo Electric Power Service Company (TEPSCO).

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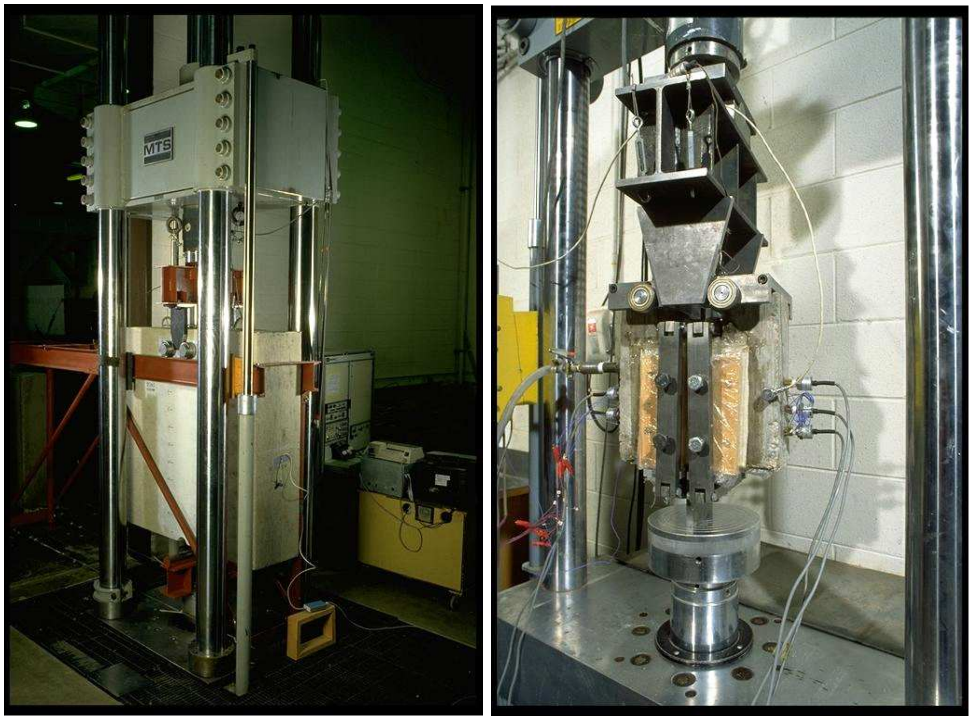

