Nuclear Energy Advanced Modeling and Simulation Campaign (NEAMS)

SHARP Integrated Performance and Safety Codes - Seismic- LLNL (Work Package MS-12LL060312)

Level 3 Milestone: M3MS-12LL0603125 "Gap Workshop Report"

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Introduction

This report documents a workshop held at Lawrence Livermore National Laboratory (LLNL) on February 27 and 28, 2012. The purpose of the workshop was to review the state of the art in simulation of seismic response of nuclear power plants, with emphasis on structures partially or fully embedded in the surrounding soil. The workshop reviewed current linear frequency-domain numerical methods (using the SASSI software, for example) and emerging time-domain methods, with the objective of identifying gaps in capability that could be addressed by R&D within the next 3-5 years.

The workshop was part of the Nuclear Energy Advanced Modeling and Simulation (NEAMS) Campaign of the US Department of Energy, Office of Nuclear Energy (NE-71). The work was conducted within LLNL Work Package MS-12LL060312, "*SHARP Integrated Performance and Safety Codes - Seismic- LLNL*" and Lawrence Berkeley National Laboratory (LBNL) Work Package MS-12LB060313, "*SHARP Integrated Performance and Safety Codes - Seismic- LBNL*". This deliverable is LLNL Level 3 Milestone: M3MS-12LL0603125, "*Gap Workshop Report*". In the DOE-NE electronic project management system, PICS-NE, the milestone description reads: "*Workshop report summarizes the major workshop outcomes, identifies gaps between SASSI and 3D time domain approaches and path forward.*" The milestone/activity at LLNL is a QRL3 activity. Independent technical review was performed by Cynthia Atkins-Duffin of LLNL, and is documented electronically in the LLNL Information Management (IM) System. In the LBNL work package, this work was conducted under Level 3 Milestone/Activity M3MS-12LB0603135, "*Conduct Workshop and Draft Summary Report*", a QRL: N/A activity.

The workshop was attended by three groups of people: an eight-member expert panel, the LLNL/LBNL project team, and management representatives from DOE and the NEAMS Campaign. The eight experts included very senior current practitioners of frequency-domain methods as well as developers and users of emerging time-domain methods. The following is the list of experts:

- Jacobo Bielak
- Justin Coleman
- Carl Costantino
- Robert Kennedy
- Stephen Mahin
- Farhang Ostadan
- John Stevenson
- Andrew Whittaker

A complete list of attendees and their contact information, including the project team and the DOE and Campaign managers, is included in Appendix 1. That appendix also includes short biographical sketches of the eight experts.

Information Provided to the Experts Prior to the Workshop

The project team provided information, incrementally, to the experts during the month prior to the workshop. This allowed them to become familiar with the project and to gather information for the discussions at the workshop.

First Set of Information

A. INVITEES

The Workshop's expert invitees are:

- Jacobo Bielak
- Justin Coleman
- Carl Costantino
- Bob Kennedy
- Stephen Mahin
- Farhang Ostadan
- John Stevenson
- Andrew Whittaker

B. OTHER WORKSHOP PARTICIPANTS AND OBSERVERS

Bob Budnitz of LBNL will chair the Workshop itself, with the task mainly of keeping things focused and on-track, and assuring that the discussions provide, in the end, what the organizers seek. He will be assisted in this by Jim Blink of LLNL who will also take detailed notes.

Other participants and observers at the workshop will include:

LLNL: Dave McCallen, Steve Bohlen, Quazi Hossain, Jerome Solberg, Mike Gerhard, Harris Greenberg, and Randy Settgast

LBNL: Jens Birkholzer, Larry Hutchings and Boris Jeremic (Boris is from UC-Davis with a joint appointment at LBNL)

DOE: Rob Versluis, DOE-NE

ANL: Keith Bradley and Dave Pointer (managers of the DOE NEAMS Program -- NEAMS stands for "Nuclear Energy Advanced Modeling And Simulation")

The LLNL and LBNL participants will play a major role in the discussions, of course, because the ongoing DOE-NE-sponsored project, being carried out by this team, is the focus here.

C. BACKGROUND FROM THE INVITATION LETTER

The following, taken from the invitation letter to each participant, provides a start on the background everyone will need.

LLNL and LBNL invite you to participate as an expert in a gap-identification workshop in support of DOE-NE's Nuclear Energy Advanced Modeling and Simulation (NEAMS) program. The workshop is focusing on seismic response of reactor structures.

OBJECTIVE of the NEAMS-SEISMIC Work: The overall objective can be stated in laymen's terms as aiming to evaluate a potential suite of integrated capabilities for the analysis of the response to earthquakes of below-grade advanced nuclear power plants that represent a substantial advance over current capabilities. The approach is to use advanced modeling and simulation tools, advanced understanding of the substance itself (how these structures respond and how the subsurface behaves as earthquake energy moves through it into the structure), and the latest real-world data on earthquakes and their effects. The advanced analysis capability should be capable of analysis starting with the incoming near-field seismic motion and ending up with the responses at specific locations in the structure, and including everything in between. Modeling from the source to the near field will receive less emphasis in the initial phase of work.

NATURE OF THE DOE-NE DELIVERABLES: A crucial point about the "deliverables" that will ultimately result from this DOE-NE project is that they are intended to be analysis tools and data to be designated as "open source", available to all. They are intended for use by designers and vendors of new reactors, the technical support of whom is one of the main roles of DOE-NE in this area, but they can be used also by independent bodies desiring the ability to do the advanced analyses that the "deliverables" will make feasible, or by regulatory bodies both domestically and abroad.

OBJECTIVE OF THE "GAP" WORKSHOP:

The "Gap" Workshop's objective is as follows:

Based on a consideration of the current state-of-the-art capability of the relevant analysis tools and data, to identify those "gaps" that, if closed through a dedicated R&D effort, can provide a substantially enhanced capability.

D. THE TECHNICAL SCOPE

The technical scope, as outlined above, covers the capabilities for *analysis of the response to earthquakes of below-grade advanced nuclear power plants.* This scope has many sub-parts, not all of which will be covered in detail in this Workshop. Specifically, the analysis capability must begin with a description of the incoming earthquake energy. We assume for these purposes that the earthquake originates in the "far field," far enough away from the reactor site that we are not here concerned with characterizing the source itself, nor the propagation and attenuation from the source to the near-field environment. Thus the incoming earthquake energy, etc., are a "given" as input for the purposes of our problem definition.

We wish to begin the scope of the Workshop's deliberations at the point in the "near field" where there starts to be an effect because the power-plant structure is present at the site. Hence

near-field effects – not just soil-structure-interactions (SSI) but also other near field effects – are within the scope here. The scope then extends to how the seismic energy passes through the subsurface into the engineered structure, and ultimately to the responses of the individual structural elements (foundations, walls, floors, etc.) that affect the ability of each safety-related structure or component in the power plant to perform its safety function.

We intend to structure the Workshop in a series of technical "modules". For each "module", the LLNL-LBNL team will begin with a short presentation to present what our team believes to be the current "state of the art," sometimes accompanied by a discussion of what our team thinks may be feasible to develop through advanced R&D over the 3-5 year time frame of interest. Then, the Workshop experts will be asked to discuss the issue(s), and to opine with their own views on what is feasible, and what is not, and why. The agenda will then move on to the next topic or "module."

During the Workshop, but especially during the experts' feedback on the second day, we expect that some input will be developed by the experts on overarching or cross-cutting questions that would be helpful to us and to our DOE sponsors. Furthermore, since the idea behind it all is a "suite of integrated capabilities" for the whole problem, we want the experts to focus some of their thinking on that topic and how it might be approached.

The context of all of this discussion is, as a reminder, the analysis of *below-grade nuclear power plants*. We interpret this to mean facilities that are entirely, or almost entirely, below grade – in contrast to facilities that are partially embedded but with substantial mass and structure above grade. We have a flexible scope here, and could include facilities in which significant parts of the major structures are wholly or mostly embedded but perhaps other parts are at the surface.

We contemplate here both large nuclear facilities of a size typical of today's LWRs, and also much smaller ones like the "small modular reactors" now being designed by several different groups around the world.

We are not specifically discussing base-isolated designs, but those are not out-of-scope either.

The technical "modules" that we are considering now (but we're still working on this breakdown) are five in number:

- characterizing the input seismic energy and motion in a way that facilitates the rest of the advanced analysis under discussion;
- analysis of the subsurface in the region where the effect of the engineered facility is significant;
- analysis of how the seismic energy enters the building, either through the foundation or through the "walls" of a completely embedded structure that might look somewhat like a cylindrical missile silo;
- analysis of propagation within the structure to "floors" or other locations where safety-important equipment is located;
- analysis of the "floor spectra" themselves at the locations of critical equipment.

A realistic description: We have in mind throughout that we are seeking a realistic description, or at least a description that approaches "realism" to the extent feasible. This typically means using a *probabilistic framework*, in order to capture the analyst's "state of knowledge", including both the aleatory and the epistemic components of the overall uncertainty. For some problems, this realistic description may be beyond us, but we do wish to seek a realistic description as our end-point, and that means seeking a realistic description of the variability and uncertainty too.

In summary, we are asking our Workshop experts to opine on this set of questions, area by area, in order to help us and DOE understand what might be done to advance things in the next 3-5 years, and why, and what is perhaps still beyond us now, and why.

E. DEFINING SOME TERMS

The Workshop's objective statement (above) uses three terms that need to be defined. They are "gap," "the current state of the art capability," and "if closed through R&D."

"Gap": As we think about the term "gap," for this Workshop we want it to mean the difference between today's capabilities and the capabilities that are feasible to develop through focused R&D over the next "few" years (say 3-5 years.) We are aware, of course, that the terms "today's capabilities" and "feasible in the next few years" can have a number of interpretations, which are discussed below.

We are concentrating on the "next few years" because a major thrust of this Workshop is to provide guidance to DOE-NE about what they might support in the way of R&D -- or indeed, whether they should support anything at all.

"Current state of the art capability": The term "current state of the art capability" could mean any of several things. For example, consider SSI. For analysis of SSI, the current capability means SASSI or something similar if one talks about the capability currently in the hands of analysts doing routine SSI analyses in the commercial engineering world. But we all know that more advanced capabilities now exist, that can handle different SSI problems or handle SASSI's problems with better fidelity, albeit not routinely used commercially. And it is those advanced capabilities that are both the jumping off point for even further development, and also the basis for some needed work before they themselves are ready for routine commercial use. This difference is why we need to decide what we mean by "current capability."

Likewise, we need to decide what we mean by the "enhanced capabilities" that we want the Workshop to help identify. Is the end-point something that is fully ready for widespread use in the commercial world? Or is it something short of that, say something that is technically entirely sound, verified and validated, but still short of being ready for commercial widespread use? Or even something short of that?

The issue comes down to "gaps between what and what?"

The Workshop organizers have decided that the focus of this Workshop needs to be on the gaps between today's advanced capabilities and the even more advanced capabilities that it is believed are ripe now for development and demonstration. However, the experts will also be asked to opine on the differences between today's advanced capabilities and current licensing practice, as a method to define more fully what today's advanced capabilities are.

As a corollary, we will not be asking the Workshop experts to think about end points that would be fully ready for routine use in the commercial world in the 3-5 year time frame -- rather, we're seeking to identify end points that could be fully technically sound in that time frame (with adequate R&D funding support), even if short of being commercially "ready," which could take a few more years.

Gaps that could be "closed … through R&D": The phrase "closed ... through R&D" is then taken to mean that the R&D at issue would have as its end point the technical demonstration of the analytical capability being worked on. This technical demonstration would need to be sufficient that there is little or no argument about the technical validity of the analytical approach being taken, for the scope that it claims to cover. Again, there could still be "a ways to go" before this capability could be placed in the hands of routine commercial practitioners at the bench. Indeed, we all know of some advanced analytical approaches that, although in wide use for many years by experts, are still not ready for widespread ordinary use – and for some of them, they perhaps never will be. That is acceptable, and on a case-by-case basis, it could be sufficient.

Specifically, if a sophisticated nuclear power reactor vendor or their utility customer can use the method, and if a sophisticated NRC analyst-reviewer can also use it or review it and affirm its appropriateness for the regulatory need at issue, that may be acceptable. (There are certainly cases like that in today's normal safety analysis practice and NRC regulatory review practice.)

F. THE WORKSHOP REPORT

Our plan is that the LLNL-LBNL workshop leaders will develop a draft of the Workshop report based on our own notes, and that this will be circulated to the outside experts for their review and endorsement. Only after the experts endorse the report will it be finalized. To the extent that there is a consensus of the experts on any topic, that's great. However, if differences of view emerge, we want the report to capture those differences, and if this means that one or more of the experts desires to write up his own personal views on a topic, we'll include those too. In other words, there will be no forced consensus.

Finally, we intend that the Workshop report will be a public document.

Second Set of Information: Questions for Thought

Advancing Simulation Capabilities for Nuclear Power Plant Seismic Response
Topics for the February 27-28 workshop at the Lawrence Livermore National Laboratory

Since the main era of design-build of the United States nuclear energy enterprise, there have been tremendous advancements in computational methods. These advancements have been across the spectrum including computational platforms, advanced algorithms, and more realistic phenomenological models. Many fields have heavily exploited these developments to transform the engineering analysis and design process (commercial aerospace, transportation systems, advanced weapons design, etc.). The nuclear power industry, as a result of 30 years of design-build quiescence, has not experienced a corresponding level of investment in simulation modernization. With renewed interest in nuclear energy providing a key component of the world's safe, clean and reliable energy base, and the emergence of new classes of reactor

technologies (e.g. Gen IV systems and Small Modular Reactors), there is strong motivation to explore the potential benefits (safety, economic, operational) of advanced simulations of nuclear power systems. The U.S. Department of Energy, a traditional leader in the advancement of simulation science and engineering, has undertaken a new project to explore the application of high performance computing to nuclear energy systems with a focus on the crucial issue of seismic safety. The pending workshop is bringing together an eminent group of subject matter experts to assist in critical thinking about the appropriate path forward, and to advise on the key opportunities for major benefit as well as the gaps and challenges to achieving a major improvement in simulation capabilities. Specific focus topics of the workshop are summarized below.

What methods and capabilities would be desirable for full characterization and modeling of the seismic response of nuclear power plants, and associated seismic safety analysis?

Discussion of the appropriate computational framework for advanced plant simulations including:

- The potential for more realistic models of plant/soil systems that capture the fully nonlinear (as opposed to traditional "equivalent linear") time-varying effects of soil system nonlinearities
- The ability to accurately simulate plant system response to beyond-design-basis events where nonlinear structural behavior may result, as an enabler to robust performance-based design
- A computational framework which can expand the possibilities of plant design space, including exploitation of emerging technologies, e.g. base isolation, composite concrete walls, energy dissipation devices, etc.
- Clear delineation of model discretization/fidelity required to adequately capture the full bandwidth of frequency response of nuclear power systems
- The ability to exploit the vast modern capabilities in efficient and powerful pre- and post-processing tools to create and validate system models, and capture/display/visualize computational data in a manner that enhances understanding
- Exploit modern methods of uncertainty quantification and probabilistic mechanics to quantify computational uncertainties
- Capture of complicating phenomena which may occur in real systems, such as wall/soil separation and foundation uplift
- The importance of characterizing the three-dimensional seismic wave field input motions which are representative of complex, multi-waveform seismic ground motions at a particular site

- Technological gaps or limitations which could threaten the full realization of an advanced simulation framework, e.g. limitations in existing phenomenological soil models, limited understanding and representation of damping mechanisms and distribution in a coupled nonlinear soil/structure system, etc.

How can advanced capabilities make a difference for plant designs, both in terms of fundamental understanding, and in NRC regulatory processes, and what barriers to use/implementation might exist?

Including discussion of:

- How advanced capabilities, which potentially relax historical idealizations embedded in current simulation methods, could reduce uncertainties and advance our understanding of seismic performance of nuclear power systems
- How advanced capabilities could improve/enhance the regulatory process
- Specific economic/safety/operational benefits which could be enabled and realized through advanced simulation approaches and tools
- Advanced computational approaches are only an enabling tool and must "fit" into a design standard or code guidance framework. Some standards (e.g. DOE Standard 1020) already have provisions for admission of nonlinear methods in the design and analysis of nuclear systems. NRC standards, on the other hand (e.g. Reg Guide 1.208), currently limit plant response to linear-elastic behavior. What barriers might exist to full implementation and exploitation of advanced simulation approaches?
- What parallel companion activities might be necessary to realize the full potential of advanced seismic simulation methods (e.g. ASCE 43 Code Committee work)?

Workshop Organization and Process

The workshop agenda, covering a full first day and half of a second day, is in Figure 1. The workshop "secretariat" consisted of James Blink (LLNL) and Robert Budnitz (LBNL), with the former focusing on logistics and documenting the discussion and the latter moderating and guiding the discussion. Appendix 1 shows the list of attendees as well as short biographies of the eight experts.

The workshop began with brief introductory presentations by the project Principal Investigator, Steven Bohlen (LLNL), who laid out the workshop's objectives, and Robert Versluis (DOE-NE-71), who provided DOE's perspectives about the workshop scope and how the results would be used. Steven Bohlen's slides are included in Appendix 2. These brief introductions were followed by three extensive technical presentations by members of the LLNL-LBNL project team (David McCallen, Boris Jeremic, and Lawrence Hutchings). The slides used by these three team members are included in Appendix 2. Each of the three technical presentations was accompanied by discussion during the presentation, followed by additional discussion following the presentation. Contributions to these discussions arose not only from the eight invited experts, but also from the other attendees. These presentations and the discussions surrounding them consumed most of the first morning.

After these presentations and discussions, shorter presentations were made by four of the experts (Andrew Whittaker, Justin Coleman, Stephen Mahin, and Jacobo Bielak). The slides or text for these presentations are included in Appendix 2. In addition, Stephen Mahin spoke extemporaneously without slides. In general, these presentations informed the project team about related current and past work at their institutions, including a brief description by Jacobo Bielak of the Domain Reduction Method (DRM), a time-domain methodology for modeling structure-soil-structure interaction in heterogeneous soil-structure systems subjected to a prescribed near-field earthquake ground motion environment.

The workshop then continued with broad group discussion, participated in by both the eight experts and the other attendees, to address the main issue before the group, namely to agree as to *the identification of the "gaps" in current capability* and *proposals to address each of those "gaps" through R&D*. While some of the discussion inevitably touched on suggestions as to the relative priorities of the various gaps or of the proposed R&D, the focus in this session was more on identifying outstanding issues rather than on assigning priorities. This group discussion consumed most of the first afternoon's time.

The eight experts and almost all of the team members (including the DOE Manager and the NEAMS Campaign managers) continued their discussions during a dinner at a local restaurant. Stephen Mahin, one of the eight experts, was kind enough to present slides on some of his current work, which seeks to extend seismic response design beyond saving lives to using structures that are resilient enough to allow rapid and inexpensive reoccupancy following major seismic events.

Figure 1: Workshop Agenda

AGENDA
LLNL-LBNL SEISMIC-GAP WORKSHOP ON 27-28 FEBRUARY, 2012

A. INVITEES: The Workshop's expert invitees are:

Jacobo Bielak	Steve Mahin
Justin Coleman	Farhang Ostadan
Carl Costantino	John Stevenson
Bob Kennedy	Andrew Whittaker

B. OTHER WORKSHOP PARTICIPANTS AND OBSERVERS

LLNL: Jim Blink, Dave McCallen, Steve Bohlen, Quazi Hossain, Jerome Solberg, Mike Gerhard, and Randy Settgast
LBNL: Bob Budnitz, Jens Birkholzer, Larry Hutchings and Boris Jeremic (Boris is from UC-Davis with a joint appointment at LBNL)
DOE: Rob Versluis, DOE-NE
ANL: Keith Bradley and Dave Pointer (managers of the DOE "Nuclear Energy Advanced Modeling And Simulation" Program)

Monday, 27 February 2012

9:00 am	Introduction – logistics etc. (J. Blink, LLNL)
9:05 am	Introduction to Workshop: goals, expectations (S. Bohlen, LLNL)
9:20 am	DOE expectations and perspective (R. Versluis, DOE)
9:35 am	Introduction: workshop format and process (R. Budnitz, LBNL)
9:40 am	Introduction to the broad technical topic (D. McCallen, LLNL)
10:10 am	Discussion
10:30 am	break
10:45 am	Topics in SSI linkage to broader issues (B. Jeremic, LBNL & UC-D)
11:15 am	Discussion
11:45 am	Topics in seismic source physics (L. Hutchings, LBNL)
Noon	Discussion
12:30 pm	Lunch break, Pizza provided by Jim and Steve
1:15 pm	Open discussion
4:45 pm	Recap, discussion about tomorrow's agenda
5:00 pm	Adjourn
6:00 pm	Dinner, Zephyr, Downtown Livermore (Steve Mahin, Speaker)

Tuesday, 28 February 2012

9:00 am	Experts meet in executive session
TBD	Reconvene with other attendees: feedback, discussion, report-out
Noon	Adjourn

The second day began with an extensive executive session of the eight invited experts. At the experts' request, four LLNL-LBNL team members (James Blink, Steven Bohlen, Robert Budnitz, and David McCallen), attended to document the deliberations and prepare for a report-out session to the full group. This session focused on prioritization, and specifically on developing a *prioritized list of "gaps"* and *proposals for R&D to address each gap*. This prioritized list and these R&D proposals were captured in slides to be used in discussions with the full group during the "report-out" session.

This executive session was followed by a final "report out" session attended by the experts, the DOE representatives, and the full LLNL-LBNL project team. This report-out session resulted in some modifications to the way the prioritized list of gaps had been explained in the earlier slides; the modifications were mostly in the nature of more complete explanations of some of the ideas, so as to assure that ambiguities were minimized and that the R&D path forward was clear to the DOE and project team attendees. The information in the modified slides has been used to produce the next section of this report, on the *Conclusions of the Experts*.

Conclusions of the Experts

As noted above, the major "deliverable" or "results" of this workshop are that *the eight experts developed both their list of gaps* and also *their recommendations for the R&D necessary to close each of the gaps*. The focus was on R&D that the experts judged to be feasible over a 3-5 year period. The R&D recommendations attempted to account for work underway in the broad (international) community, rather than restricting it in any geographical or institutional way. Also, the experts did not specifically express where or by whom their recommendations for R&D could be carried out. It was sufficient, in their minds, that the R&D be judged to be fully feasible, within the near future, by organizations and individuals with state-of-the-art knowledge relative to linear and non-linear geometries and material behavior subjected to dynamic cyclic loads applied to a finite element solution in the time domain. It was also noted that any resultant analytical tasks developed should be executable by knowledgeable structural design and analysis organizations or individuals.

There was some limited discussion of the ongoing work now underway as part of this DOE-NEAMS work package. It was recognized that the current work package comprises some of the initial steps in executing the 3-5 year effort; the LLNL-LBNL team in turn noted that the expert recommendations were largely consistent with the planning documented in PICS-NE for this work package, although the planning is clearly neither as extensive nor as detailed, and only includes work in this fiscal year.

The experts concluded that six areas of R&D work are to be recommended. The experts determined that two of the areas are of high priority, and that important parts of these two could be executed in parallel.

- Nonlinearities Associated with the Interface of the Structure and Soil
- Arbitrary, Spatially-Distributed, Wave Fields

The work scope of this work package is aligned with those areas, and will begin exploring the parameter space outlined by the experts for these areas.

The other four areas that the experts recommended for R&D can also be worked on in parallel with each other, but are largely not within the current scope of this work package.

- Nonlinear Hysteretic Models of Structural Elements
- Seismic Isolators
- Nonlinear Soil
- Internal Fluid-Structure Interaction

In addition to these six areas, another area was discussed extensively during the Workshop but was not explicitly recommended by the experts, in part because the topic was somewhat out-of-scope. This topic is:

- Methods for Developing Realistic Three-component, Time-domain "Records" from a Scattered Wave field, as Input to Soil Models.

Although the topic was outside the Workshop's narrow scope, there was a sentiment expressed during the Workshop that ultimately this type of modeling work on the input motions to the soils model will be an important constituent of the long-sought realistic numerical model of the entire "system". More discussion of this topic is included in Appendix 2, just prior to the presentation slides of Lawrence Hutchings.

First Top-Priority Task: Nonlinearities Associated with the Interface between the Structure and the Soil

One of the two high priority tasks is to develop time-domain analysis methods and then software to handle local nonlinearities associated with the interface of the soil and the structure (geometric non-linearity). These nonlinearities include the following:

- Local high compression stresses in the area of interface between the soil and structure (localized soil nonlinearities are the results of these high stresses)
- Slip due to shear forces
- Gaps due to inability to transfer tension
- Buoyancy effects for embedded structures.

This high-priority task should begin by comparing a linear finite element algorithm in the time domain to SASSI[1] results. This comparison analysis should assume both linear or elastic geometric and material soil and building properties. It should also strive to develop an explanation of any differences in results between the time domain results and the SASSI results. This comparison should be performed for three levels of excitation; 0.3 g, 0.5 g and 1.0 g peak ground accelerations.

The experts emphasized that the software resulting from this task should not omit any existing SASSI capability. For example, when seismic waves reflecting from the structure encounter the boundaries of the SASSI calculation, these waves do not reflect back toward the structure; the time-domain software should have similar characteristics for its domain boundaries at the sides and the bottom.

The experts recommended that the software be developed in an incremental fashion. The first calculation is intended to be a verification of the time-domain method. It would be comparable to a SASSI calculation if it uses a structure that is "glued" to an (equivalent) linear soil model, with the seismic wave being a vertically-propagating, horizontally-polarized, shear wave. The

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[1] Original reference: Lysmer, J., et al., "SASSI - A System for Analysis of Soil-Structure Interaction," Report No. UCB.'GT/81-02, Geotechnical Engineering, University of California, Berkeley, 1981.
Latest UC Reference: Lysmer, J., et al., "SASSI2000 -Theoretical Manual," Revision 1, Geotechnical Engineering, University of California, Berkeley, 1999.
Other References: The code has been adopted by several private companies, resulting in proprietary versions that use the same algorithms but work on modern PC software.

"glued" interface will prevent sliding and gaps that cannot be calculated by SASSI, and hence are undesirable in a verification calculation against an alternative code. The model should calculate in-structure response spectra at several locations, and should be compared with SASSI results at several ground motion amplitudes. The experts advised doing the initial calculation with a half-space (homogeneous) soil, and then proceeding to a layered soil structure. It was noted that previous efforts in this area have taught the community that care must be taken in areas such as damping in order that a time-domain model can successfully reproduce SASSI results.

It is important that the coupling between the two horizontal directions and the vertical direction during the sliding and gapping is maintained. Some programs can handle the sliding and gapping, but with no consideration for coupling, making the results less decisive

Once the time-domain model is verified to reproduce SASSI results[2], the suite of calculations (at several ground motion amplitudes and for single and multiple soil layers) should be repeated including, incrementally, the above nonlinearities.

The experts discussed the buoyancy nonlinearity that arises when a structure is embedded, even partially, below the water table. The frictional force preventing slipping of the structure along the soil interface (for a shallowly-embedded structure) is the coefficient of friction times the normal force, and the normal force is the downward weight of the structure less the upward buoyancy of the wet soil material displaced by the structure. For a structure with a considerable "empty" volume, the buoyancy can be a significant fraction of the weight, and thus can lead to possible slipping in a simple calculation. However, it needs to be realized that the fluid in the soil cannot support shear stress, and hence a realistic model that accounts for potential slipping must account for the soil deformation rather than treating the structure and soil as two rigid bodies that slip against each other.

For buoyancy effects, it is important to separate the issue of pore pressure and liquefaction from buoyancy and vertical inertia forces. The latter is more relevant to nuclear structures, and for some designs this has become a barrier. The current design approach is a simple hand calculation of static buoyancy force less vertical inertia. This is overly conservative given the short duration of peak accelerations. A rigorous 3D time domain analysis will permit uplift and should provide a more realistic estimate of uplift even if the current hand calculations show a factor of safety less than unity.

Second Top-Priority Task: Arbitrary, Spatially-Distributed, Wave Fields

The second of the two high priority tasks is to develop time-domain analysis methods and then software to handle fully three-dimensional incident wave fields that are produced from measurements or from models of propagation of seismic waves from a seismic source such as a fault rupture. These wave fields can be spatially distributed at the model boundaries, with

[2] Some of the experts noted that reproducing SASSI results with a time-domain model could be difficult

varying phase and amplitudes from point to point. As in the other top priority task, the work should be incremental. SASSI can calculate response to planar waves at various inclination angles to the vertical[3] as well as response to surface waves, and the time-domain model should be run to compare with SASSI results.

The effort should start with free-field motion without any structure present. The free-field motion must be carefully examined to evaluate the contents of the wave field frequency-by-frequency, and the coherency of the motion point-by-point. Both uniform and layered sites must be considered. Without a rigorous assessment of the wave field in the free-field, any study of the effect on the structure may become too complex to understand.

As for the other high priority task, the model should calculate in-structure response spectra at several locations, and should be compared with SASSI results at several ground motion amplitudes. The experts advised doing the initial calculations with a half-space (homogeneous) soil, and then proceeding to a layered soil structure.

A logical follow-on to the two top priority tasks is a series of calculations with the time-domain approach, which would include nonlinear soil-structure behavior, local heterogeneities, and spatially-distributed wave fields. The results could then be compared to the corresponding SASSI results in order to determine the practical significance of these effects, which cannot be captured by SASSI[4].

Other Important Task: Nonlinear Hysteretic Models of Structural Elements

Advanced design features associated with advanced light water reactors (LWRs) and small modular reactors (SMRs) can improve design margin and result in lower cost systems. An important recent example is a steel-concrete (SC) wall in which concrete is placed between two steel plates with multiple tie bars. Other features worthy of additional study include low-rise shear walls and braced frames used in traditional construction. The performance of these features can sometimes be non-linear, and the time-domain approach is thus well suited to analyze their performance. Current SASSI capabilities allow only for linear elastic analyses to be performed.

In discussing these advanced design features, the experts noted that a) recent experience with SC walls reveals that the confinement of the concrete during the elevated temperature curing time, followed by shrinkage as the concrete cools, results in cracked concrete that has less of a stiffness change during the cyclic loading of a seismic event, and b) recent tests of low-rise reinforced concrete (RC) walls have generated data different than that predicted with advanced models and computer codes.

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[3] The experts noted that inclined plane wave calculations will be useful, but that the users of the models should be aware that actual seismic wave fields are very complex

[4] The experts noted that the challenge will be to determine the correct answer to compare to the two model results

The work in this task involves developing realistic constitutive models, benchmarked with appropriate data, which can capture the behavior of these structural elements during earthquakes. There is a need for understanding the behavior for both design-basis earthquakes and earthquakes whose size is substantially beyond the design basis. Formerly, this was a formidable modeling challenge because of limitations in computer size and power, but that limitation has been swept away, and modern algorithm development has also provided advanced, but non-validated, tools for the modeler. The experts judged that this area is ripe for a major advance. The advance will, in turn, enable the use of these advanced elements in reactor design in situations now precluded because they cannot be analyzed with sufficient accuracy, and hence a regulatory safety case cannot be supported at this time. It will also enable changes in industry consensus codes and later in the safety regulations themselves. These changes are not presently allowed, partly due to the inability of current methods to perform sufficiently realistic analyses.

Other Important Task: Seismic Isolators

Ultimately, the time-domain modeling capability must include the capability to calculate the performance of seismic isolators. Both elastomeric and sliding isolators should be considered. The models should address the effects of energy dissipation that lead to changes in the hysteretic behavior of the components.

A good deal of research work is already underway to understand isolator behavior, including both experimental studies and the development of advanced analytical methods. The experts emphasized that continuing support for this work is important. One major theme of the ongoing work, which requires a time-domain model, is on understanding the behavior of the isolators when subjected to extreme earthquake motions well-beyond the design basis, with an emphasis on understanding what happens if an isolator system were to reach its boundary (or "moat"). This can lead to large impact forces, and in turn, transmit large motions up into the structure above the isolators. Work on this important issue, both experimental and analytical, is already under way but needs additional support. A second area is consideration of how horizontal seismic motions coming into the facility can produce vertical motions due to the rocking flexibility of the isolation system. A third area is working on how isolator performance in nuclear reactor systems can be understood well enough to allow its inclusion in the consensus design codes and later in the nuclear–safety regulatory process[5]. This body of recommended isolator R&D work, taken as a whole, is intended to expedite the acceptance of base isolation of nuclear reactor facilities as a viable and useful option for the designer.

Other Important Task: Nonlinear Soil

[5] ASCE 4 already includes isolators, and a NUREG on isolation is in final draft form with US NRC.

The experts emphasized that the inability to model nonlinear soil behavior is a significant limitation of the elastic SASSI model, and that care must be taken in interpreting SASSI results[6] because, at high shear strain levels, the equivalent linear soil model used in SASSI overstates resonances in response spectra and understates the ability of the soil to pass high frequencies to the structure. A time-domain model can directly calculate nonlinear response of soil to seismic waves; however, the experts strongly cautioned that care must be taken to use nonlinear constitutive models that capture the behavior of real soils. They further noted that the simplest useful 3D constitutive model, a Coulomb-Mohr model, does not correctly capture nonlinear behavior. It is very important that downhole array data be used and that the model be validated based on free-field motions, before the model is applied to SSI calculations used for design or regulation.

One of the experts, Carl Costantino, agreed to review the previous work in this area, and provide his insights to Boris Jeremic of the project team. In turn, Boris Jeremic will communicate with the other team members. The experts concluded their discussion of this task with a strong call for verification of soil models, and where possible, validation against data, with associated management of uncertainties.

Other Important Task: Internal Fluid-Structure Interaction

The experts noted that some SMR design concepts include pools of water. They emphasized the need for a time-domain approach to enable simulation of the sequential interaction of the structure with the fluid (causing both pressure waves and fluid movement), and then the interaction of the fluid back with the structure. They noted that in off-normal scenarios, the model should be able to calculate the behavior of the system under seismic loading after some of the water has been vaporized. Finally, they noted that the model must properly include the nature of the physical contact of the fluid and the structure.

[6] Some experts noted that equivalent linear properties in SASSI are established from nonlinear mechanical properties. So care must be taken with nonlinear constitutive models, but arguably the equivalent linear properties are even more uncertain.

APPENDIX 1: Contact Information for the Workshop Attendees and Biographical Sketches of the Eight Experts

Table A1-1 provides contact information for the experts, the project team, and the DOE/Campaign management attendees.

Table A1-1: Contact Information

Name	Phone Number	E-Mail Address
The Eight Experts		
Jacobo Bielak	(412) 268-2958	jbielak@cmu.edu
Justin Coleman	(208) 419-8754 (208) 533-0433	justin.coleman@icp.doe.gov
Carl Costantino	(845) 354-2602	carl@cjcassoc.com
Robert Kennedy	(760) 751-3510	bob@rpkstruct.com
Stephen Mahin	(510) 693-6972	mahin@berkeley.edu
Farhang Ostadan	(415) 768-3734	ostadan@bechtel.com
John Stevenson	(216) 587-3805	jstevenson4@earthlink.net
Andrew Whittaker	(716) 645-4364	awhittak@buffalo.edu
DOE and Campaign Management		
Keith Bradley (NTD, ANL)	(630) 252-4685 (925) 321-5790	ksbradley@anl.gov
David Pointer (IPSC Lead, ANL)	(630) 252-1052	david.pointer@anl.gov
Robert Versluis (DOE-NE-71)	(301) 903-1890 (202) 834-2292	ROB.VERSLUIS@nuclear.energy.gov
The LLNL Team		
James Blink	(925) 423-9449	blink1@llnl.gov
Steven Bohlen	(925) 699-2972	bohlen1@llnl.gov
Robert Ferencz	(925) 422-0571	ferencz1@llnl.gov
Michael Gerhard	(925) 422-8368	gerhard1@llnl.gov
Harris Greenberg	(925) 422-6024	greenberg6@llnl.gov
Michelle Herawi	(925) 423-4964	herawi1@llnl.gov
Quazi Hossain	(925) 423-2289	hossain1@llnl.gov
Eric Keldrauk	(925) 423-2119	keldrauk1@llnl.gov
David McCallen	(925) 423-1219	mccallen2@llnl.gov
Arthur Rodgers	(925) 423-5018	rodgers7@llnl.gov
Randolph Settgast	(925) 424-3057	settgast1@llnl.gov
Jerome Solberg	(925) 422-5971	olberg2@llnl.gov
The LBNL Team		
Jens Birkholzer	(510) 486-7134	JTBirkholzer@lbl.gov
Robert Budnitz	(510) 486-7829	rjbudnitz@lbl.gov
Lawrence (Larry) Hutchings	(510) 486-7446	ljhutchings@lbl.gov
Boris Jeremic (UC-Davis)	(530) 754-9248	jeremic@ucdavis.edu

The remainder of this Appendix contains the abbreviated biographical sketches of the eight experts.

Jacobo Bielak

Dr. Jacobo Bielak received his PhD degree from the California Institute of Technology. He is a University Professor in the Department of Civil and Environmental Engineering at Carnegie Mellon University.

Dr. Bielak's research is in the area of computational mechanics with special emphasis on earthquake engineering and engineering seismology. The main objective of his work is to contribute to the understanding of earthquake-related phenomena, in an end-to-end approach, from the earthquake source, propagation path, and site effects; to the coupled response of structures in highly heterogeneous media and large urban regions susceptible to high seismic hazard.

Dr. Bielak was a member of the original Applied Technology Council committee that drafted the first tentative seismic provisions for soil-structure interaction, which are now, in modified form, part of the NEHRP seismic provisions. He was the developer of the Domain Reduction Method (DRM), an efficient methodology for modeling earthquake ground motion and coupled soil-structure response in localized regions with complex geometry and large contrasts in material properties. Recognition for his work includes the Gordon Bell Prize for Special Accomplishment Based on Innovation, and the ACM/IEEE SC06 HPC Analytics Challenge Award. He is a Member of the National Academy of Engineering, a Distinguished Member of the American Society of Civil Engineers, and also a Member of the Mexican Academy of Engineering and of the Mexican Academy of Sciences.

Justin Coleman

Mr. Justin Coleman, PE, holds an MS in Engineering Structures and Mechanics from Idaho State University. His thesis topic was *Seismic Base Isolation of Residential Buildings using Crumb Rubbe*r. He is currently employed with CH2M-WG as an engineer on the Calcine Disposition Project at the Idaho National Laboratory site. He has performed time- and frequency-domain seismic analyses for DOE Hazard Category 2 and 3 nuclear facilities for ten years, including dynamic soil structure interaction analyses. He has also performed nonlinear impact analyses using Explicit Finite Element (FE) codes for spent nuclear fuel and high-level waste projects for ten years. His impact analysis work includes using nonlinear constitutive equations to model concrete, lead, and steel to predict material behavior. He is a member of the ASCE-4 Dynamic Analysis of Nuclear Structures (DANS) Committee and the lead of the Chapter 3, "Modeling of Structures," subcommittee. His current project includes developing a virtual testing program using nonlinear constitutive models to predict the shape of high-level waste stainless steel cans that will be subject to temperatures up to 1000°C and pressures up to 15,000 psi.

Carl Costantino

Dr. Carl J. Costantino, PE, is Professor Emeritus in the Department of Civil Engineering at The City College of the City University of New York. He holds a PhD from the Illinois Institute of Technology, an MSCE from Columbia University, and a BCE from City College of New York.

Dr. Costantino has conducted research on stress wave propagation through soil and rock materials primarily associated with the seismic response of structures, with special emphasis on evaluation of critical facilities. He has focused on the study of large strain and nonlinear effects on wave propagation, soil-structure interaction, and the influence of pore water on dynamic response.

Dr. Costantino is a Seismic Consultant to both the Nuclear Regulatory Commission and the US Department of Energy. He has performed seismic studies of critical facilities for various divisions of NRC and DOE at both the design and review stages; assisted with evaluation of advanced reactor systems; developed computer programs (SIM, CARES, SLAVE, SLAM Codes) for use in review of facility designs; assisted various divisions and field offices of DOE in soils and seismic evaluations of critical facilities; performed safety evaluations for storage facilities (WIPP, Yucca Mountain); assisted in the development of DOE safety assessment criteria; and presented results to Defense Nuclear Facilities Safety Board.

Dr. Costantino is a Soils Consultant to the New York City Transit Authority. He has supported the design and evaluation of existing and new subway systems and ancillary structures; developed criteria used for evaluation of subway systems in and adjacent to the World Trade Center site since 9/11; assisted in evaluation and control of rehabilitation procedures used at the WTC site by other agencies whose activities impact the new and existing systems; provided guidance on soil and foundation projects at both the design and construction stages; assisted in the development of Standards for Structural Design, Field Designs, and Soil Exploration; conducted laboratory testing of soil samples; designed and inspected field monitoring programs; and developed criteria for incorporation of new seismic design standards into the NYCTA system.

Robert Kennedy

Dr. Robert P. Kennedy, PE, holds PhD and MS degrees in Structural Engineering, and a BS in Civil Engineering, all from Stanford University. He has forty years experience in static and dynamic analysis plus design of special purpose civil and mechanical-type structures (particularly for the nuclear, industrial, petroleum, and defense industries), and design of structures to resist extreme loadings (including seismic, missile impact, blast loads, extreme wind, impulsive loads, and nuclear environmental effects).

In the area of Seismic Ruggedness of Nuclear Facilities, Dr. Kennedy developed performance-goal based seismic design criteria sections of ASCE/SEI Standard 43-05 "Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities," and DOE Standard 1020 "Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities." He was the Chairman of the Senior Seismic Review and Advisory Panel (SSRAP) that jointly advised both nuclear power utilities and the U.S. NRC on issues relating to seismic

ruggedness of existing nuclear power plants. He was a member of the NRC Expert Panel on Seismic Margin for nuclear power plants. He is the co-author of Electric Power Research Institute (EPRI) Seismic Margin Methodology Report (EPRI-6041) and Methodology for Developing Seismic Fragilities (EPRI TR-103959). He has provided technical direction on the seismic fragility portion of seismic probabilistic risk assessments and seismic margin evaluations for more than 30 nuclear power plants. Dr. Kennedy developed the methodology most commonly used for such studies and is the author of many technical papers thereon. He has taught numerous short courses on seismic PRA methodology in U.S., Spain, Taiwan, and People's Republic of China. He is a consultant on seismic evaluation or design for more than 50 nuclear facilities throughout the world. Dr. Kennedy is the Past Chairman of the ASCE committee on seismic analysis of nuclear facilities, and the Past Chairman of the ASCE committee which wrote ASCE Standard 4-86 "Seismic Analysis of Safety Related Nuclear Structures". Dr. Kennedy has directed seismic analyses of nuclear power plant buildings and components, as well as nonlinear seismic response analyses investigations. He evaluated the effects of differential earth movement (faulting) on nuclear facilities, and performed a number of dynamic soil-structure interaction analyses of nuclear reactor containment buildings that accounted for the nonlinear effects of base slab uplift. He directed a nonlinear seismic evaluation of a nuclear facility to demonstrate increased seismic capacity. He evaluated concepts for seismic response mitigation and increased energy absorption

In the area of Dynamic Loads on Nuclear Facilities, Dr. Kennedy has extensive experience in the analysis of nuclear facilities subjected to extreme dynamic loads including effects of blast loads, external missile and aircraft impact, and impulsive loading resulting from loss-of-coolant accident and SRV discharge. He is the prime developer of the method currently in extensive use by the nuclear industry in the United States for evaluating the local effects of missile impact on concrete. He is a consultant on the effects of aircraft impact for several nuclear plants. He is a consultant to the Nuclear Regulatory Commission on stand-off distances required for structures to withstand blast loads from TNT or Gaseous Hydrogen detonation. He is a consultant to General Electric on effects of pool swell loads resulting from LOCA, and on the increased dynamic reserve margin available in structures subjected to impulsive loads. He is a consultant to G.E. and the Mark I, Mark II, and Mark III Owner's Group on combination of responses from multiple dynamic loadings. He is a consultant on Mark II and Mark III evaluations to address the conservatism and uncertainty associated with standard structural analyses for SRV loadings. He is a consultant on methods of response combination and an expert witness at the Black Fox hearings. He is a consultant to the Mark I and Mark III groups on conservatism, uncertainty, structural modeling, and load definition for new dynamic loads. He is a consultant on three Mark III BWR plants with free-standing steel containment (Leibstadt, Allens Creek, and River Bend), in order to evaluate realistic containment response to SRV loadings, as prior approaches were over-conservative and lead to serious design problems. Dr. Kennedy developed floor response spectra for final design of attached piping for the Leibstadt plant by coupled analysis, such that beneficial effects of energy feedback are included. He developed a method to account for the coupling of equipment and piping to the main structure and to account for energy feedback from the subsystem to the structure. He also developed a method to account for random phasing of multiple harmonics of condensation oscillation loading in

order to compute responses more compatible with measured results. He is a Member of the ASCE committee on impact and impulse analysis of nuclear facilities, and the ACI committee that developed code for the design of nuclear safety-related concrete structures subjected to impact and impulse loads.

Dr. Kennedy is a Member of the National Academy of Engineering. He was the recipient of the 1992 ASCE Stephen Bechtel Energy Engineering Award for seismic criteria development work for energy facilities. Dr. Kennedy is also a Fellow of the California Council on Science and Technology

Stephen Mahin

Dr. Stephen Mahin is the Byron and Elvira Nishkian Professor of Structural Engineering at the University of California, Berkeley, and is Director of the Pacific Earthquake Engineering Research Center. He received his BS, MS, and PhD degrees from the University of California, Berkeley. After working as a consultant for the seismic design of buildings, offshore platforms, and nuclear power plant facilities, he joined the faculty at UC Berkeley. He has carried out research on a wide variety of topics related to the seismic behavior and design of building, bridge and infrastructure systems, and is internationally recognized for the integration of experimental, theoretical, and computational research in developing guidelines for improving seismic safety and performance. He has more than 300 technical papers, and has supervised the research of more than 80 students. He has received several major awards, including the Huber Research Prize and Norman Medal from ASCE, and the James Cooper Award from FHWA. Dr. Mahin was recently elected to the ASCE/OTC Hall of Fame, and has served in leadership positions in several academic and professional organizations.

Farhang Ostadan

Dr. Farhang Ostadan, PE is a Bechtel Fellow with more than 30 years experience in earthquake engineering. As Chief Engineer for Bechtel, he has overall responsibility and manages the efforts of a large and diverse group of specialists in locations across the US and around the globe. His projects involve major transportation, power and energy concerns, and petrochemical and nuclear fuel sources. He has contributed to numerous standard nuclear power plant designs including the new modular reactors and has published over 40 technical papers on topics relating to earthquake engineering. Dr. Ostadan co-developed a method for dynamic soil-structure interaction analysis (SASSI) currently in use by industry worldwide. He is a frequent lecturer at both universities and research organizations.

Dr. Ostadan holds a PhD in Civil Engineering from the University of California, Berkeley, a MS in Civil Engineering from the University of Michigan, and a BS in Civil Engineering from the University of Tehran. He has been an ASCE Fellow since 2010. He is a member of the ASCE-4 committee and is responsible for Chapter 5 on SSI. He is Chairman of ANS 2.2, Seismic Instrumentation of Nuclear Power Plant Structures, and is Chairman of the Structural Mechanics in Reactor Technology Conference to be held in August 2013. He is also President-elect of the IASMiRT board (www.iasmirt.org/board.php).

John Stevenson

Dr. John D. Stevenson is a Senior Consultant for J.D. Stevenson, Consulting Engineer Co. He has over 40 years experience worldwide in the design, analysis and construction of nuclear power plants and other nuclear safety related structure, systems and components. He holds a PhD in Civil Engineering from Case Western Reserve University. He is, or has been, a member of various committees dealing with the structural-civil/mechanical design of the ACI, AISC, ANS, ASCE, ASME B&PVC Section III for the past 35 years. He serves as the Chairman of the Technical Advisory Committee to the IAEA Center for Seismic Safety. He also serves as an outside expert to the US NRC and DNFSB. He has authored over 50 papers and 3 books on the subject of nuclear safety related structures, systems and components design and analysis for extreme loads. His career has included Manager of Structural Systems and Balance of Plant Engineering for the Westinghouse Atomic Power Division, and he has acted as a Corporate Manager of Quality Assurance for a major A/E firm as well as the Founder and President of a five-office consulting engineering firm until he retired.