Figure 1: Large Dry and Small Wet Wedge Splitting Tests

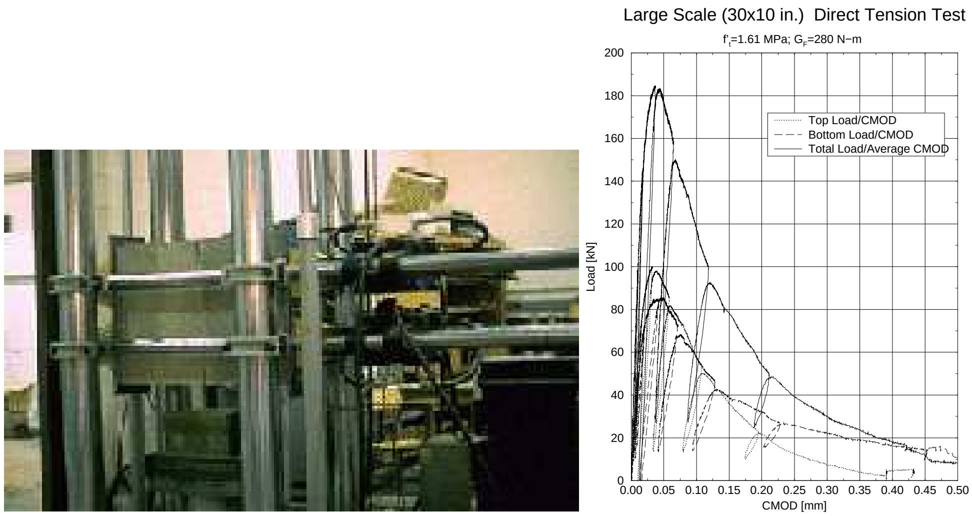

Figure 2: Large Scale Direct Tension Test

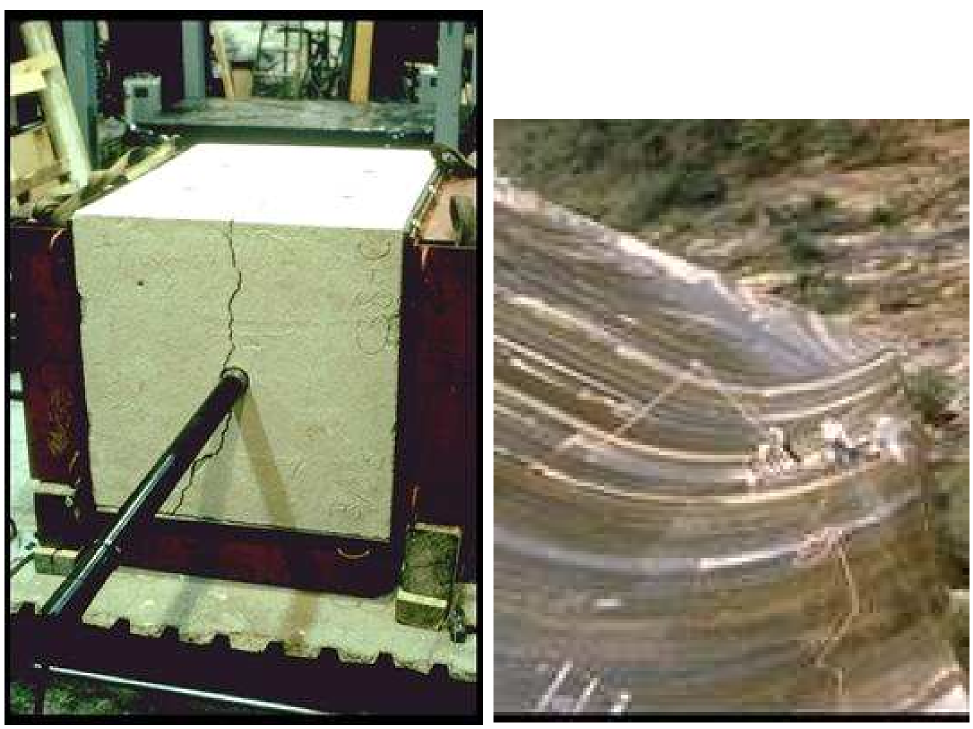

Figure 3: Use of Pressurized Probes to Determine in-situ Concrete Properties in a Dam

Figure 4: Large Scale Testing of Concrete Joints Subjected to Reverse Cyclic Loading