Andrew Whittaker

Dr. Andrew Whittaker, PE, is Professor and Chair in the Department of Civil, Structural, and Environmental Engineering at the University at Buffalo and is Director of the NSF-funded NEES facility that is housed in the Department. He is the Director of the NSF-funded earthquake research center, MCEER. He holds a PhD in Structural Engineering, and an MS in Civil Engineering, both from the University of California at Berkeley, and a BE in Civil Engineering from the University of Melbourne.

Dr. Whittaker served for seven years as President of the Consortium of Universities for Research in Earthquake Engineering (CUREE), which is a not-for-profit corporation in the United States. In 2010-2011 he served on a National Research Council committee to develop a 20-year research agenda for earthquake engineering research in the United States; he was the only academic structural/geotechnical engineer on the committee.

Dr. Whittaker has led the development of numerous multi-campus, multidisciplinary proposals including the $30M USD NEHRP Consultants Joint Venture, which is a joint venture of CUREE and the Applied Technology Council. He developed and leads the University of Buffalo involvement in three Indefinite Delivery Indefinite Quantity (IDIQ) contracts with US federal agencies on topics related to blast engineering and infrastructure protection; the lead organizations for the IDIQ contracts are CUBRC and Black and Veatch. Dr. Whittaker served as a member of the Board of Directors for the Earthquake Engineering Research Institute (EERI) from 2008-2010, as a member of the Board of Directors for the World Seismic Safety Initiative (WSSI) from 2008-2010, and currently serves on the Advisory Committee of the Southern California Earthquake Center.

Dr. Whittaker's current research interests include

- Seismic behavior of low aspect ratio walls of conventional and composite (SC) construction; performance assessment; predictive equations; fragility functions

- Blast engineering of buildings and infrastructure: clearing effects; material models at high strain rates; progressive collapse; hydrocode analysis; ground shock
- Nuclear structures: fragility evaluation of conventional and isolated power plants; modular SC construction for Gen III+ plants; Gen IV power plants; seismic isolation
- Performance-based earthquake engineering: procedures for loss computations; scaling earthquake ground motions; simplified methods of analysis
- Seismic hazard analysis: hazard characterization for performance-based design; near-fault shaking; site amplification; rotational components of ground motion
- Seismic protective systems: new isolation systems; analytical models for isolators; system response.

Dr. Whittaker served as the Associate Director of the Pacific Earthquake Engineering Research (PEER) Center from 1998 to 2000. He was the Associate Director of the Earthquake Engineering Research Center from 1993 to 1998). Dr. Whittaker has provided consulting, peer-review and expert-witness services to private companies and to local, state, and federal government agencies in the United States, South America, Europe, United Kingdom, Russia, Australia, and Asia. A focus of his consulting work is the application of performance-based seismic design and advanced blast engineering to tall and ultra-tall buildings, bridges, and power-related infrastructure.

Dr. Whittaker received the Gold Award from the James Lincoln Arc Welding Foundation, the Grand Award from the American Council of Engineering Companies, and the Diamond Award from the New York Association of Consulting Engineers.

Dr. Whittaker is a Fellow of the member of the Institute of Engineers Australia; a Member of the American Society of Civil Engineers, the American Concrete Institute, the Consortium of Universities for Research in Earthquake Engineering, the Earthquake Engineering Research Institute, and the Australian Earthquake Engineering Society; and is an Associate Member of the Structural Engineers Association of New York.

Dr. Whittaker serves on a number of state, national and international committees for the American Association of State Highway and Transportation Officials (AASHTO), the American Concrete Institute, the American Society of Civil Engineers, the Applied Technology Council, the Building Seismic Safety Council, the California Department of Transportation, the Consortium of Universities for Research in Earthquake Engineering, the US Department of Homeland Security, the Earthquake Engineering Research Institute, the National Academy of Science/National Research Council, the National Institute of Standards and Technology, the Southern California Earthquake Center, the Structural Engineers Association of California, the Structural Engineers Association of Northern California, the United States Geological Survey, the University of California, Berkeley, the University of California, San Diego, and the World Seismic Safety Initiative. He serves on ASCE Standard 4 Committee, the ASCE Nuclear Structures Committee, and ACI Committee 349.

Dr. Whittaker serves on the International Editorial Board of the archival Wiley journal, The Structural Design of Tall Buildings and the Editorial Board of the Electronic Journal of Structural Engineering.

APPENDIX 2: Presentations

This appendix contains the presentations made at the workshop, in the sequence in which they were presented.

The first four presentations are by the project team:

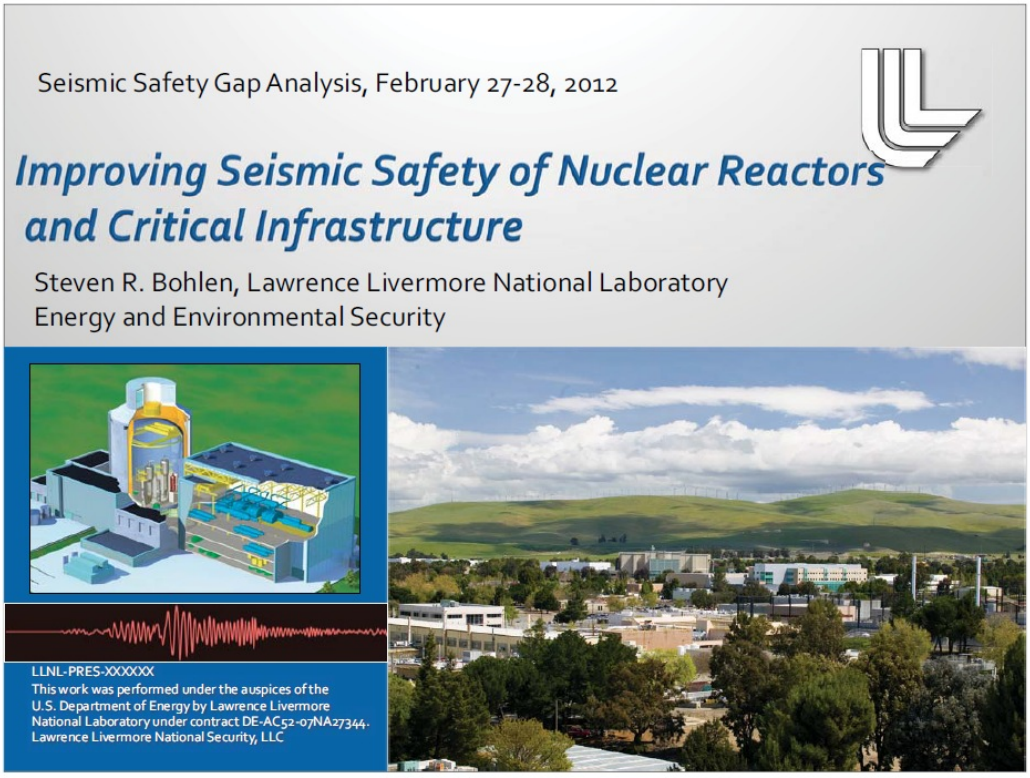
- Steven Bohlen
- David McCallen
- Boris Jerevic
- Lawrence Hutchings

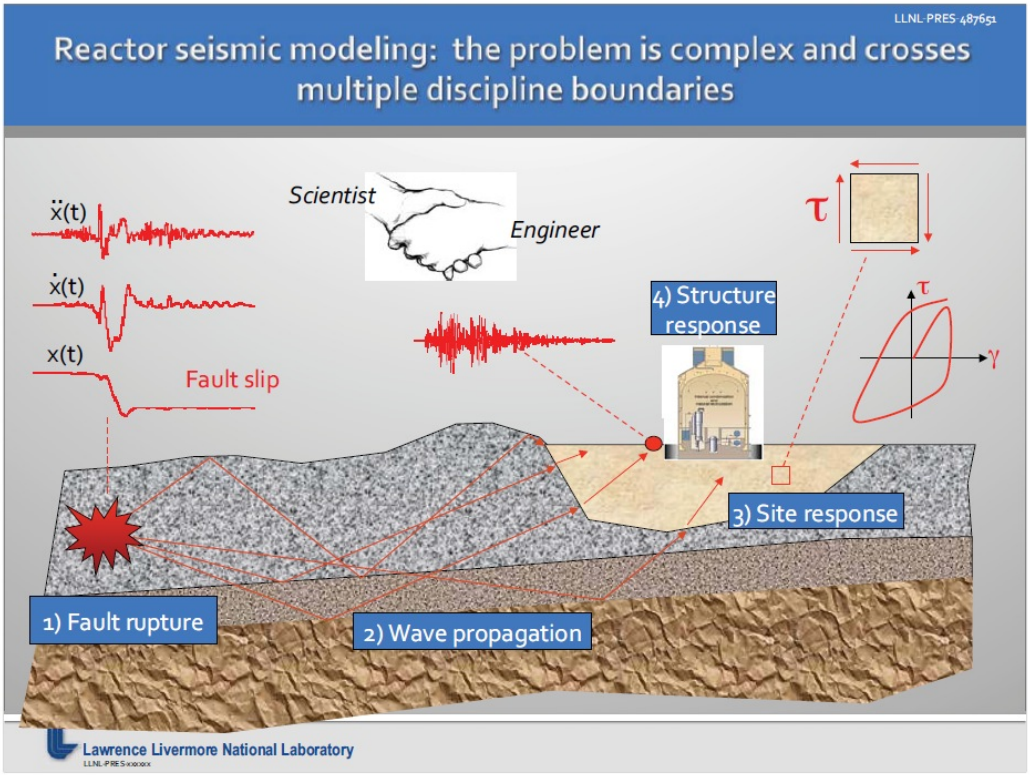
The remaining three presentations are by the experts:

- Andrew Whittaker
- Jacobo Bielak
- Justin Coleman

Presentation of Steven Bohlen, LLNL

This presentation was released by LLNL as LLN-PRES-523922.


Seismic Safety Gap Analysis, February 27-28, 2012
Improving Seismic Safety of Nuclear Reactors and Critical Infrastructure
Steven R. Bohlen, Lawrence Livermore National Laboratory
Energy and Environmental Security
LLNL-PRES-XXXXXX
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC


LLNL-PRES-487651
Reactor seismic modeling: the problem is complex and crosses multiple discipline boundaries
Scientist
Engineer
ẍ(t)
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x(t)
Fault slip
τ
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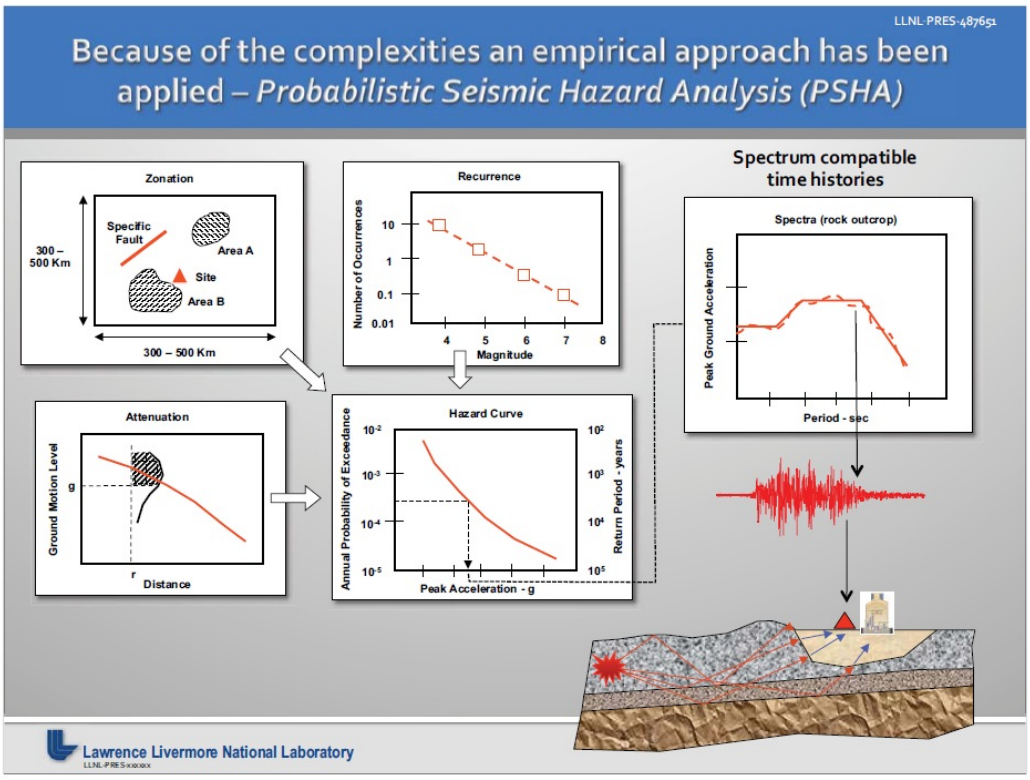
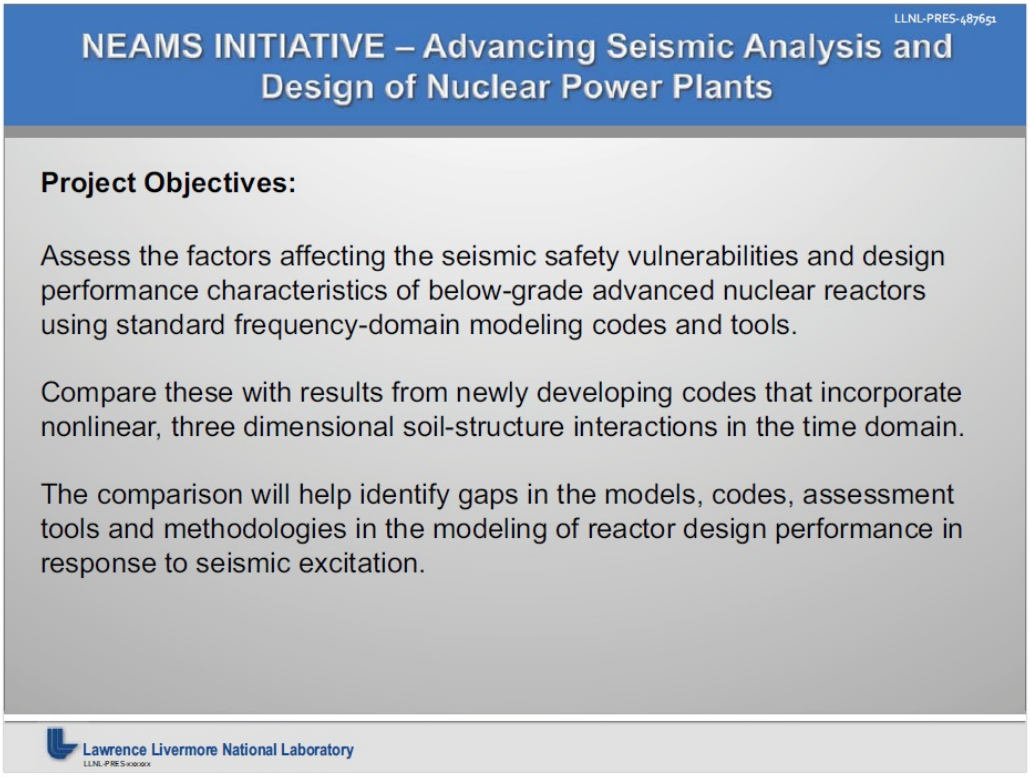
4) Structure response
3) Site response
1) Fault rupture
2) Wave propagation
Lawrence Livermore National Laboratory


LLNL-PRES-487651
Because of the complexities an empirical approach has been applied – Probabilistic Seismic Hazard Analysis (PSHA)
Zonation
Specific Fault
Area A
Site
Area B
300 – 500 Km
300 – 500 Km
Recurrence
Number of Occurrences
Magnitude
Spectrum compatible time histories
Spectra (rock outcrop)
Peak Ground Acceleration
Period - sec
Attenuation
Ground Motion Level
Distance
Hazard Curve
Annual Probability of Exceedance
Return Period - years
Peak Acceleration - g
Lawrence Livermore National Laboratory


LLNL-PRES-487651
NEAMS INITIATIVE – Advancing Seismic Analysis and Design of Nuclear Power Plants
Project Objectives:
Assess the factors affecting the seismic safety vulnerabilities and design performance characteristics of below-grade advanced nuclear reactors using standard frequency-domain modeling codes and tools.
Compare these with results from newly developing codes that incorporate nonlinear, three dimensional soil-structure interactions in the time domain.
The comparison will help identify gaps in the models, codes, assessment tools and methodologies in the modeling of reactor design performance in response to seismic excitation.
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LLNL-PRES-487651

NEAMS INITIATIVE – Advancing Seismic Analysis and Design of Nuclear Power Plants

- **Laboratory Responsibilities**
  - ANL – NEAMS Seismic safety vision and future
  - BNL – Execution of SASSI analysis for model problems
  - LBNL – Seismic input motions (accelerations of 0.2, 0.5, 0.9g); non-linear soil models, Gap Analysis Workshop
  - LLNL – Project leadership; Integration of non-linear soil model with Diablo structural mechanics code; execution of 3-D SSI analysis of model problems; Gap Analysis Workshop
  - ORNL – Generic SMR design, simplified but technically interesting

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LLNL-PRES-xxxxxx

LLNL-PRES-487651

Soil – Structure Interactions: A Few Challenging Issues

- Time-domain versus Frequency-domain
  - Time-domain – explicit versus implicit
- Earthquake motion input
- Boundary Conditions
- Material non-linearity – Soil material models
- Geometric non-linearity
  - Soil/Structure contact
  - Structural joints (esp. as a source of damping)

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NEAMS INITIATIVE – Advancing Seismic Analysis and Design of Nuclear Power Plants

Strategy

- Initialize with vertically propagating shear waves and a simple soil (begin with conditions in which SASSI output and 3-D nonlinear time domain models will be similar)
- Add complexity in seismic input (3-D, non-vertical seismic motions)
- Add complexity in soil model

Challenges

- Characterization of soil damping and energy loss in the soil
- Energy-transmitting vertical boundary characterization

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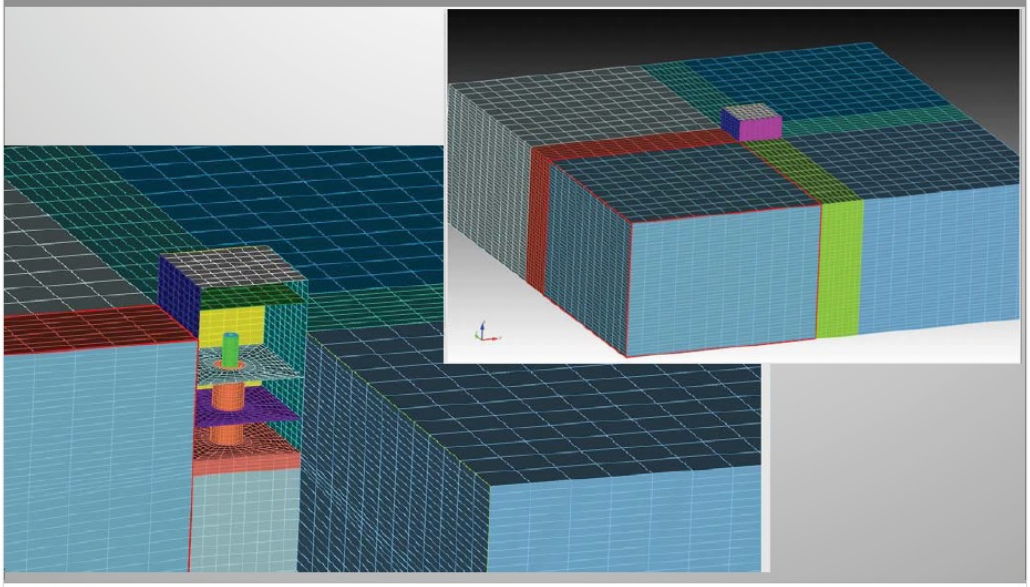
Reactor Model: Sectional Overview



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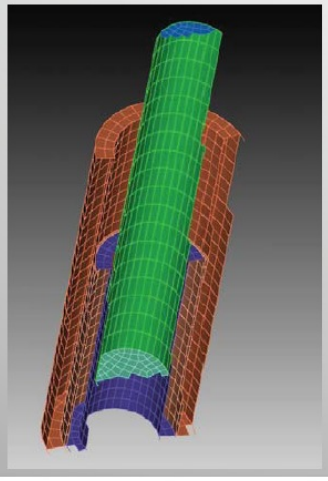
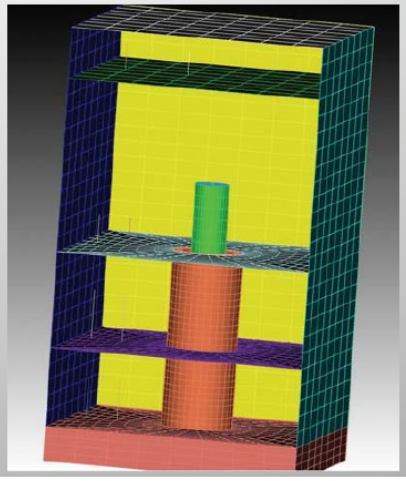
Reactor Model: Sectional Overview

Shell element baseline for structure, but solid elements may also be used, especially where the structural member has a low aspect ratio (pier, basemat)





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NEAMS INITIATIVE – Gap Analysis Workshop – Initial Questions

- **What methods and capabilities would be desirable for full characterization and modeling of the seismic response of nuclear power plants, and associated seismic safety analysis?**
- **How can advanced capabilities make a difference for plant designs, both in terms of fundamental understanding, and in NRC regulatory processes, and what barriers to use/ implementation might exist?**

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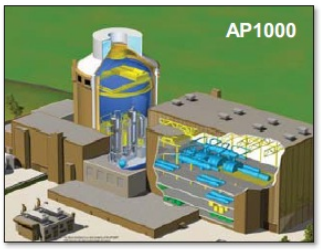
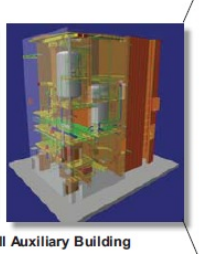
Presentation of David McCallen, LLNL

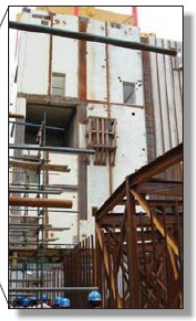
This presentation was released by LLNL as LLN-PRES-537891.

Advanced Simulations for the Seismic Response of Nuclear Power Systems

A Workshop at the Lawrence Livermore National Laboratory
February 27, 2012







Sanmen China Composite Wall Auxiliary Building

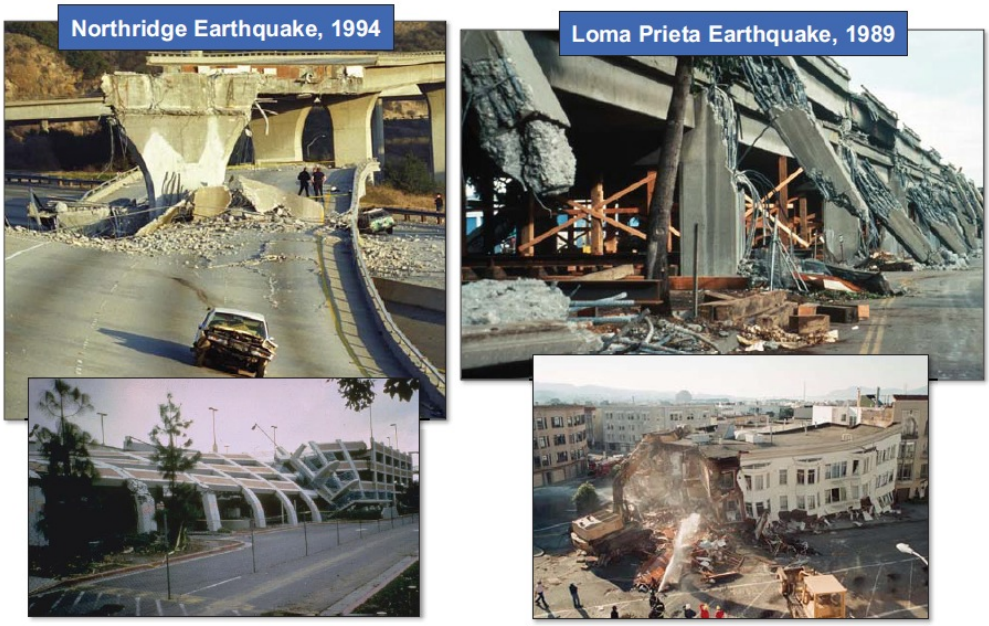
David McCallen
Deputy Principal Associate Director
Global Security Principal Directorate

GlobalSecurity
Anticipate • Innovate • Deliver

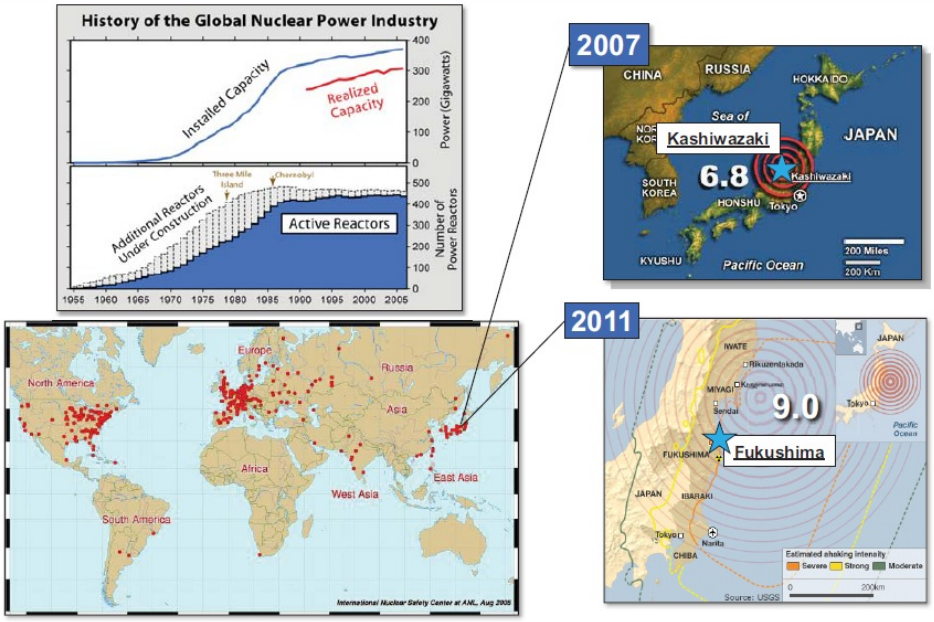
Summary of topics

- Seismic performance of nuclear plants (sparse data!)
- Seismic design of U.S. nuclear facilities
- A vision for comprehensive, predictive simulations
  - Leveraging modern simulation tools
  - Full realization of performance based design

Major earthquakes in California have provided us hundreds of observations on seismic performance of major structures

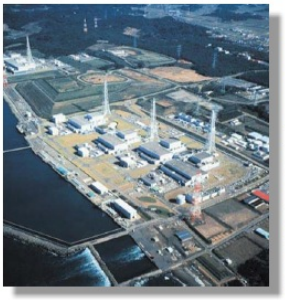


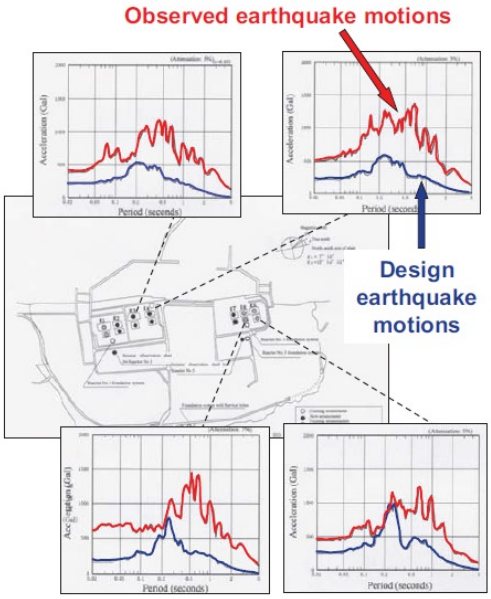
In contrast, over ~50 years only 2 nuclear plants have been subjected to nearby, very large earthquakes



At Kashiwazaki the observed motions at the plant exceeded the seismic design basis motions substantially

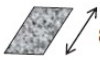
Kashiwazaki Nuclear Power Station





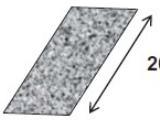
At Kashiwazaki the Seismic Hazard was underestimated due to misinterpretation of the fault rupture potential

Historical evolution of the interpretation of the FB Fault



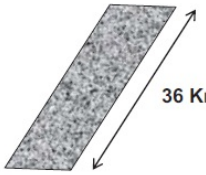
8 Km

1990's
Fault identified but judged inactive



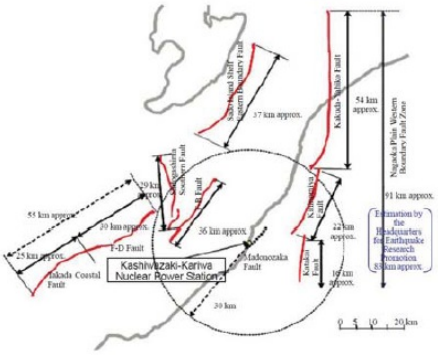
20 Km

2003
Re-evaluated as an active fault capable of M=7 earthquake, but motions not controlling based on attenuation analysis



36 Km

2008
Re-evaluated as an active fault capable of M=7 earthquake,

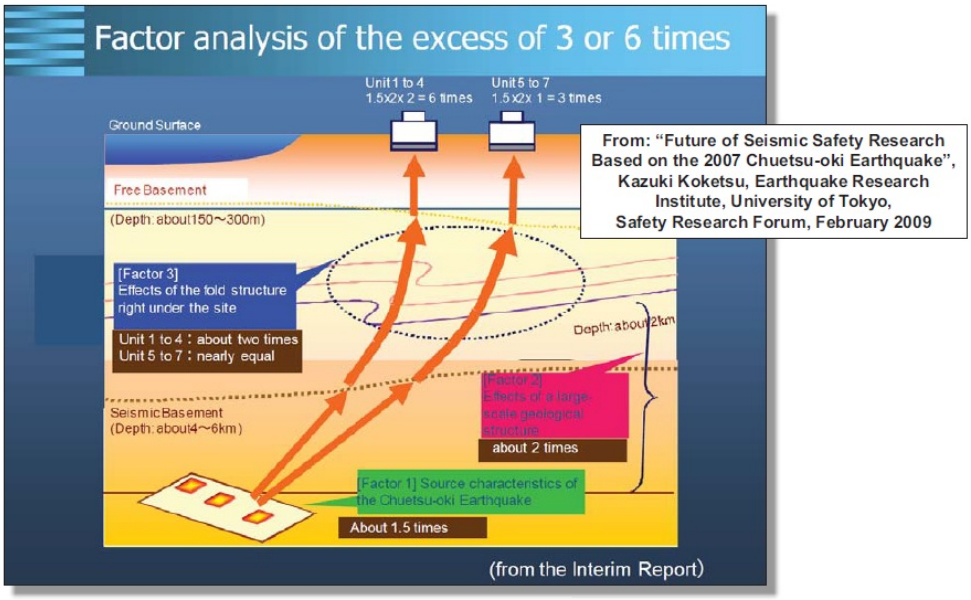


Maximum Acceleration of Design basis ground Ground Motion Ss

(Unit: Gal (cm/s²))

Earthquake for investigation	Design basis ground ground motion	NS direction		EW direction		UD direction	
		Arahama side	Ominato side	Arahama side	Ominato side	Arahama side	Ominato side
F-B Fault	Ss-1	2300	1050	2300	1059	1050	650
	Ss-2	847	848	1703	1200	510	466
Katakai Fault (Nagaoka Plain Western Boundary Fault Zone)	Ss-3	600		600		400	
	Ss-4	589	428	574	826	314	332
	Ss-5	553	426	554	664	266	346

Source-to-site propagation was also a focus of intense study



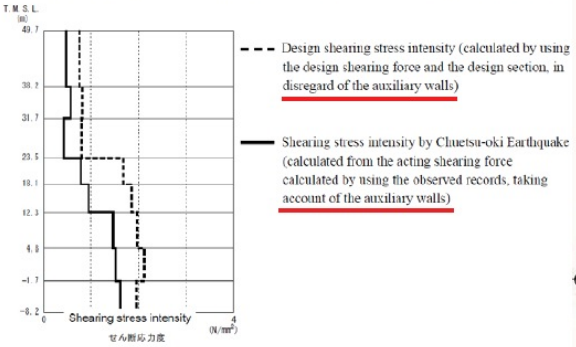
From: "Future of Seismic Safety Research Based on the 2007 Chuetsu-oki Earthquake", Kazuki Koketsu, Earthquake Research Institute, University of Tokyo, Safety Research Forum, February 2009

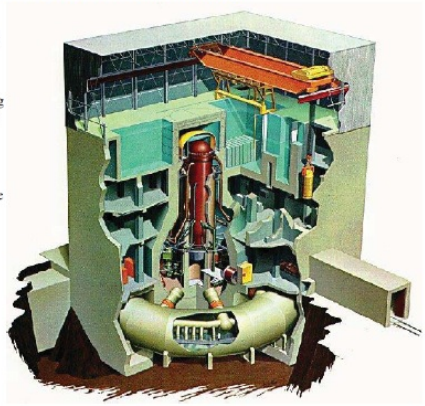
The design ground motions were exceeded by a substantial margin, why wasn't there more damage to the main structures?

Nuclear and Industrial Safety Agency (NISA) Report

"At the time of the Chuetsu-oki Earthquake, observation results superior to the maximum acceleration determined from the reference earthquake motion S2-D were obtained on the base of the mat of the unit 7 reactor building. However, seismic resistant walls and RCCV of the Unit 7 Reactor Building had been designed with a sufficient margin based on the design shearing stress intensity superior to the shearing stress intensity by the Chuetsu-oki Earthquake, and this seems to be the reason why only minimal damage was caused to the reactor building"

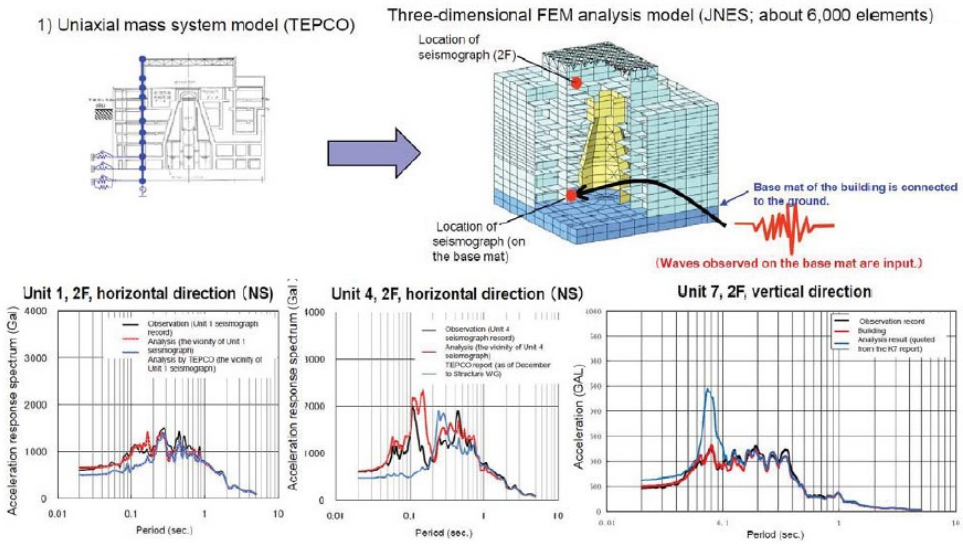
Fig. 2: Design shearing stress intensity and shearing stress intensity by Chuetsu-oki Earthquake



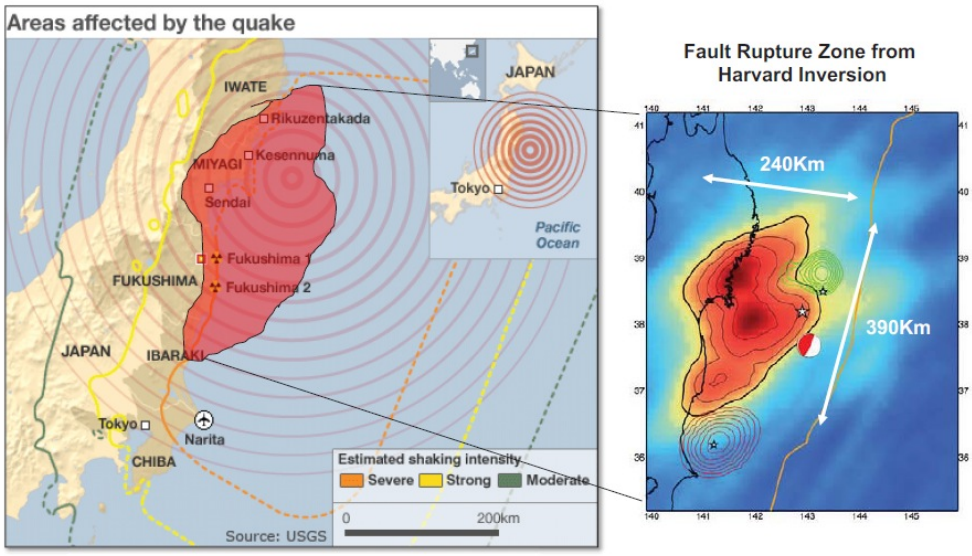


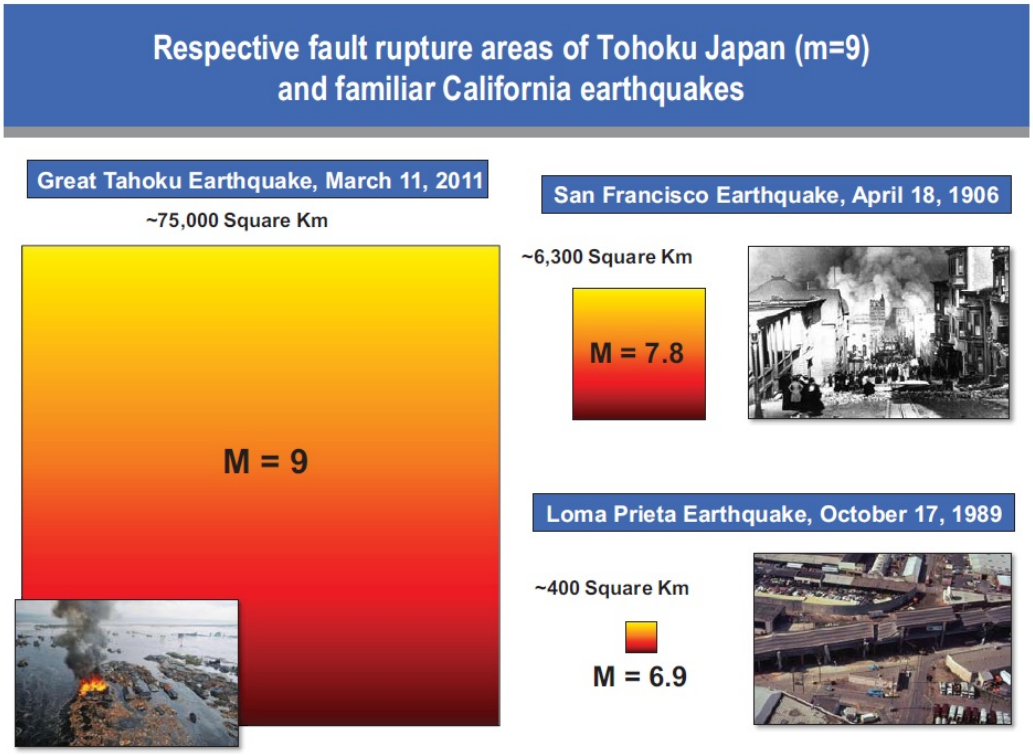
Japanese analysis indicated historical 1D "stick" computational models are not fully representative of plant system response

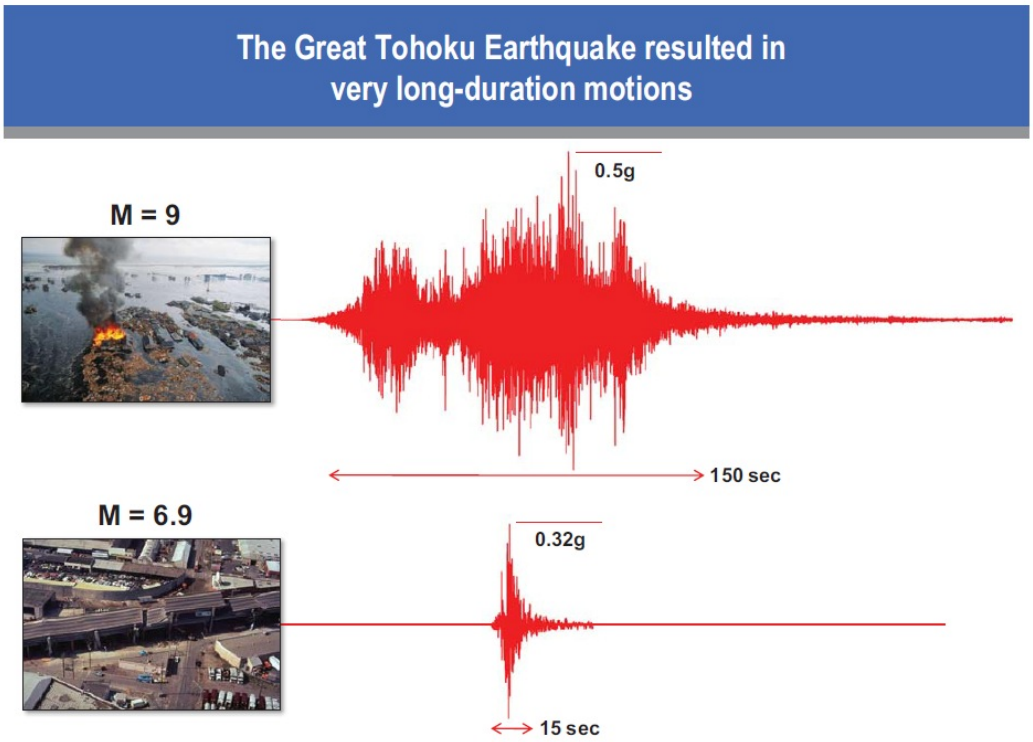
【Results of Three-Dimensional Finite Element Method (FEM) Analyses by JNES】



The recent M=9 Tohoku Earthquake in Japan was a truly great earthquake – only 5 this century of this magnitude

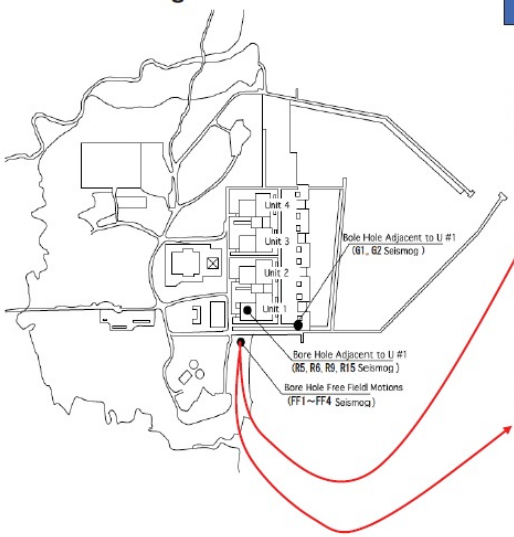



Respective fault rupture areas of Tohoku Japan (m=9)
and familiar California earthquakes
Great Tahoku Earthquake, March 11, 2011
~75,000 Square Km
M = 9
San Francisco Earthquake, April 18, 1906
~6,300 Square Km
M = 7.8
Loma Prieta Earthquake, October 17, 1989
~400 Square Km
M = 6.9

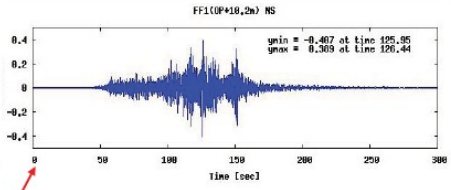

The Great Tohoku Earthquake resulted in
very long-duration motions
M = 9
0.5g
150 sec
M = 6.9
0.32g
15 sec

The motions at the Fukushima site, while long in duration, were not of excessively large amplitude