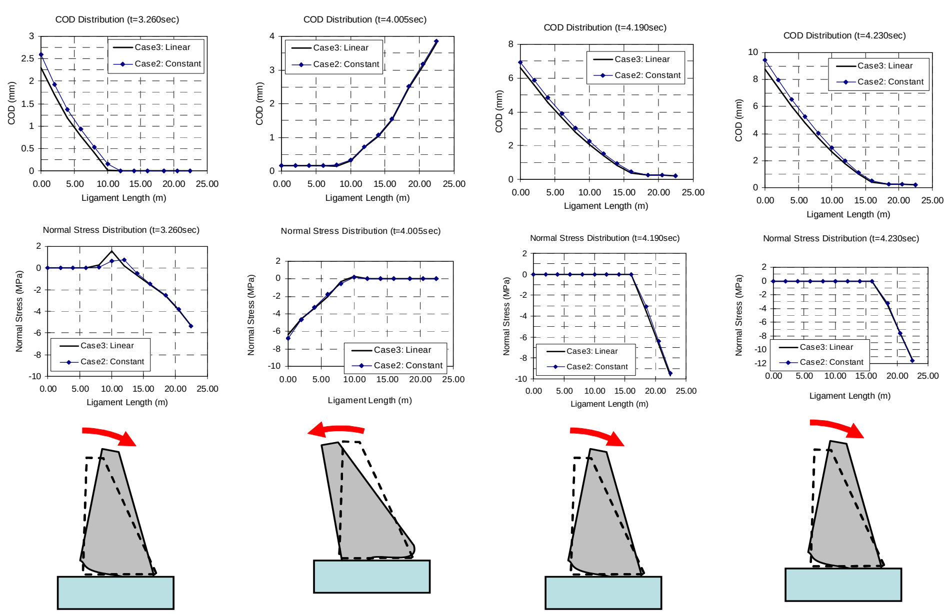

Figure 5: Special Interface Elements Simulating Cohesive Crack Joints During Seismic Excitation. Note Out of Phase Crack Opening Displacements and Cohesive Stresses