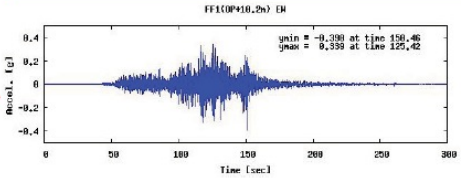
Plant design motions ~ 0.45 G



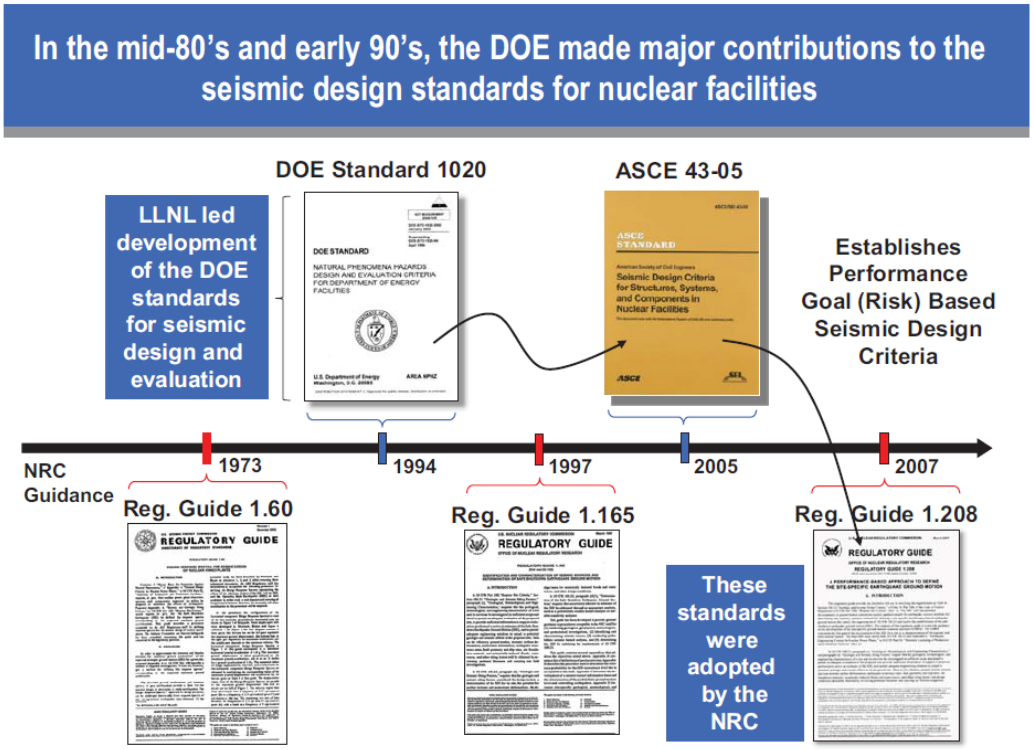
Peak N-S Free Field Motion = 0.41 G

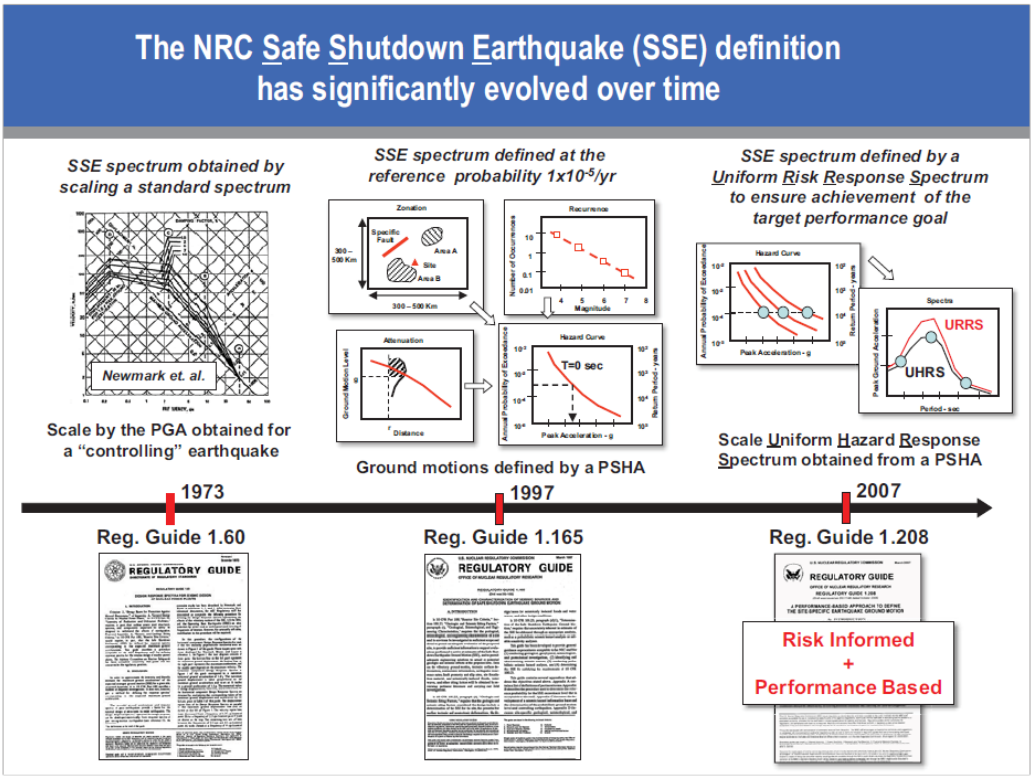


Peak E-W Free Field Motion = 0.39 G

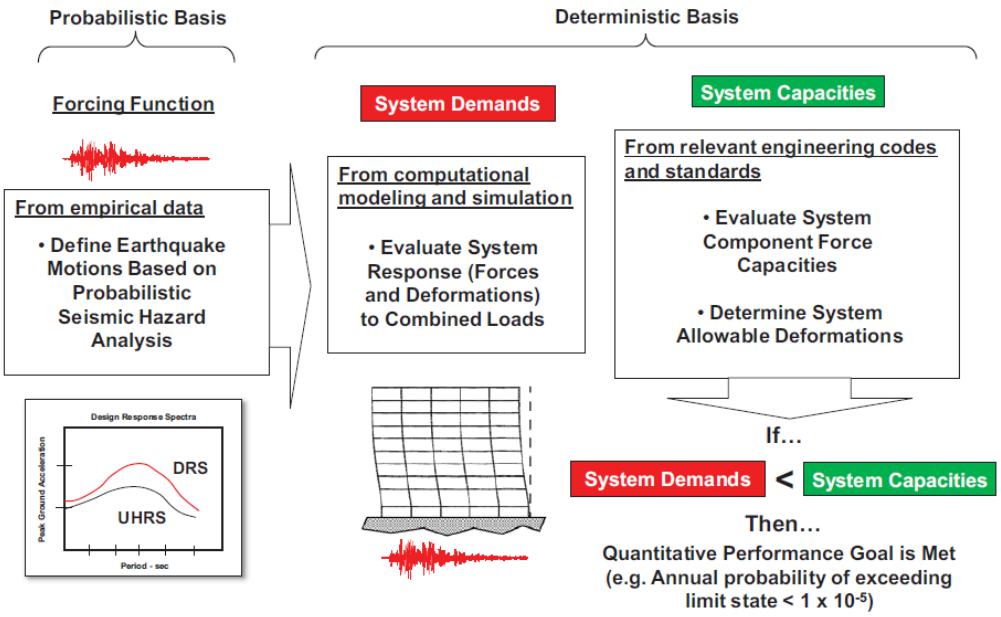


Seismic Design of U.S. Facilities


In the mid-80's and early 90's, the DOE made major contributions to the seismic design standards for nuclear facilities
DOE Standard 1020
ASCE 43-05
LLNL led development of the DOE standards for seismic design and evaluation
Establishes Performance Goal (Risk) Based Seismic Design Criteria
NRC Guidance
1973
1994
1997
2005
2007
Reg. Guide 1.60
Reg. Guide 1.165
Reg. Guide 1.208
These standards were adopted by the NRC


The NRC Safe Shutdown Earthquake (SSE) definition has significantly evolved over time
SSE spectrum obtained by scaling a standard spectrum
SSE spectrum defined at the reference probability 1x10-5/yr
SSE spectrum defined by a Uniform Risk Response Spectrum to ensure achievement of the target performance goal
Newmark et. al.
Scale by the PGA obtained for a "controlling" earthquake
Ground motions defined by a PSHA
Scale Uniform Hazard Response Spectrum obtained from a PSHA
T=0 sec
URRS
UHRS
1973
1997
2007
Reg. Guide 1.60
Reg. Guide 1.165
Reg. Guide 1.208
Risk Informed
+
Performance Based

The current Performance-Based Design Standards utilize a mixture of probabilistic and deterministic procedures



ASCE 43-05 considers broad nuclear facilities (not just nuclear power plants) and characterizes by *Design Category* and *Limit States*

Limit State
(Establishes Analysis Methodology, Design Procedures, Acceptance Criteria)

Seismic Design Category
(Establishes Design Earthquake Level)

	A Large Permanent Distortion (short of collapse)	B Moderate Permanent Distortion	C Limited Permanent Distortion	D Essentially Elastic Response Behavior
1	ASCE-7	ASCE-7	ASCE-7	NA
2	ASCE-7	ASCE-7	NA	NA
3	ASCE 43-05	ASCE 43-05	ASCE 43-05	ASCE 43-05
4	ASCE 43-05	ASCE 43-05	ASCE 43-05	ASCE 43-05
5	ASCE 43-05	ASCE 43-05	ASCE 43-05	ASCE 43-05

The performance-based approach adopted by the NRC utilizes the ASCE 43-05 methodology, but restricts plants to elastic behavior

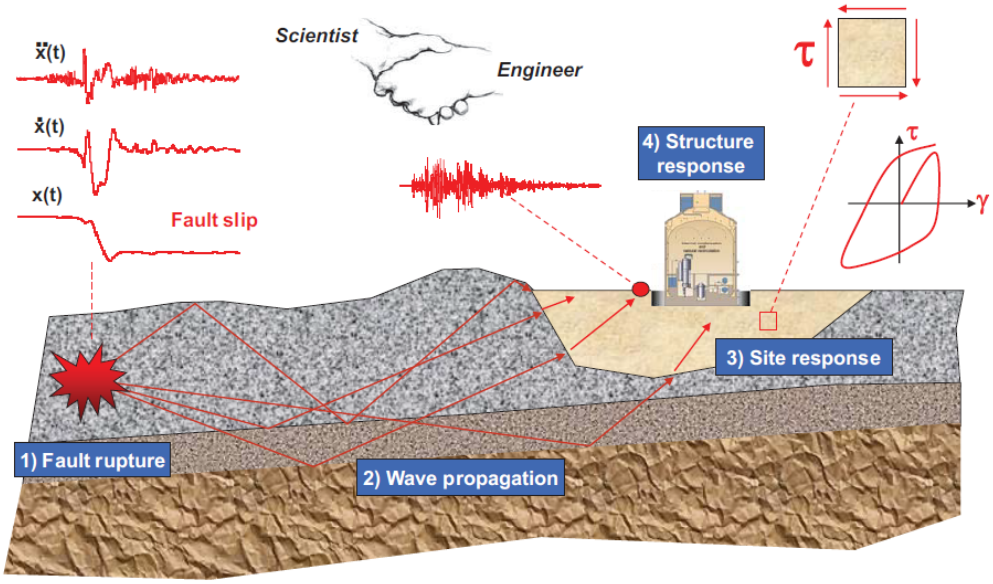
NRC adoption of ASCE 43-05 in Regulatory Guide 1.208

"A performance-based approach is described in Chapters 1 and 2 of ASCE 43-05… The performance-based approach employs Target Performance Goal (P_F), Probability Ratio (R_P), and Hazard Exceedance Probability (H_D) criteria to ensure that nuclear power plants can withstand the effects of earthquakes with a desired performance, the desired performance being expressed as the target value of 1 x 10^{-5} for the mean annual probability of exceedance of the onset of significant inelastic deformation (FOSID). This approach targets a performance criteria which is defined relative to the onset of inelastic deformation; instead of relative to the occurrence of failure of the SSC"

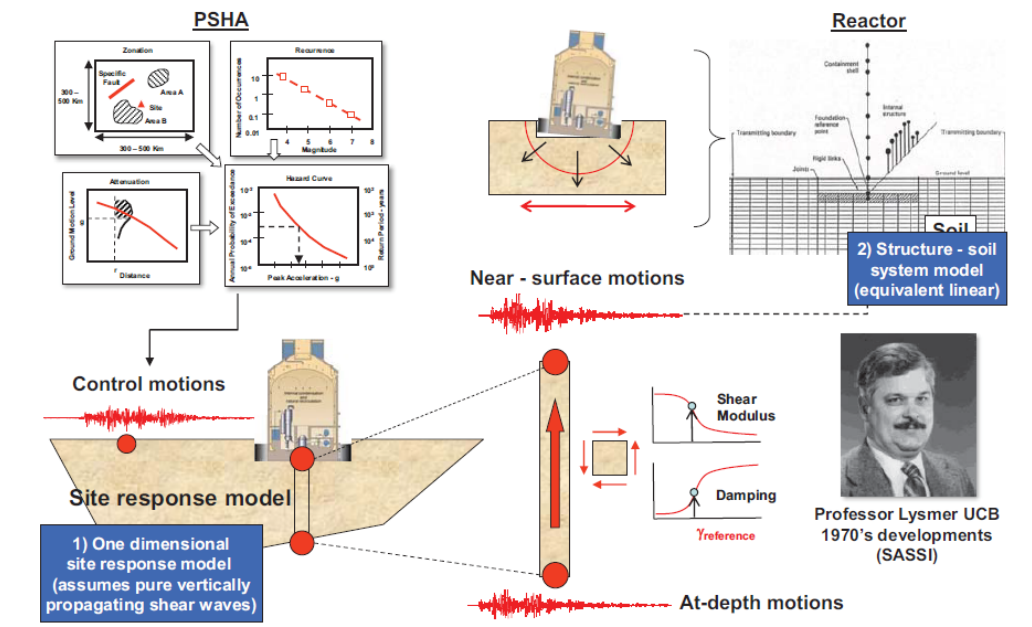
	A Large Permanent Distortion (short of collapse)	B Moderate Permanent Distortion	C Limited Permanent Distortion	D Essentially Elastic Response Behavior
1	ASCE-7	ASCE-7	ASCE-7	NA
2	ASCE-7	ASCE-7	NA	NA
3	ASCE 43-05	ASCE 43-05	ASCE 43-05	ASCE 43-05
4	ASCE 43-05	ASCE 43-05	ASCE 43-05	ASCE 43-05
5	ASCE 43-05	ASCE 43-05	ASCE 43-05	ASCE 43-05

NRC restricts Nuclear plants to Seismic Design Category 5 and Limit State D

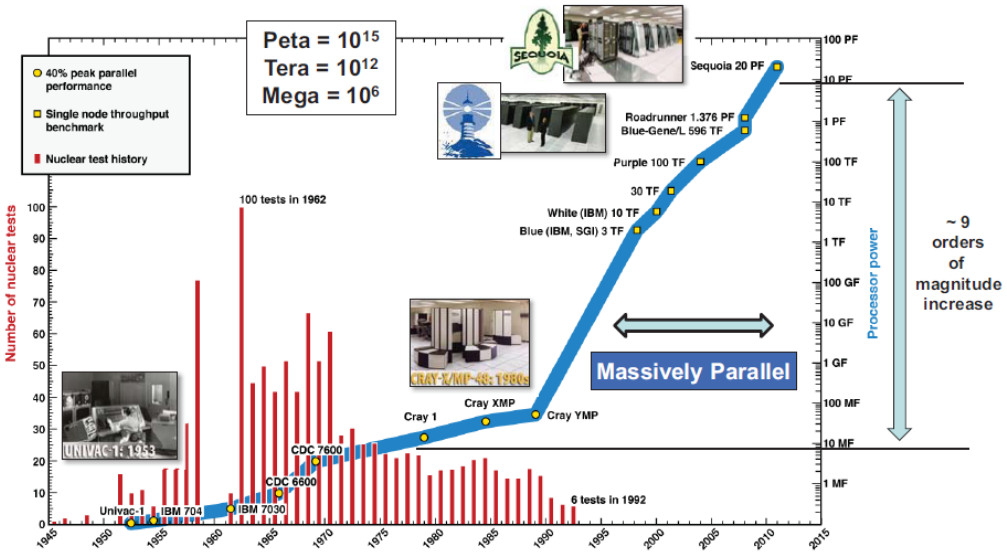
The actual problem is very complex and crosses multiple discipline boundaries



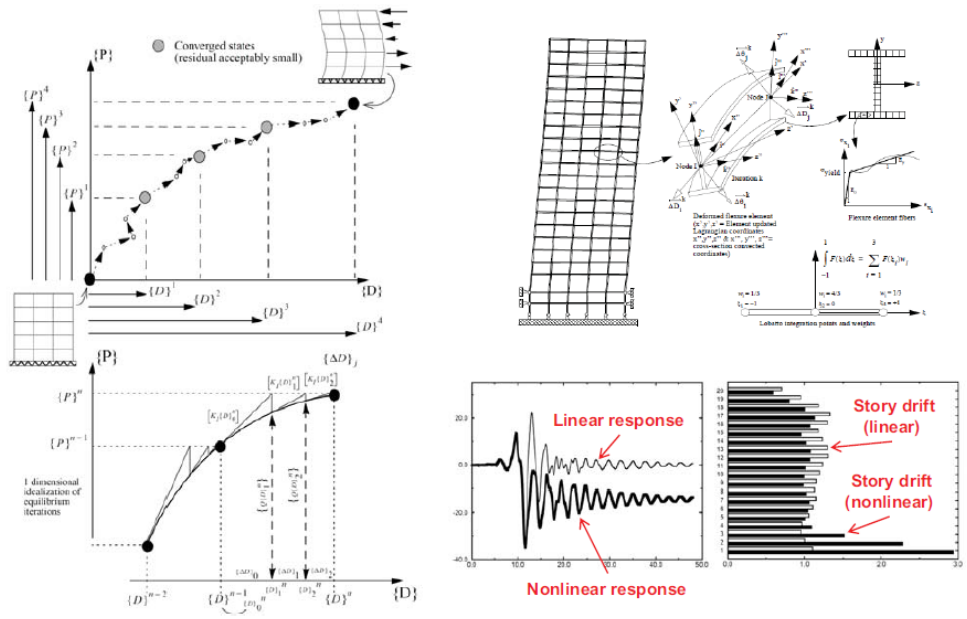
For nuclear systems, simulations are applied, but to a significantly simplified idealization of the actual problem



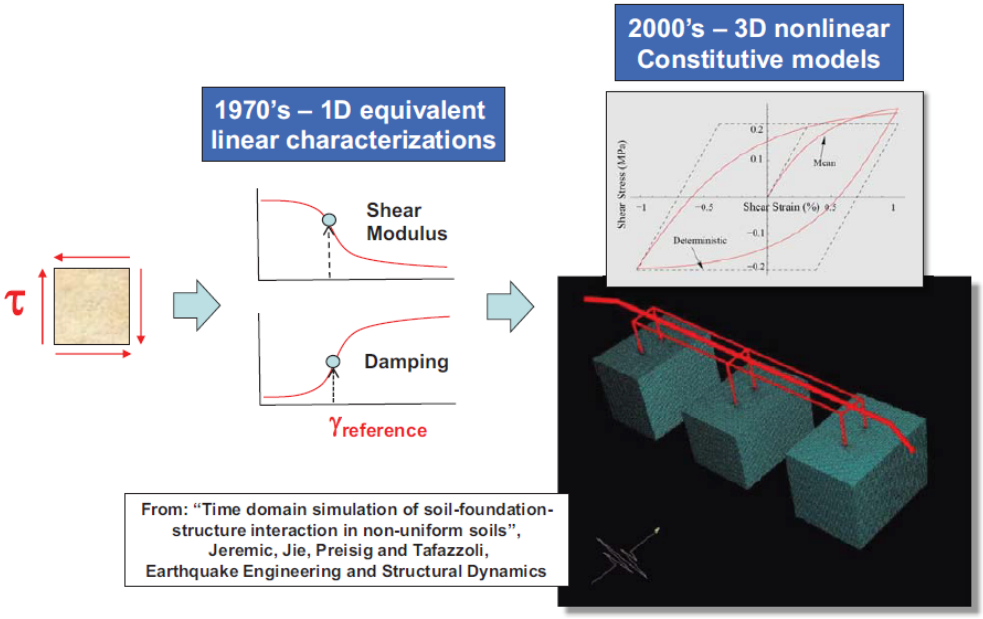
What's changed - we are no longer encumbered by the computational hardware limitations of the 1970's



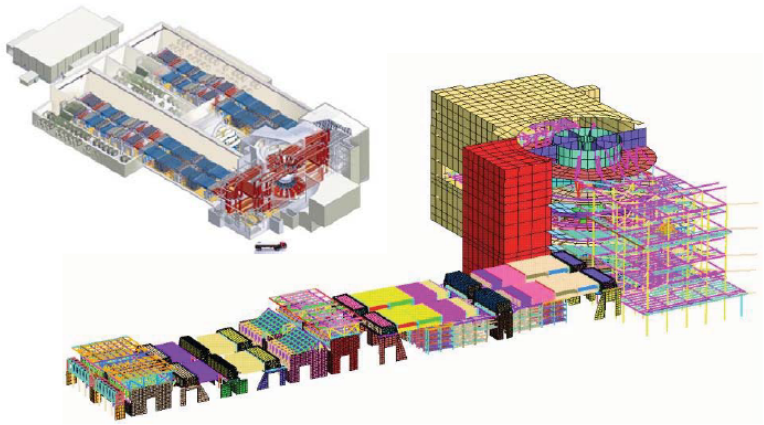
What's changed – tremendous advances in computational mechanics, especially nonlinear methodologies



What's changed – significant advancements in our understanding, and the ability to model, nonlinear soils behavior

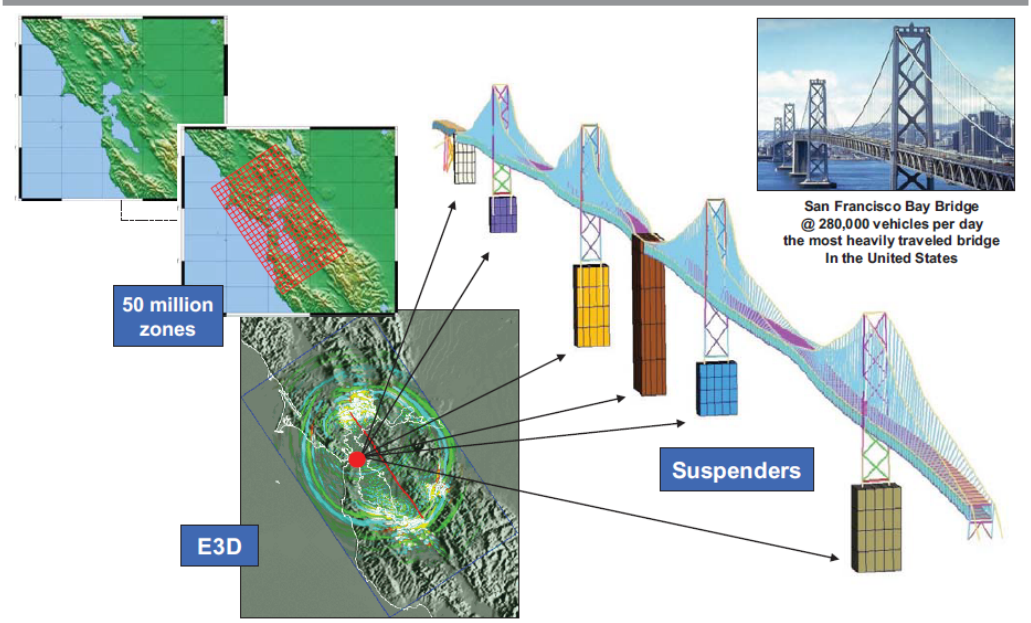


From: "Time domain simulation of soil-foundation-structure interaction in non-uniform soils", Jeremic, Jie, Preisig and Tafazzoli, Earthquake Engineering and Structural Dynamics



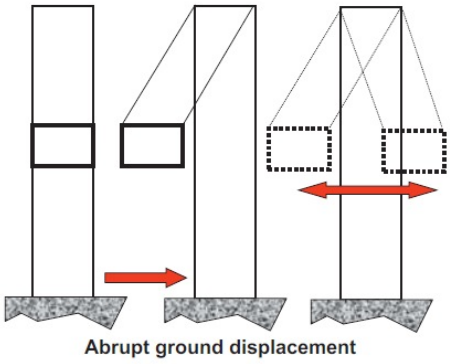
High Performance Simulations

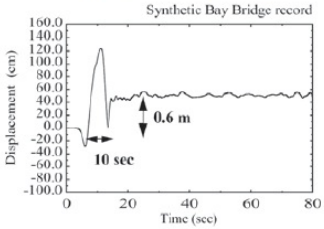
Providing insight on critical issues – the response of long-span bridges to low frequency, near-fault ground motions

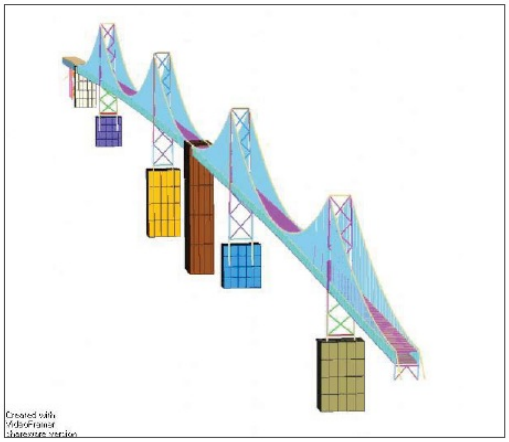


Computational exploration of rupture scenarios

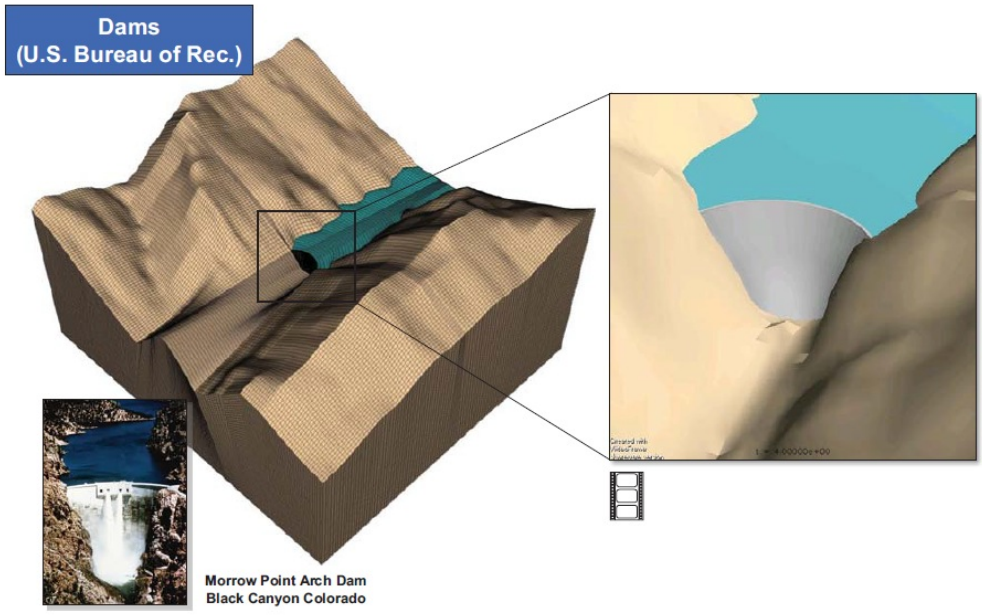
Long period motions have major effect on bridge response!