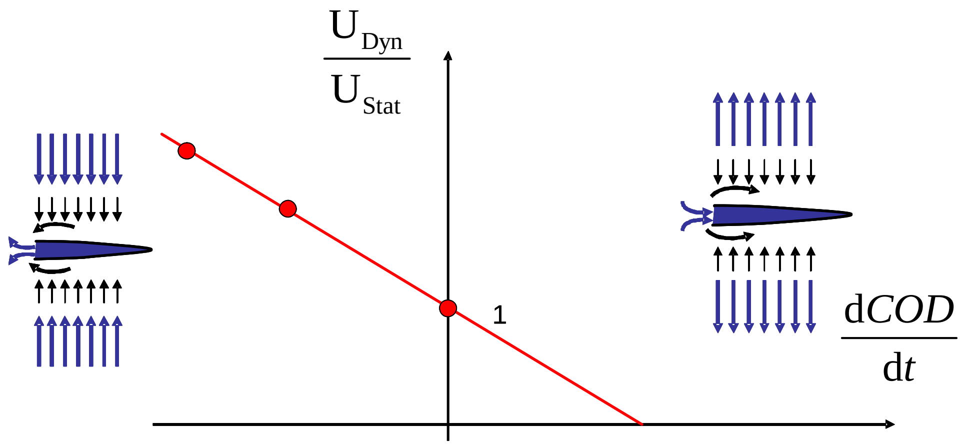

Figure 6: Dynamic Uplift in a Joint

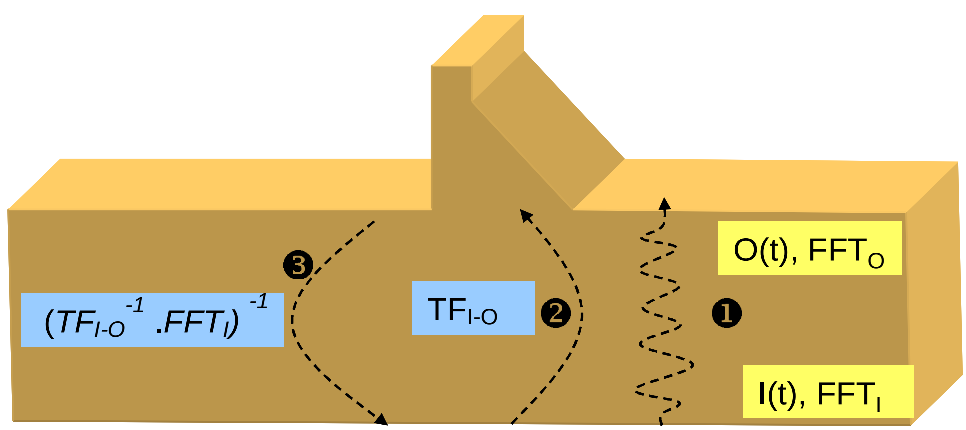

Figure 7: Deconvolution of Seismic Record

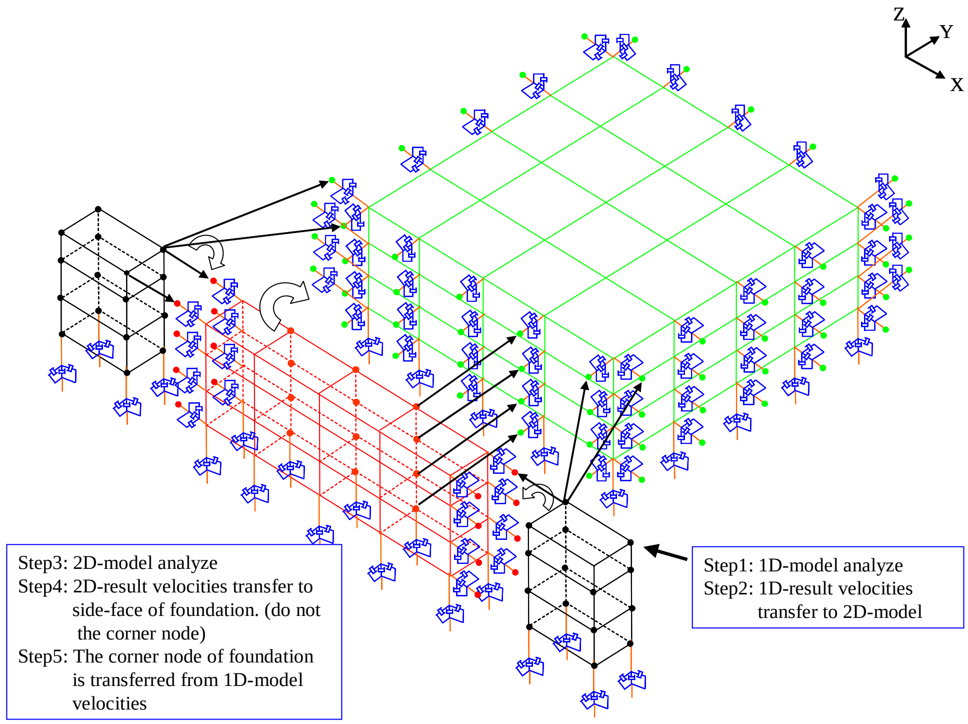