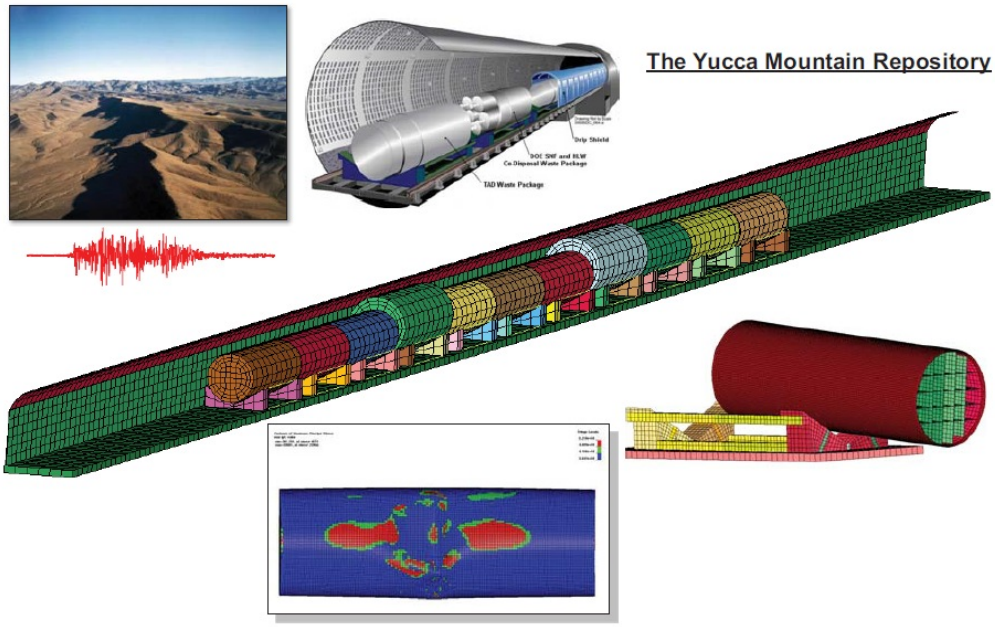




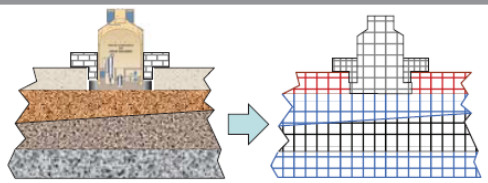
Moving beyond traditional idealizations for the seismic response of dam systems



The seismic analysis of complex, highly nonlinear systems

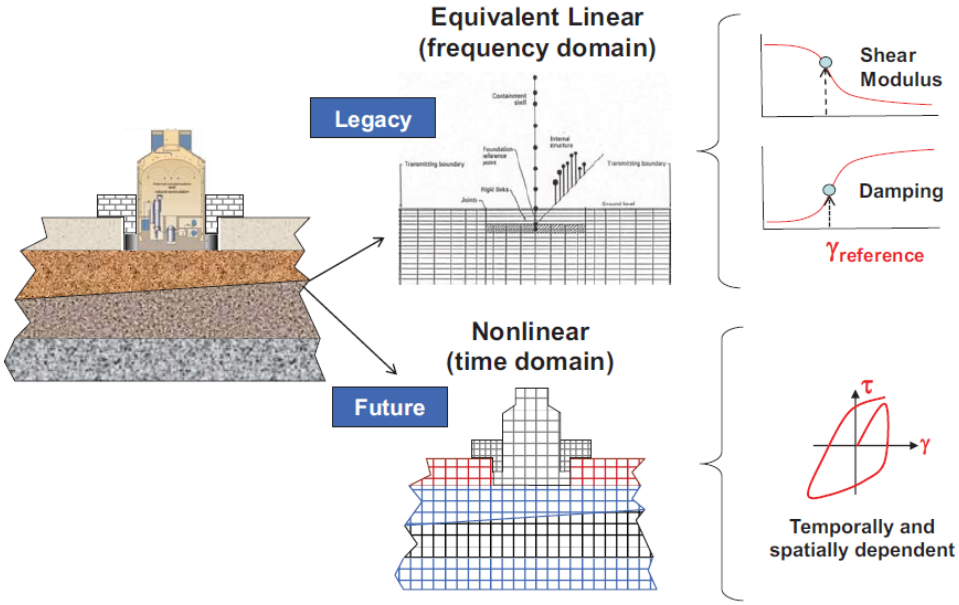


What simulation end-state would be desirable for nuclear power plant systems?



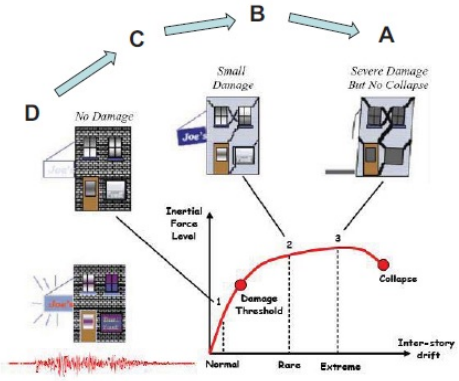
- A simulation model capable of representing the nonlinear response of plant/soil systems
- Capabilities for accurately simulating plant response for extreme (beyond design basis) events
- A simulation model capable of exploring new technology design options (composite walls, base isolation, new reactor configurations, e.g. SMRs)
- Leverages existing massive investment in modern simulation codes and pre- and post-processors

Need #1 – Implement fully nonlinear, detailed 3D model time domain solutions for plant / soil interaction response

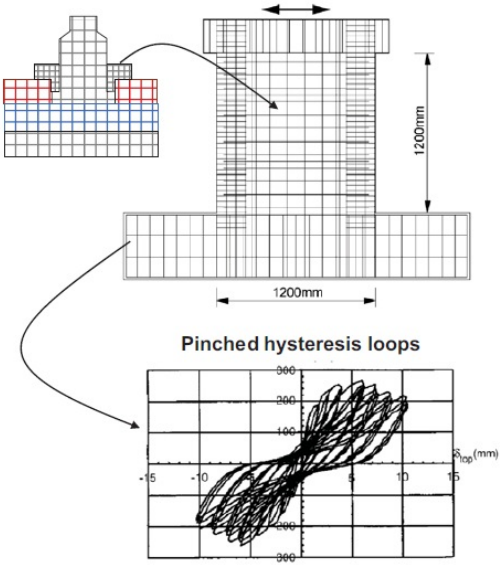


The Japanese are moving expeditiously in exactly this direction

Need #2 – realistic models for exploring plant response for beyond design basis seismic events

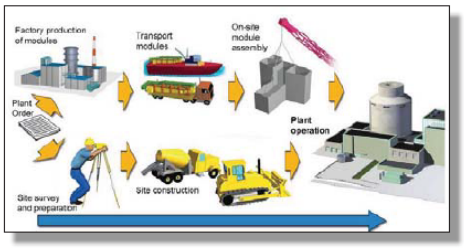


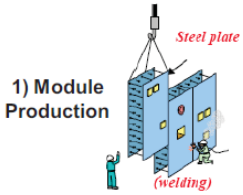
Courtesy UC Berkeley Civil Engineering



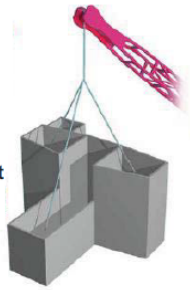
Need #3 - Realistic and accurate simulation models can enable exploration of new technologies and new reactor types

"Seismic (category 1) buildings cost 3 times as much as non-seismic (i.e. UBC seismic) buildings"
- Westinghouse

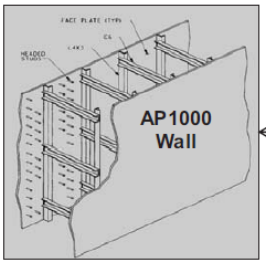


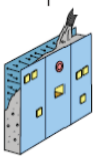


1) Module Production



2) Module Placement

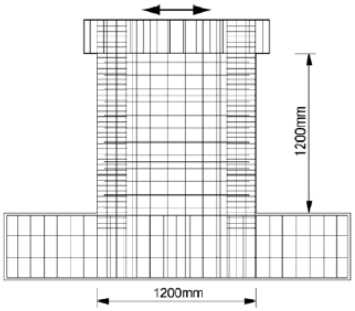




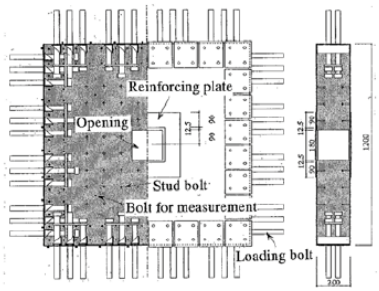
3) On-site Concrete Pour

Composite walls appear to exhibit enhanced nonlinear behavior

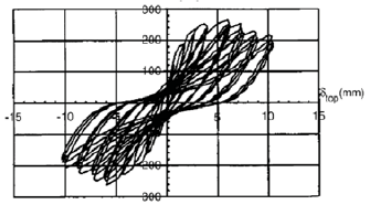
Typically reinforced low-rise concrete walls



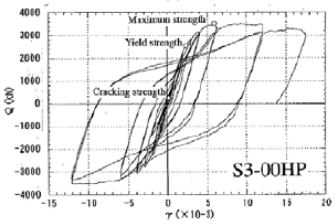
Composite walls



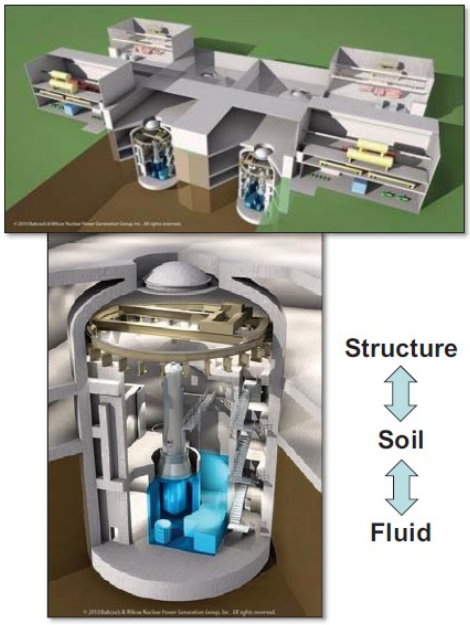
Pinched hysteresis loops



Good ductile behavior



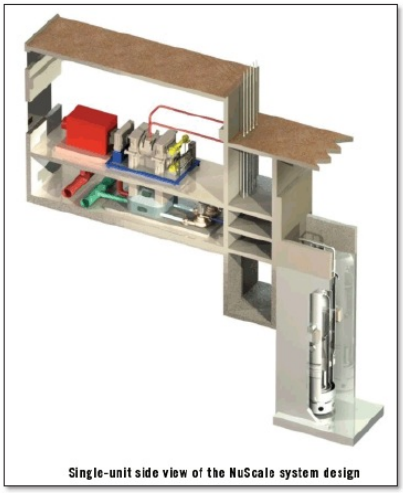
Design advancements for Small Modular Reactors (SMRs)



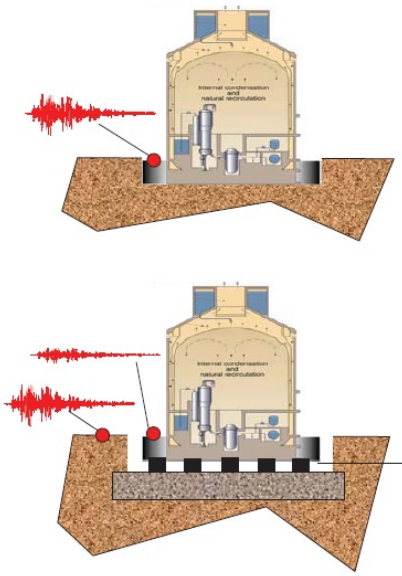
Structure

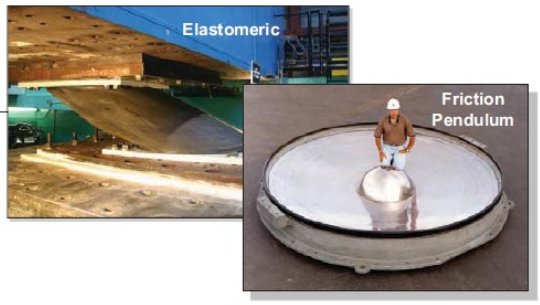
Soil

Fluid

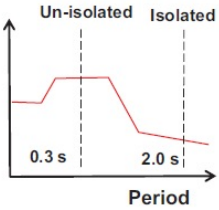


Base isolated systems

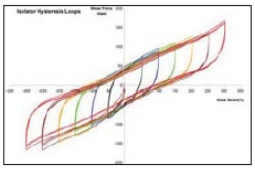




Input modification

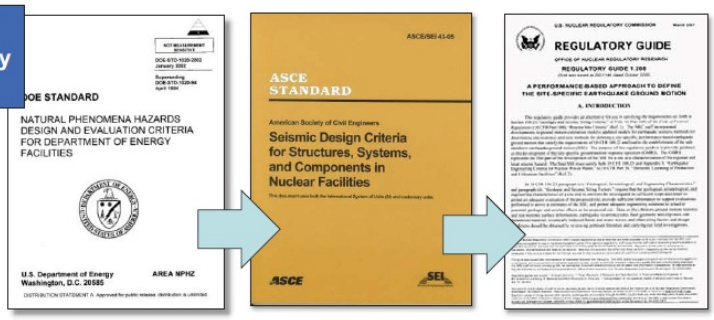


Damping

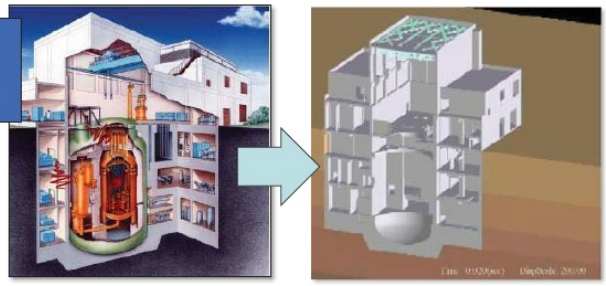


The DOE can bring the necessary simulation expertise to bear to demonstrate the path forward

Good news: We have a regulatory framework



We will explore the utility of advanced simulations



We would like to solicit your collective expert advice and input

- **What methods and capabilities would provide the most benefit and leverage?**
- **How can advanced capabilities make a difference and what barriers to implementation (technical or regulatory) might exist**

Please think expansively in terms of what could be not what is

Presentation of Boris Jeremic LBNL/UC-Davis

Soil Behavior Prospects for Seismic Response of Nuclear Power Plants

Boris Jeremić

Professor, University of California, Davis
Faculty Scientist, Lawrence Berkeley National Laboratory, Berkeley

February 27th-28th. 2012
Lawrence Livermore National Laboratory

Outline

Motivation

Current Capabilities
- Seismic Energy Input and Dissipation
- Current Deterministic Modeling Capabilities and Examples
- Uncertain Engineering Material Behavior

Capabilities within 3-5 Years
- Look Into Near Future

Summary

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Summary

Motivation

- **Physics based modeling and simulation** of seismic behavior of Nuclear Power Plant Structures, Systems and Components (NPPSSC)
- Development and use of **high fidelity** numerical models, with **uncertainty** quantification and propagation
- Accurate following of the **flow of seismic energy** (input and dissipation) within NPPSSC soil-foundation-structure (SFS) system
- Eventually, **directing**, in space and time, with **high confidence**, seismic energy flow in the soil-foundation-structure system
- **Education** for researchers, professional practice.

Outline

Motivation

Current Capabilities
- Seismic Energy Input and Dissipation
- Current Deterministic Modeling Capabilities and Examples
- Uncertain Engineering Material Behavior

Capabilities within 3-5 Years
- Look Into Near Future

Summary

Seismic Energy Input and Dissipation for an Entire NPP SFS System

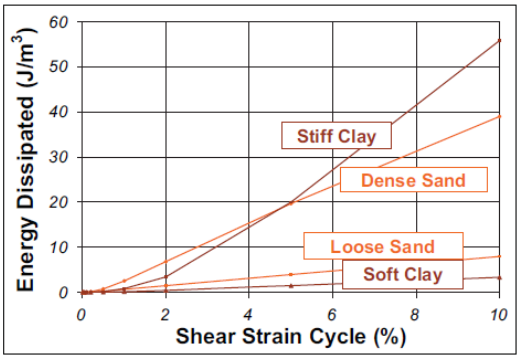
- Energy influx, body and surface waves, 3D, inclined
- Mechanical dissipation outside of SFS domain:
  - Radiation of reflected waves
  - Radiation of oscillating SFS system
- Mechanical dissipation inside SFS domain:
  - Plasticity of soil/rock subdomain
  - Plasticity of foundation – soil/rock interface
  - Viscous coupling of porous solid with pore fluid (air, water)
  - Plasticity/damage of the structure
  - Viscous coupling of structure/foundation with fluids
- Numerical energy dissipation/production

High Fidelity Modeling and Simulation

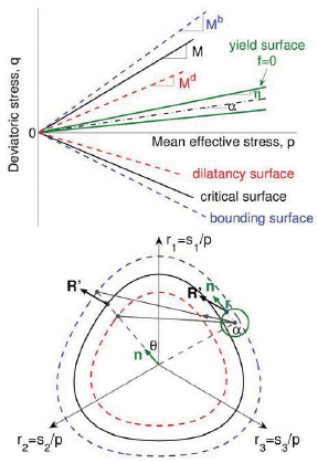
- **Material models** (nonlinear anisotropic elastic; elastic-Plastic: SANISand and SANIClay)
- **Finite Elements** (dry and saturated, u-p (small and large def.), u-p-U (small def.))
- **Numerical Procedures** (Constitutive level: explicit, implicit; Finite element: explicit, implicit; High Performance Computing (Dynamic Computational Load Balancing → Plastic Domain Decomposition)
- **Verification** (extensive) and **Validation** (limited)
- **Stochastic** (probabilistic) modeling and simulations (uncertain material, geometry, loads)

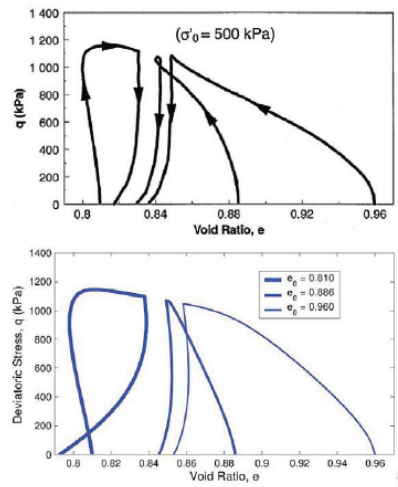
Energy Dissipation by Plasticity

- Plastic work ($W = \int \sigma_{ij} d\epsilon_{ij}^{pl}$)
- High Fidelity elastic-plastic models for soil, rock, concrete
- Energy dissipation capacity for different soils



High Fidelity Elastic-Plastic Model for Soil: Manzari-Dafalias





Energy Dissipation by Viscous Coupling

- Viscous coupling of porous solid and fluid
- Energy loss per unit volume is $E_{vc} = n^2 k^{-1} (\dot{U}_i - \dot{u}_i)^2$
- Natural in $u - p - U$ formulation:

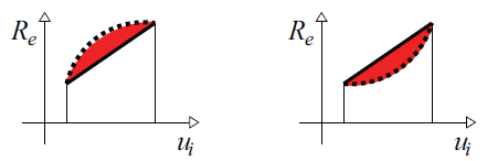
$$\begin{bmatrix} (M_s)_{KijL} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & (M_f)_{KijL} \end{bmatrix} \begin{bmatrix} \ddot{\bar{u}}_{Lj} \\ \ddot{\bar{p}}_N \\ \ddot{\bar{U}}_{Lj} \end{bmatrix} + \begin{bmatrix} (C_1)_{KijL} & 0 & -(C_2)_{KijL} \\ 0 & 0 & 0 \\ -(C_2)_{LjiK} & 0 & (C_3)_{KijL} \end{bmatrix} \begin{bmatrix} \dot{\bar{u}}_{Lj} \\ \dot{\bar{p}}_N \\ \dot{\bar{U}}_{Lj} \end{bmatrix}$$

$$+ \begin{bmatrix} (K^{EP})_{KijL} & -(G_1)_{KiM} & 0 \\ -(G_1)_{LjM} & -P_{MN} & -(G_2)_{LjM} \\ 0 & -(G_2)_{KiL} & 0 \end{bmatrix} \begin{bmatrix} \bar{u}_{Lj} \\ \bar{p}_M \\ \bar{U}_{Lj} \end{bmatrix} = \begin{bmatrix} \bar{f}^{solid}_{Ki} \\ 0 \\ \bar{f}^{fluid}_{Ki} \end{bmatrix}$$

$$(C_{(1,2,3)})_{KijL} = \int_\Omega N_K^{(u,u,U)} n^2 k_{ij}^{-1} N_L^{(u,U,U)} d\Omega$$

Numerical Energy Dissipation

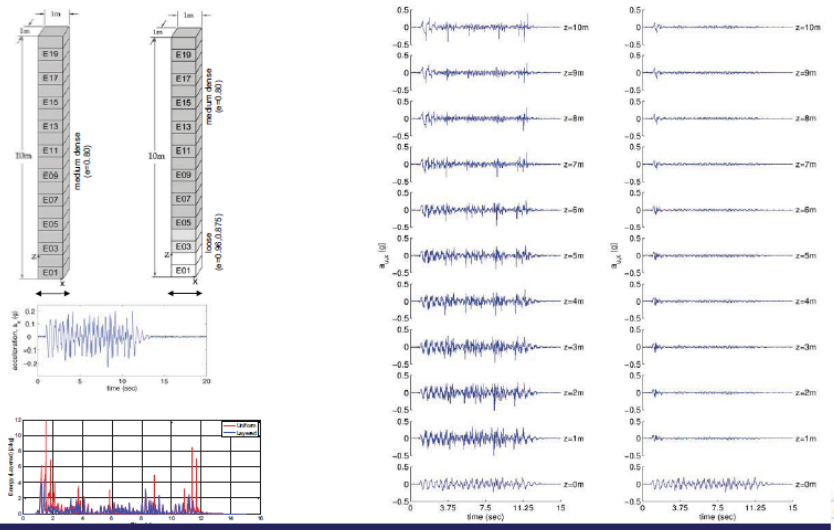
- Newmark and Hilber-Hughes-Taylor can be made non-dissipative for elastic system $\alpha = 0.0, \beta = 0.25; \gamma = 0.5,$
- Or dissipative (for elastic) for higher frequency modes:
  - N: $\gamma \geq 0.5, \quad \beta = 0.25(\gamma + 0.5)^2,$
  - HHT: $-0.3\dot{3} \leq \alpha \leq 0, \quad \gamma = 0.5(1 - 2\alpha), \quad \beta = 0.25(1 - \alpha)^2$
- For nonlinear problems, energy cannot be maintained
  - Energy dissipation for steps with reduction of stiffness
  - Energy production for steps with increase of stiffness



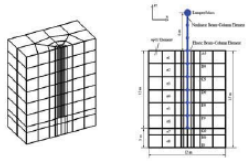
Nonlinear Modeling and Simulation Examples

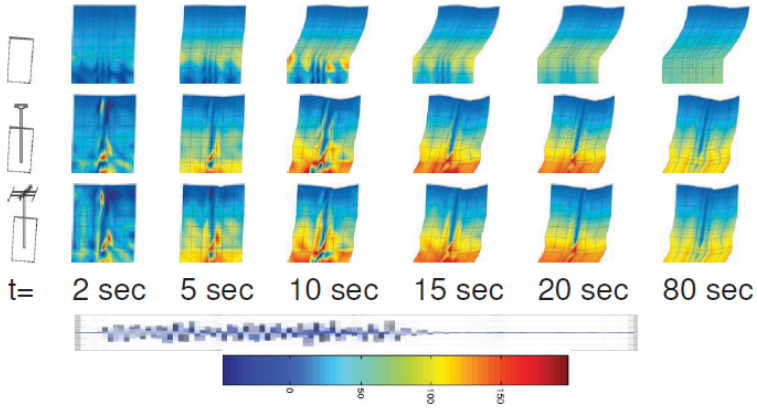
- Staged construction (numerical)
- High Fidelity modeling
- Following energy dissipation (space, time)
- Select examples:
  - Passive base isolation by liquefaction
  - Bridge pile foundations in liquefiable, sloping ground
  - Full Bridge SFS model with variable soils and incoherent motions
  - Nuclear Power Plant with nonlinear base slip (passive isolation)

Passive Base Isolation in Uniform and Layered Soils



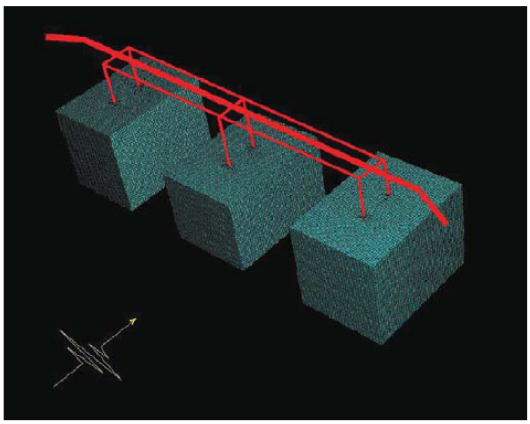
Pile in Liquefiable Sloping Ground



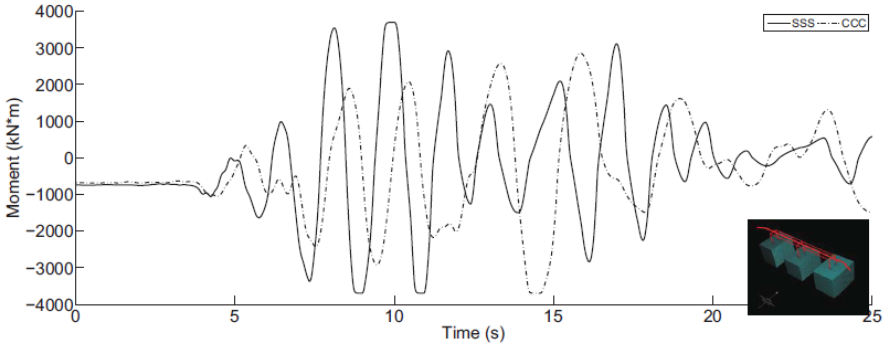


Bridge ESSI System

- Variable foundation soil
- Incoherent, vertical seismic wave
- Number of Earthquakes
- Frequencies up to 10Hz resolved (for nonlinear soil)
- Parallel (PDD) simulations with up to 1.5M DOFs

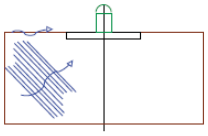


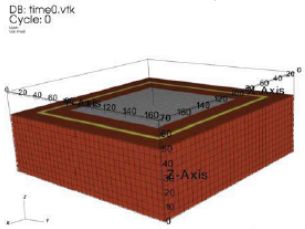
Short Period E.: Left Bent, Bending Moments

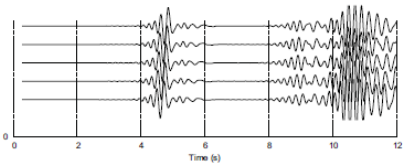


Nuclear Power Plant with Base Slip

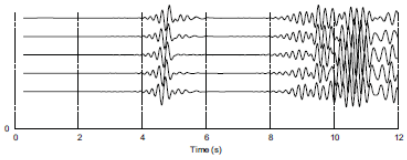
- Low friction zone between concrete foundation and soil/rock
- Inclined, 3D, body and surface, seismic wave field (wavelets: Ricker, Ormsby; real seismic, etc.)





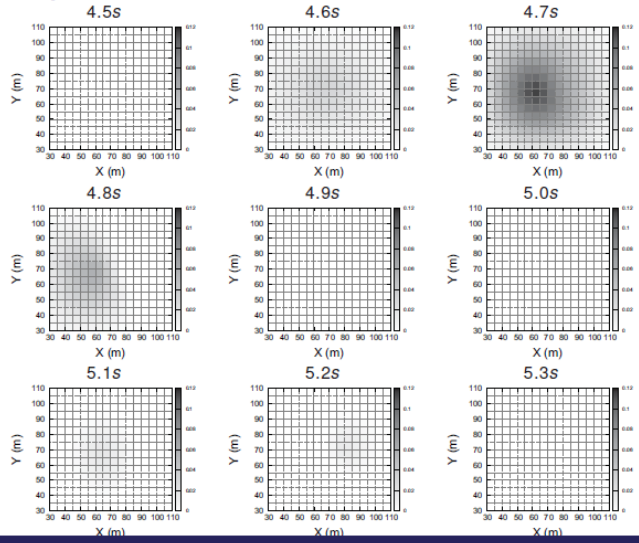


horizontal

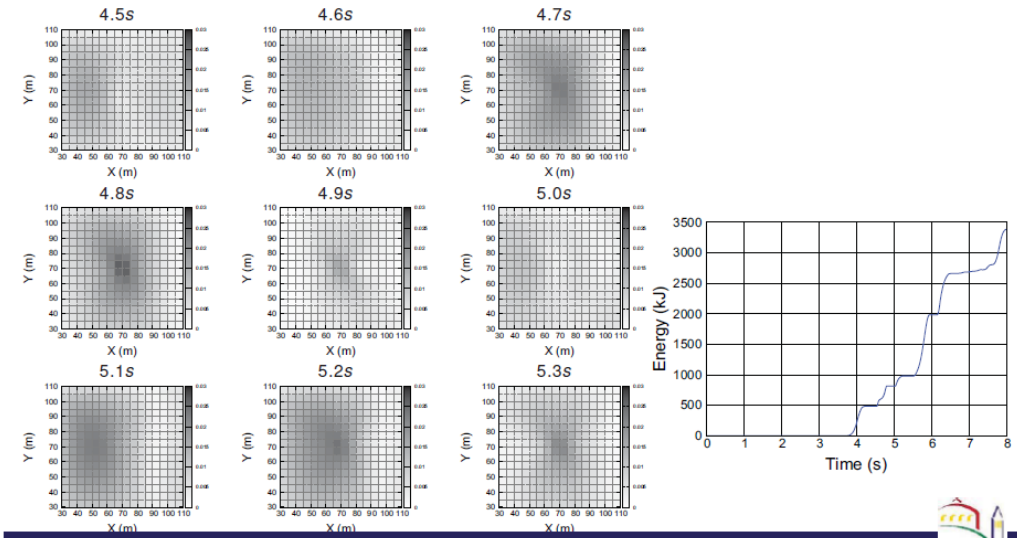


vertical

Gaping Response (45° Ricker Wavelet)

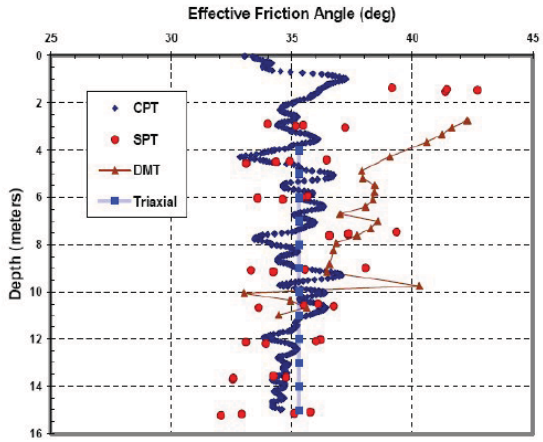


Slipping Response and Energy Dissipated (45° Ricker)



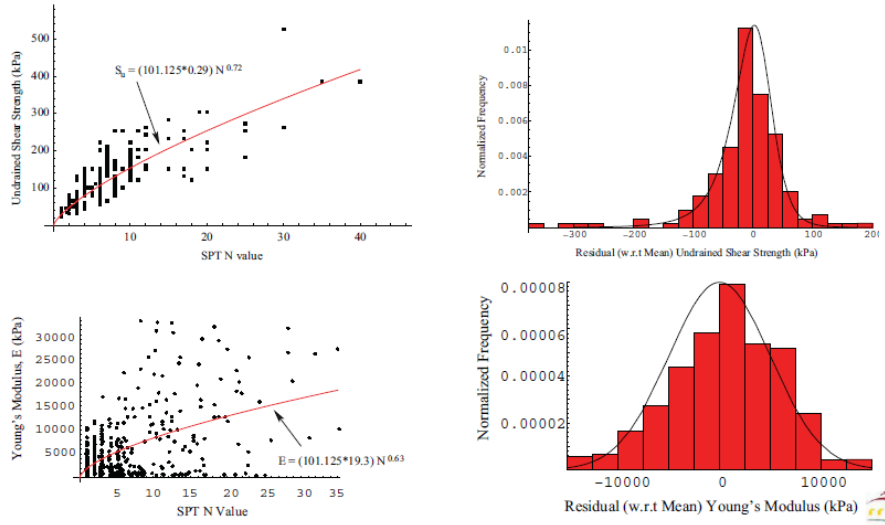
Material Behavior Inherently Uncertain

- Spatial variability
- Point-wise uncertainty, testing error, transformation error



(Mayne et al. (2000)

SPT Data: Shear Strength and Elasticity



Uncertainty Propagation through Constitutive Eq.

- Incremental el–pl constitutive equation $\Delta\sigma_{ij} = E_{ijkl}\Delta\epsilon_{kl}$

$$E_{ijkl} = \begin{cases} E^{el}_{ijkl} & \text{for elastic} \\ E^{el}_{ijkl} - \dfrac{E^{el}_{ijmn} m_{mn}\, n_{pq} E^{el}_{pqkl}}{n_{rs} E^{el}_{rstu} m_{tu} - \xi_* h_*} & \text{for elastic–plastic} \end{cases}$$

Probabilistic Stress Solution: Eulerian–Lagrangian form of FPK Equation

$$
\begin{aligned}
\frac{\partial P(\sigma_{ij}(x_t,t),t)}{\partial t} &= \frac{\partial}{\partial \sigma_{mn}}\Bigg[\Bigg\{\Big\langle \eta_{mn}(\sigma_{mn}(x_t,t),E_{mnrs}(x_t),\epsilon_{rs}(x_t,t))\Big\rangle \\
&+ \int_0^t d\tau\, Cov_0\Bigg[\frac{\partial \eta_{mn}(\sigma_{mn}(x_t,t),E_{mnrs}(x_t),\epsilon_{rs}(x_t,t))}{\partial \sigma_{ab}}; \\
&\quad \eta_{ab}(\sigma_{ab}(x_{t-\tau},t-\tau),E_{abcd}(x_{t-\tau}),\epsilon_{cd}(x_{t-\tau},t-\tau)\Bigg]\Bigg\} P(\sigma_{ij}(x_t,t),t)\Bigg] \\
&+ \frac{\partial^2}{\partial \sigma_{mn}\partial \sigma_{ab}}\Bigg[\Bigg\{\int_0^t d\tau\, Cov_0\Bigg[\eta_{mn}(\sigma_{mn}(x_t,t),E_{mnrs}(x_t),\epsilon_{rs}(x_t,t)); \\
&\quad \eta_{ab}(\sigma_{ab}(x_{t-\tau},t-\tau),E_{abcd}(x_{t-\tau}),\epsilon_{cd}(x_{t-\tau},t-\tau))\Bigg]\Bigg\} P(\sigma_{ij}(x_t,t),t)\Bigg]
\end{aligned}
$$

Eulerian–Lagrangian FPK Equation and (SEP)FEM

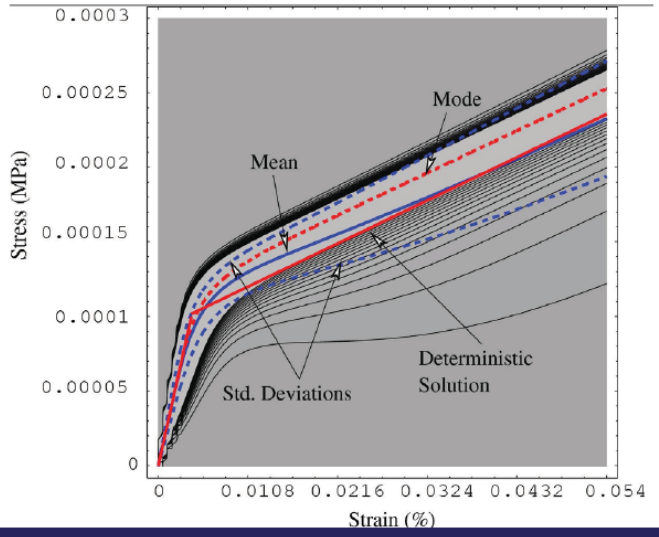
- Advection-diffusion equation

$$
\frac{\partial P(\sigma_{ij},t)}{\partial t} = -\frac{\partial}{\partial \sigma_{ab}}\left[N^{(1)}_{ab}P(\sigma_{ij},t) - \frac{\partial}{\partial \sigma_{cd}}\left\{N^{(2)}_{abcd}P(\sigma_{ij},t)\right\}\right]
$$

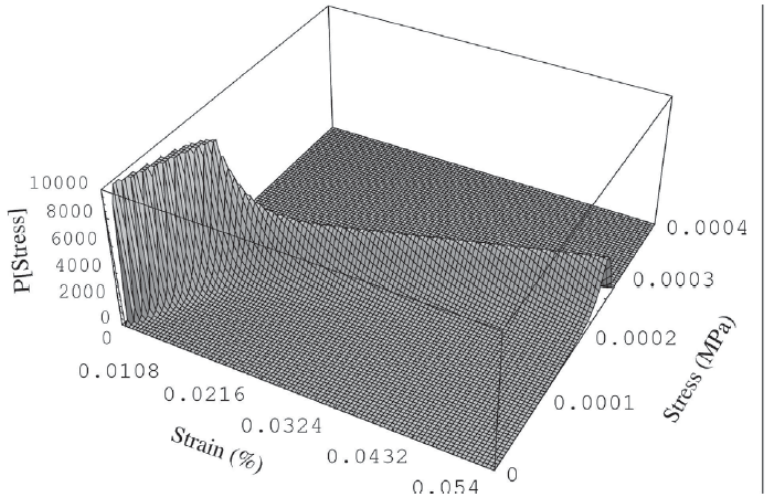
- **Complete** probabilistic description of response
- **Second-order exact** to covariance of time (exact mean and variance)
- Any uncertain FEM problem ($\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} = \mathbf{F}$) with
  - uncertain material parameters (stiffness matrix $\mathbf{K}$),
  - uncertain loading (load vector $\mathbf{F}$)

  can be analyzed using PEP and SEPFEM to obtain PDFs of DOFs, stress, strain...

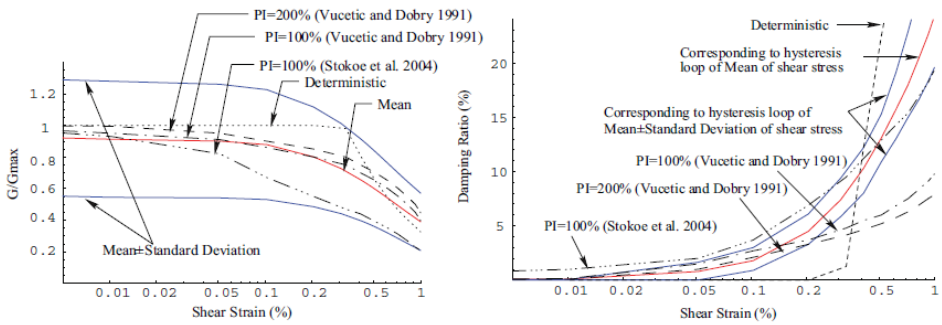
Probabilistic Elastic-Plastic Response



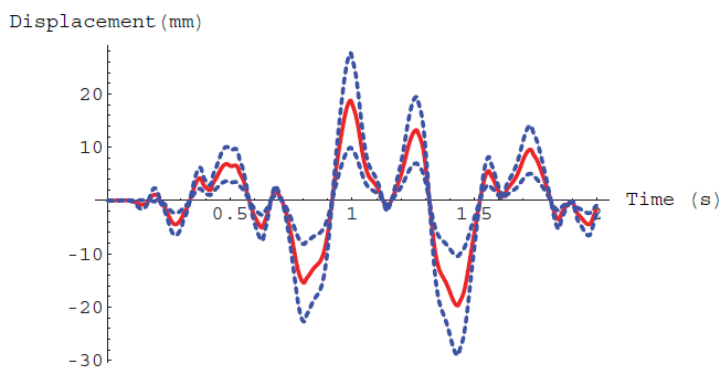
Probabilistic Elastic-Plastic Response



G/G_{max} and Damping Response

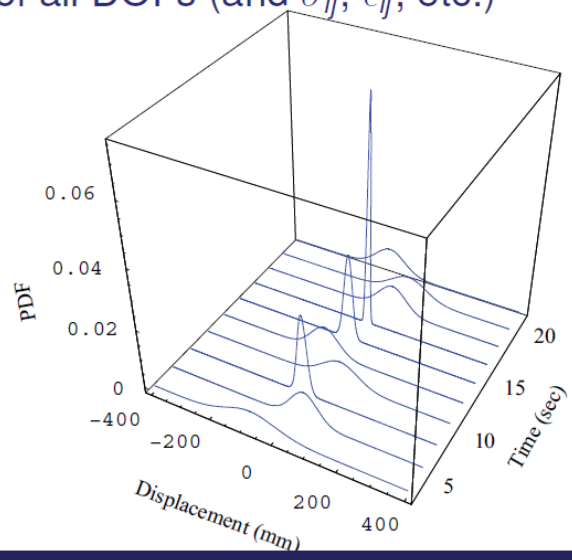


Seismic Wave Propagation through Stochastic Soil



Mean± Standard Deviation

Full PDFs of all DOFs (and σ_{ij}, ϵ_{ij}, etc.)



Outline

Motivation

Current Capabilities
- Seismic Energy Input and Dissipation
- Current Deterministic Modeling Capabilities and Examples
- Uncertain Engineering Material Behavior

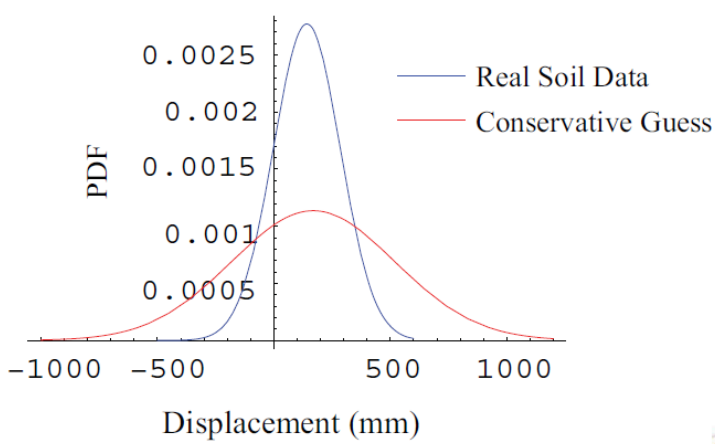
Capabilities within 3-5 Years
- Look Into Near Future

Summary

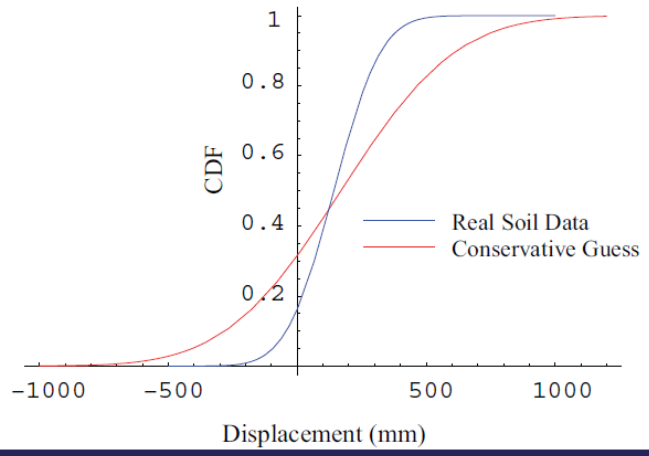
High Fidelity Stochastic Modeling and Simulation for Risk Informed Decision Making

- Forward uncertainty propagation (Fokker-Planck or forward Kolmogorov)
  - Propagate uncertainty in material (stiffness) and loads
  - Develop analytic fragility curves for all/any DOFs, σ_{ij}, ϵ_{ij}, etc. for an NPP (Structure, Systems and Components)
- Backward uncertainty propagation (backward Kolmogorov)
  - Given limits on risk, improve material and loads characterization
  - Optimize safety, equalize risk for
    - Seismic Source, Path,
    - Soil/Rock, Foundation
    - Structures, Systems and Components

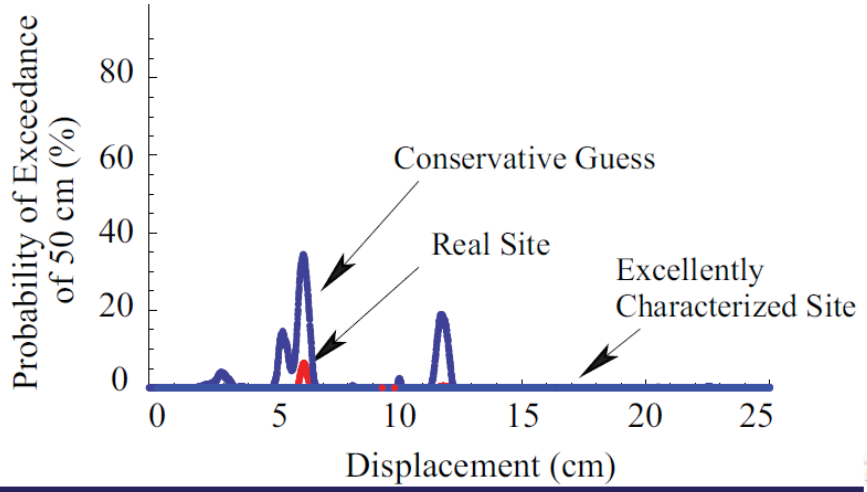
Example: Displacement PDF at 6 s



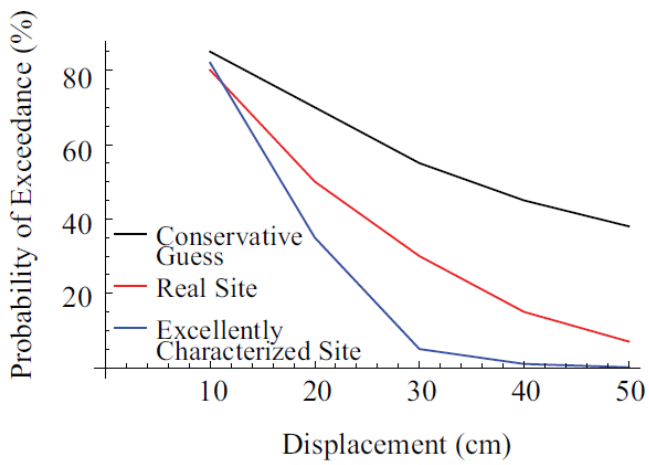
Example: Displacement CDF, Fragility (Non-Exceedance) at 6 s



Probability of Exceeding 50cm Displacement



Risk of Unacceptable Deformation



Full 3D, Time Domain, Elastic-plastic Uncertain SSI Simulations

- Fully quantify all sources of risk using Stochastic Elastic-Plastic Finite Element Method simulation
  - seismic source and path
  - site response
  - Soil/rock Structure Interaction
  - Structure, Systems and Components
- Use gained knowledge for **risk informed decision making on safety and economy**

Outline

Motivation

Current Capabilities
- Seismic Energy Input and Dissipation
- Current Deterministic Modeling Capabilities and Examples
- Uncertain Engineering Material Behavior

Capabilities within 3-5 Years
- Look Into Near Future

Summary

Summary

- **Interplay** of **Uncertain Earthquake**, **Uncertain Soil/Rock**, and **Uncertain Structure** in time domain **probably** plays a decisive role in seismic performance of NPPs
- Improve **risk informed decision making** through high fidelity **Stochastic Elastic-Plastic Finite Element Method** simulations
- **Education and training** of users will prove essential

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B. Jeremić, S. Kunnath and F. Xiong. Influence of Soil–Structure interaction on Seismic Response of Bridges. *International Journal for Engineering Structures*, Volume 26, Issue 3, February 2004, pp. 391-402

Presentation of Lawrence Hutchings, LBNL

This section of Appendix 2 includes slides presented by Lawrence Hutchings of LBNL. Prior to the slides, this section summarizes the discussion at the workshop, prompted by some of the slides, about methods for developing realistic three-component, time-domain seismic "records" from a scattered wavefield, as input into soils models. Although this topic is related to seismic motion effects on embedded nuclear power plant structures and equipment, it is not within the scope of the current DOE-sponsored project, nor within the specific scope of this Workshop, and hence is discussed in this appendix rather than the main body of the report.