Figure 8: Finite Element Discretization of the free field; Outline of Procedure

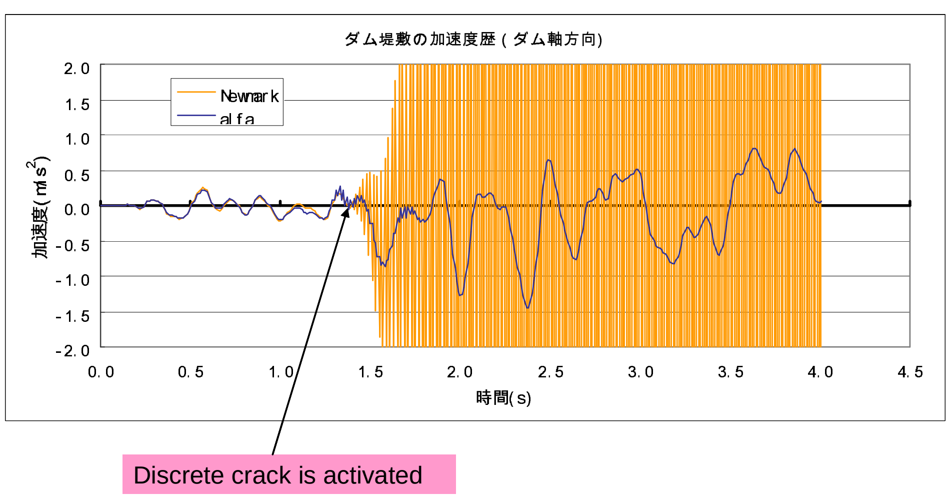

Figure 9: Effect of Time integration Scheme on Dynamic Response with Discrete Cracks

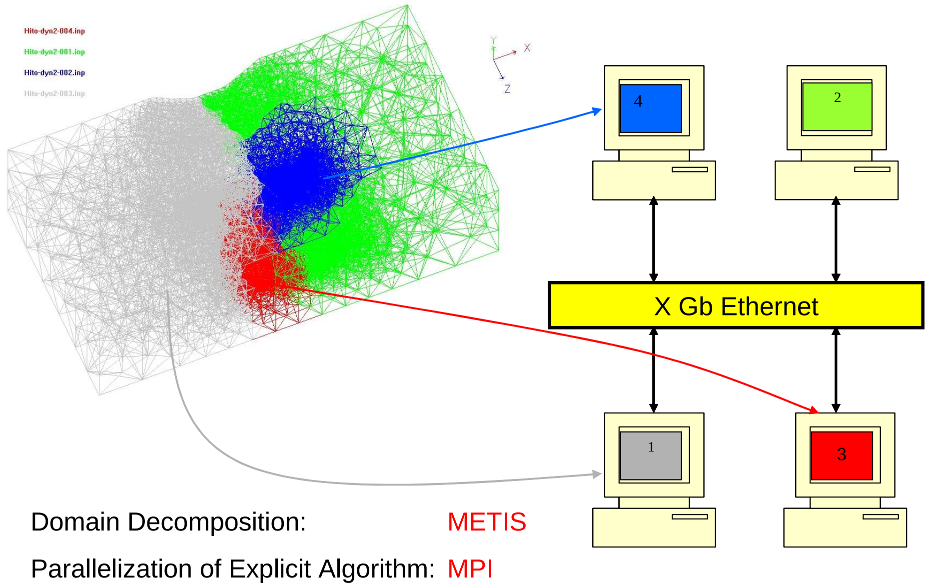

Figure 10: Explicit Distributed Computation of an Arch Dam

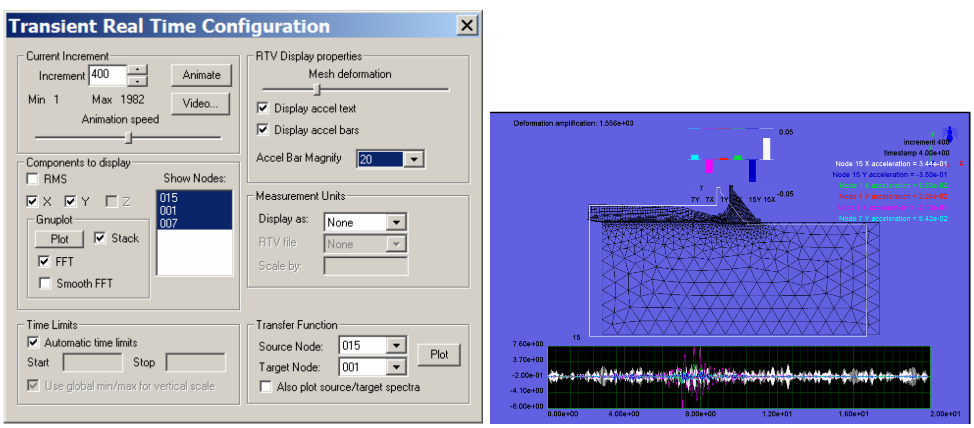

Figure 11: Real Time Display of Nonlinear Seismic Analysis of a Dam

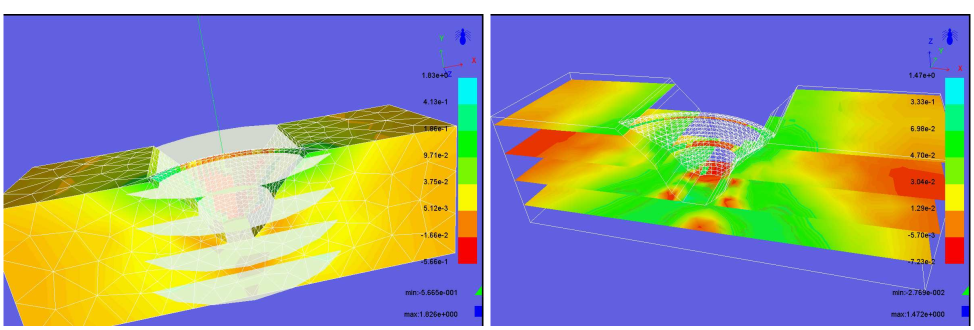

Figure 12: Postprocessing visualization

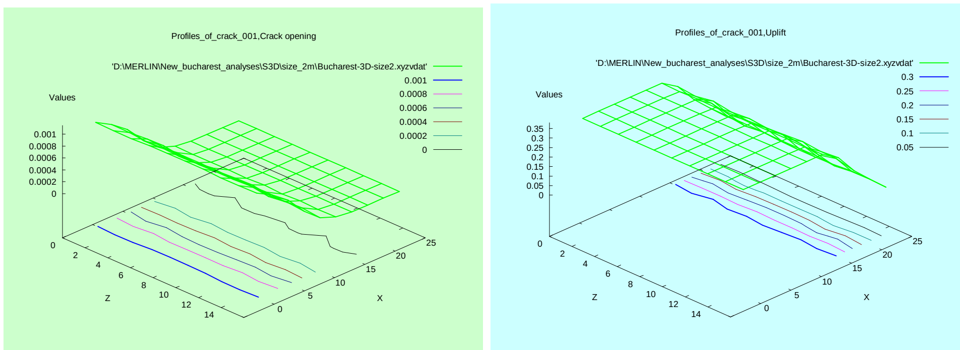

Figure 13: 3D Crack Opening Displacement Profile of a Joint, and Corresponding Nonlinear Uplift Pressures

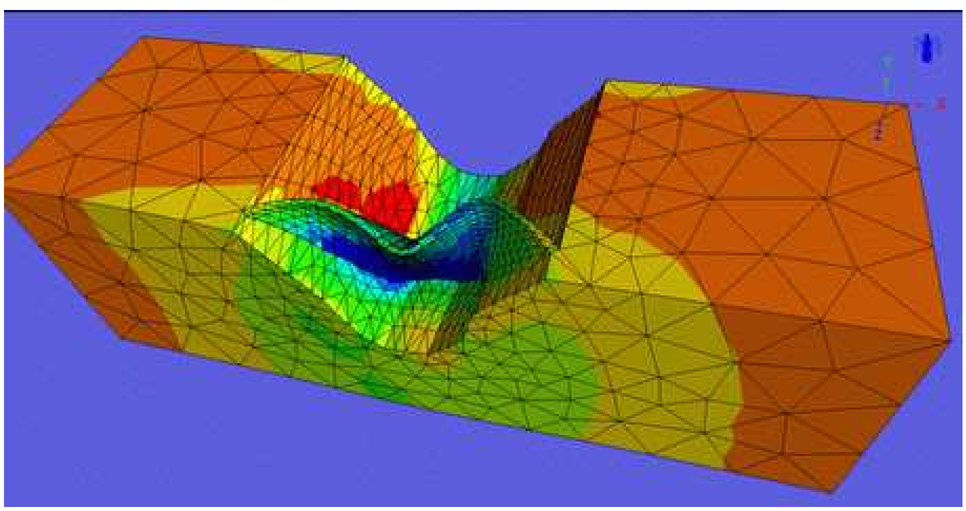

Figure 14: Example of Joint Sliding During and Earthquake

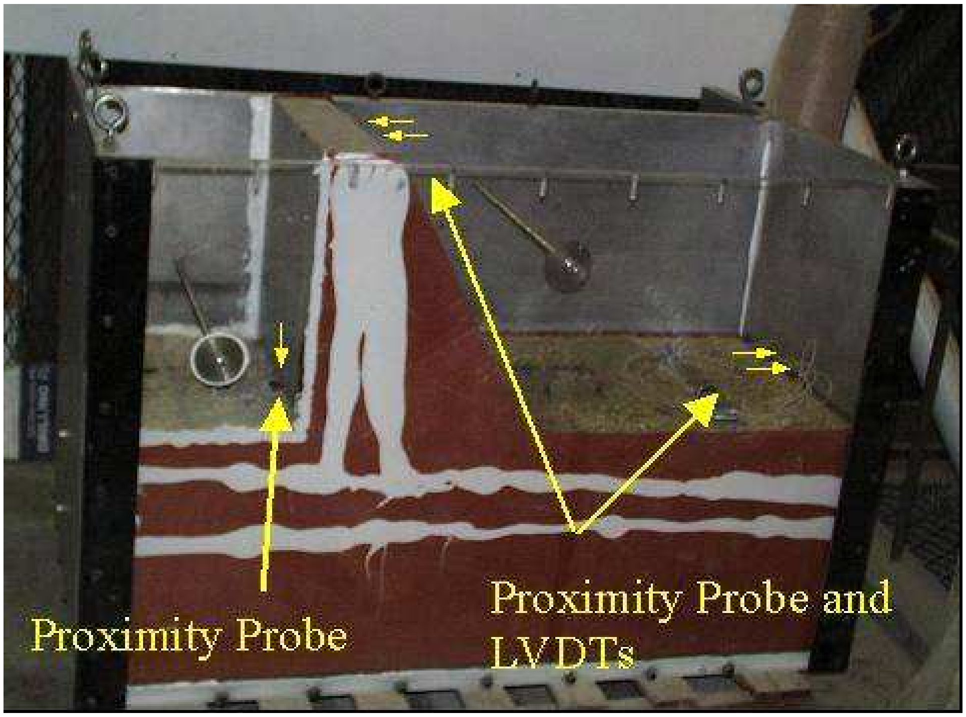

Figure 15: Aluminum container showing dam model and accompanying instrumentation

Figure 16: Centrifuge Facility at Obayashi Corporation, and Gravity Dam model

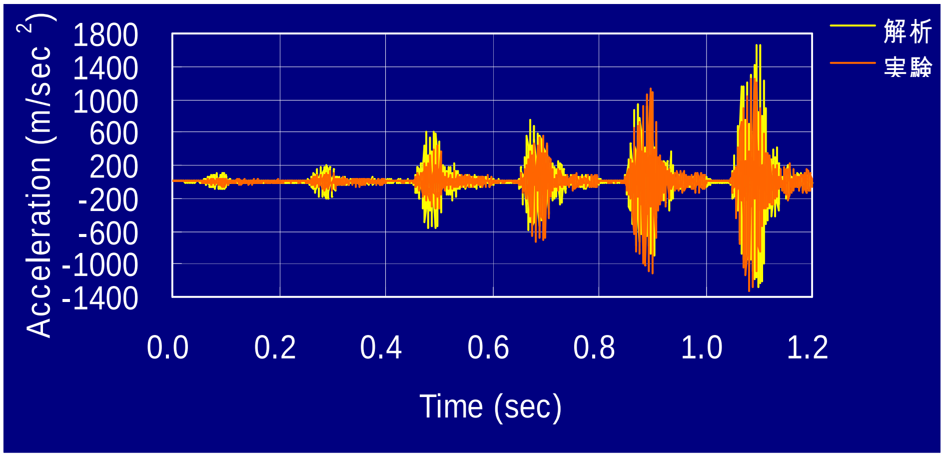

Figure 17: Crest Acceleration of Dam Model: Yellow Predictive Analysis, Orange: Experiments