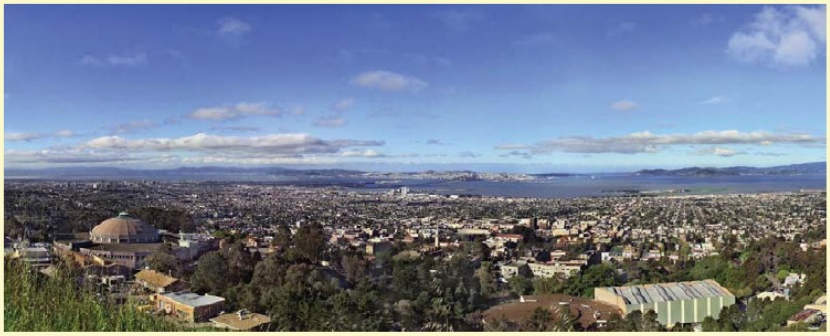
Methods for developing three-component, time-domain seismic "records" include earthquake rupture models, regional wave propagation, and local geologic scattering. The motion is linear and will couple with the soils models to drive the non-liner effects in the soils and structure. It was recognized during the workshop discussion that ultimately such input ground motions could be necessary in order to calculate the response of buried structures realistically. Further, it was argued that computing ground motions offer the best means to get realistic input motions, because recordings of ground motions at surface or basement sites from previous earthquakes, are point recordings that do not provide the point-to-point variability that is important for SSI problems.

Synthetic ground motions can be calculated for realistic fault ruptures from earthquakes that may impact a specific site, and these motions and can incorporate the actual geology of the site. This is in contrast to the use of recordings from other sources and geologies that may or may not be relevant to the specific site. Further, recorded ground motions are generally limited to frequencies less than 25 Hz, which limits the ability to examine high frequency effects on structures. Finally, calculating synthetic ground motions allows one to carry out experiments to understand the structural response sensitivity to geologic heterogeneity, rupture propagation and near-source effects, source-site geometric effects on the wavefields, and non-linearities in soil response caused by different size earthquakes.

Given the above, there was a sentiment expressed during the Workshop that ultimately this type of modeling work on the input motions to the soils model will be an important constituent of the long-sought realistic numerical model of the entire "system."

ESD EARTH SCIENCES DIVISION

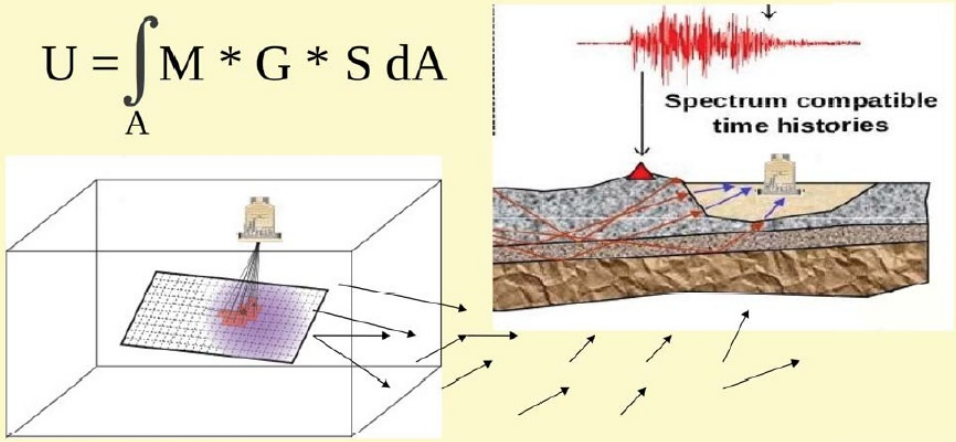
Site Specific, Broadband, Strong Ground Motion Synthesis for SSI



ESD EARTH SCIENCES DIVISION

Synthesized Ground Motion

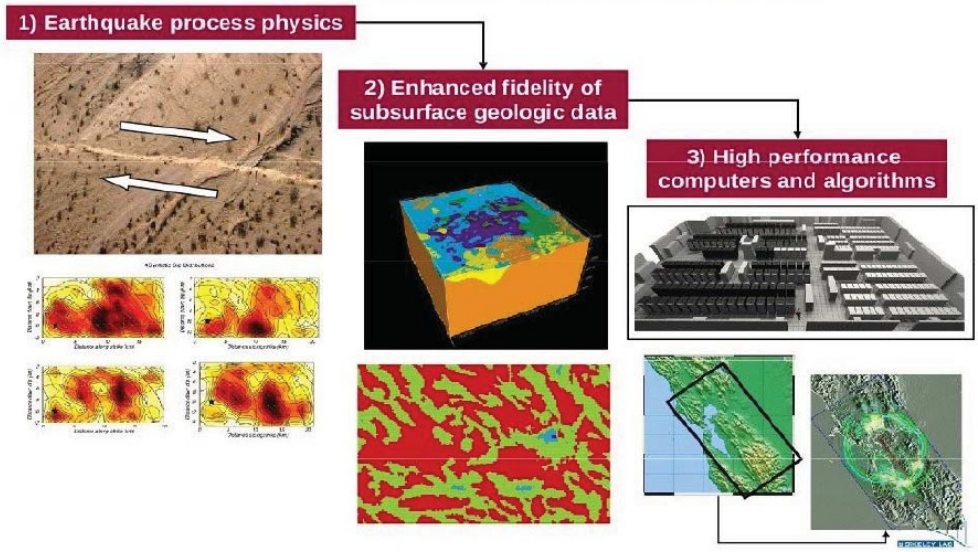
$$U = \int_A M * G * S \, dA$$



- This Talk: Green's Functions & Site Response
- Will talk a little about earthquake simulations
- Will talk a little about physics-based PSHA

ESD EARTH SCIENCES DIVISION

Computational Approaches exist to model ground motion from the source to the site



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Synthesized Ground Motion

- Spectrum compatible time histories based upon conventional PSHA
- DC – 50 Hz
- Full 3D scattered wavefield
- Multiple input points to soils models
- Source and Site Specific
- Linear response
- Physics based

ESD EARTH SCIENCES DIVISION

Why not use Empirical Ground Motion (EGM) records?

- EGM records are at a single point, no point-to-point variability
- EGM typically is band limited 0.2 to 25.0 Hz
- EGM is for a different geology
- EGM is for different earthquakes

ESD EARTH SCIENCES DIVISION

Synthetic Green's functions

- FK Sommerfeld integral, reflectivity (Saikia, 1994)
  - 1D layered half-space
  - DC – 25 Hz
  - Regional wave propagation
- Finite difference: *E3D & WPP* (LLNL, 1996, 2000)
  - resolution of velocity model scales with highest frequency
  - DC – 25 Hz (5M nodes for 1X1X1 Km, 1.5 km/s - S-waves)
  - Local 3D geology (60 m resolution)
- Stochastic method: *SMSIM* (Boore, 1996)
  - Frequencies > 25 Hz
  - does not require high-resolution velocity model
  - widely used approach to ground motion estimation for hazard

Spectral Shaping: *H/V spectral ratio (Nakamura 1990)*
  - Frequencies 0.5 - 50 Hz

Site Geology Characterization

Linear response local geology

- Passive tomography
- Reflection/Refraction Surveys
- Borehole data
- Validate models with synthesized records

Site Characterization from Ambient Noise

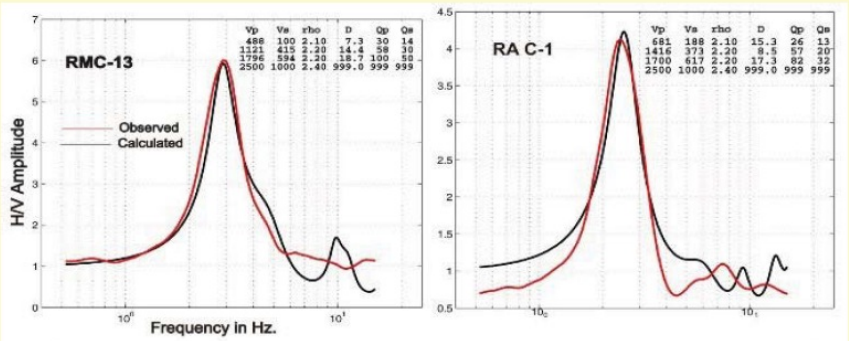
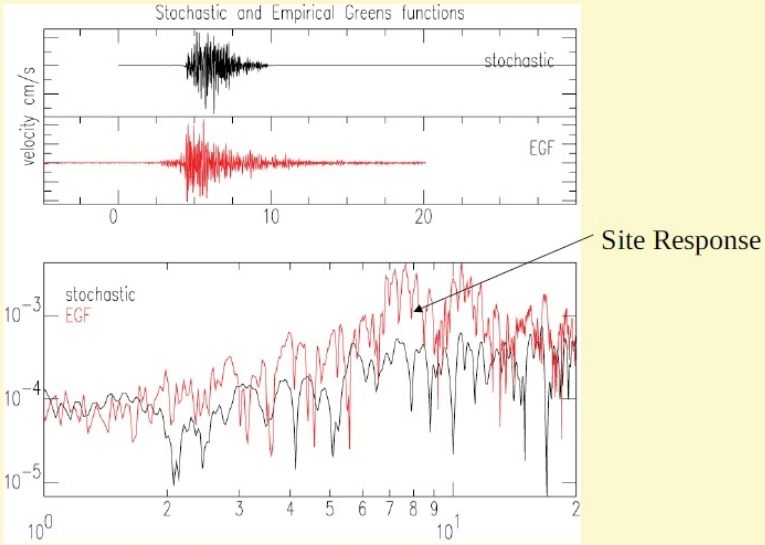


Fig.6 .samples of the matching theoretical and observed HVSR curves. The resulted velocity model is also shown in each graph with the same caption of table(1). 999.0 half space parameter.

From El-hady et al., 2011

ESD EARTH SCIENCES DIVISION

Empirical and Stochastic Green's Functions



Simulations of Hayward Fault rupture scenarios

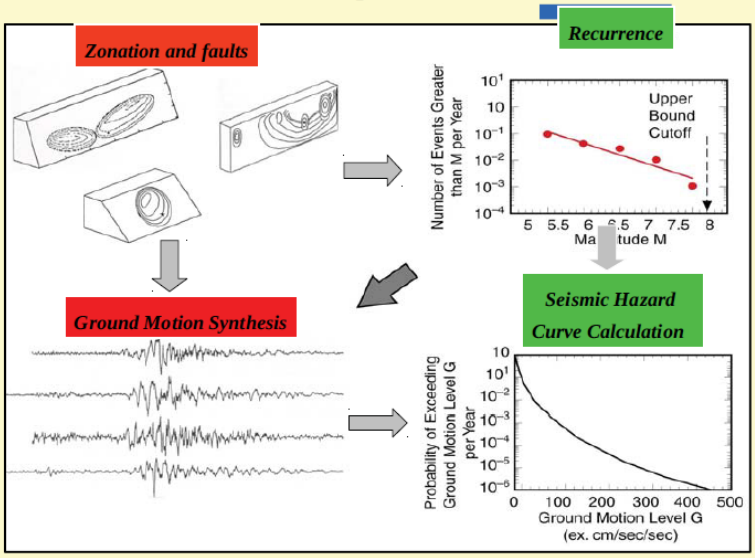
Source Models

Validate models with synthesized records

- Dynamic
  - Dietrich (1990)
  - Johnson (2005)
  - Day (2006)
- Quasi-dynamic
  - Boatwright (1980)
  - Ross (1996)
  - Dietrich (2010)
- Kinematic
  - Spudich (1995)
  - Hutchings (1996)
  - Dreger (2000)

Physically-based PSHA

Synthesize rupture, propagation, and site response



ESD EARTH SCIENCES DIVISION

Questions

- Can we calculate realistic synthetic GM
- Does Synthetic GM offer an improvement over Empirical GM
- Are the uncertainties in Source, Path and Site manageable
- Does 3D scattered wavefield make a difference for SSI
- Extend to Pb-PSHA & PSRA – performance based risk
- Can sophisticated analysis be utilized by industry

Presentation of Andrew Whittaker, Expert Panel

Universities

NTU	=	National Taiwan University
Purdue	=	Purdue University
UB/LBNL	=	University at Buffalo/Lawrence Berkeley National Laboratory
UCB	=	University of California, Berkeley
UCD	=	University of California, Davis
UP	=	University of Patras
UW	=	University of Washington

Industry

RPK	=	Robert Kennedy
FO	=	Farhang Ostadan
MW	=	Michael Willford

University at Buffalo

- Seismic probabilistic risk assessment procedures (UB, NTU)
  - Benefits of seismic isolation in terms of safety
  - Reduced seismic capacity of SCCs if plant isolated
- Seismic isolation systems (UB)
  - Including uncertainty and variability in isolator characteristics (RPK)
  - Seismic isolation provisions of ASCE 4; DoE/NRC requirements (RPK)
  - Beyond design basis response of isolated NPPs
  - NUREG
  - Numerical models of isolators under extreme loadings (LBNL)
  - Effect of impact on the hard stop
  - Issues relevant to SMRs
- Soil-structure interaction (UB, UCD, UCB, FO, MW)
  - Frequency- vs time-domain techniques
  - Structure-soil-structure interaction
  - Performance-based assessment
- Rotational components of earthquake ground motion (UB, UP)
  - Single and multiple station procedures
- Weapons effects on conventional and isolated nuclear structures (UB)
  - Air-shock and ground shock
  - Effect of weapon shape and point of detonation on near-field overpressure distributions
- Treatment of accidental torsion in nuclear structures (UB)
  - Guidance for ASCE 4

- Low aspect ratio RC walls (UB, UCB, UW)
  - Large-scale testing
  - Numerical models, system modeling and studies
  - Performance-based design
  - Fragility functions for performance/risk assessment
- Low aspect ratio SC walls (UB, Purdue)
  - Large-scale testing
  - Numerical models, system modeling and studies
  - Performance-based design
  - Fragility functions for performance/risk assessment

University of California, Berkeley/LBNL

University of California, Davis

Presentation of Jacobo Bielak, Expert Panel

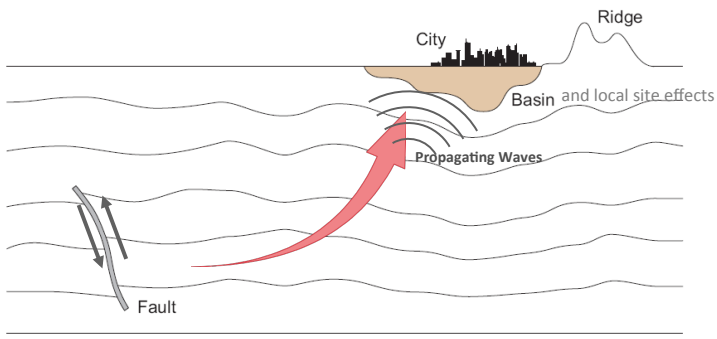
Simulation of Earthquake Impacts using the DRM

Jacobo Bielak, Yigit Isbiliroglu, and Ricardo Taborda

Carnegie Mellon University

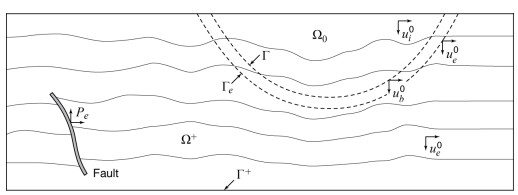
End-to-End: From the source to the response of complex engineering systems.

- Spanning geological to engineering scales
- Multiple uncertainties (source rupture, material model: background and local)

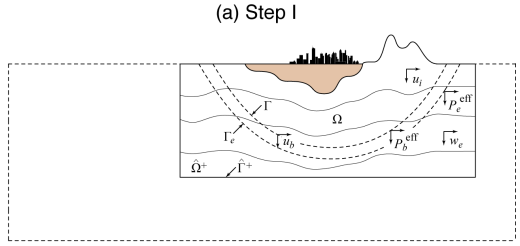


Domain Reduction Method (DRM)

To deal with local regions of interest



(a) Step I

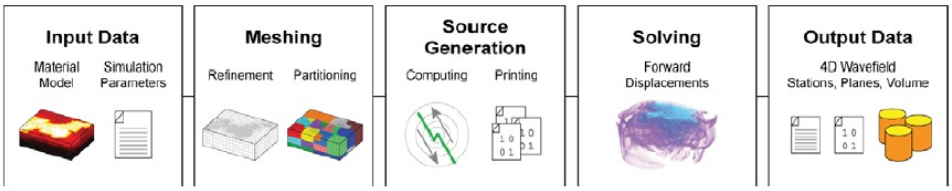


(b) Step II

Bielak et al, BSSA 2003

Simulation Engine: Hercules

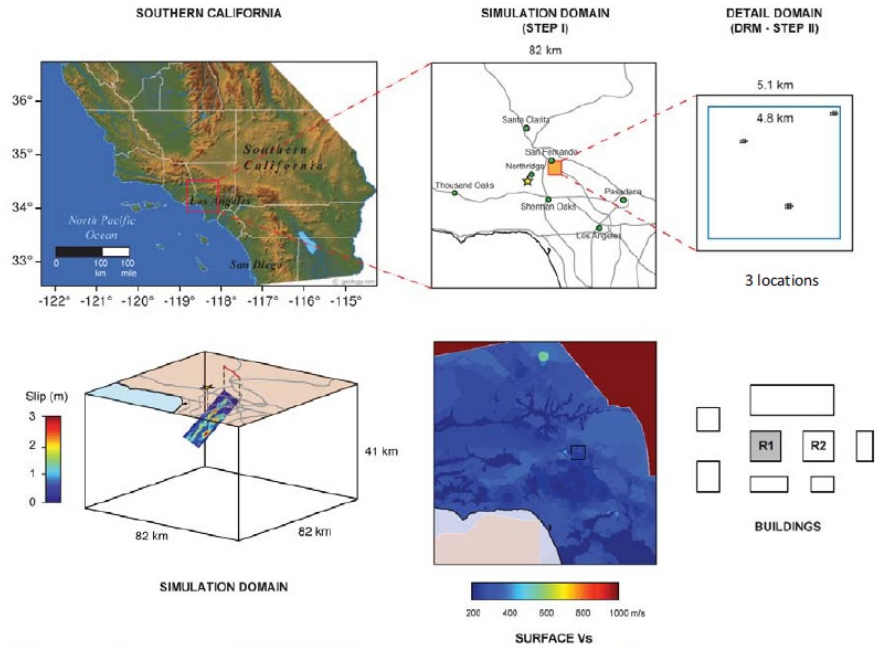
Hercules is our end-to-end octree-based finite element parallel software for large-scale earthquake simulations (Tu et al., 2006; Taborda et al., 2010)



Hercules has been thoroughly tested and used for verification (Bielak et al., 2010) and validation (Taborda et al., 2009, 2012) studies.

- TeraShake (2005–2007) SCEC
- ShakeOut (2007–2009) SCEC+USGS
- Chino Hills (2008–2011) CMU+SCEC
- Volvi (2008–2010) Euroseis E2VP

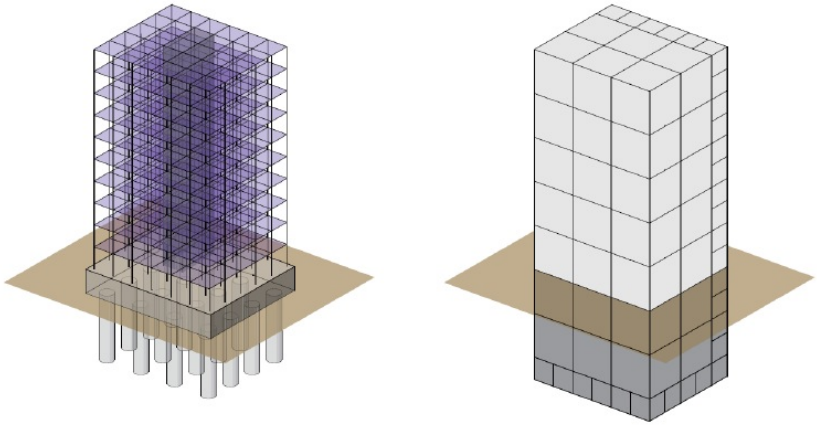
Case Study: Northridge



Source model corresponds to Graves and Pitarka (2010)

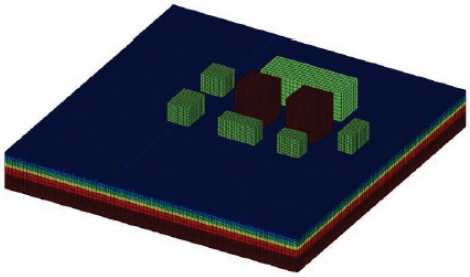
SCEC Velocity Model

Building Models -- Approach

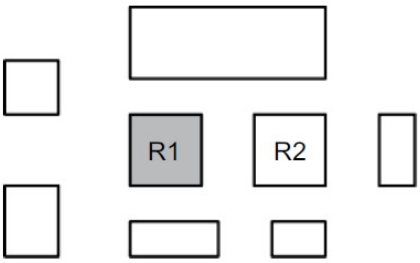


(a) Real structure **(b)** Blocks model

Case Study: A Typical Power Plant



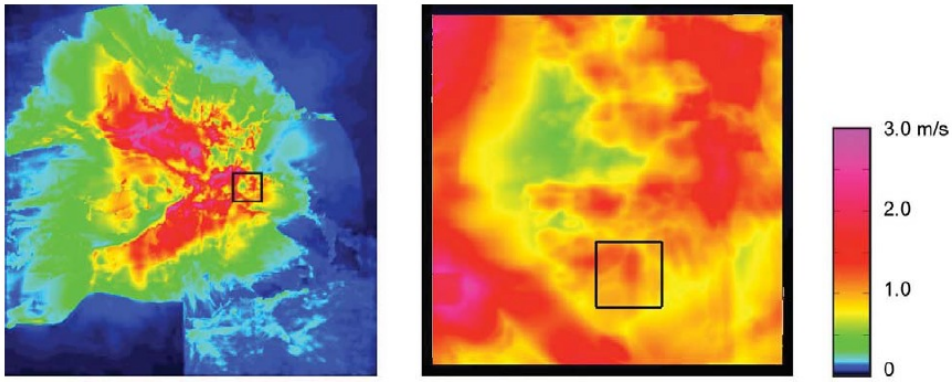
R1: Reactor 1
Reference Structure



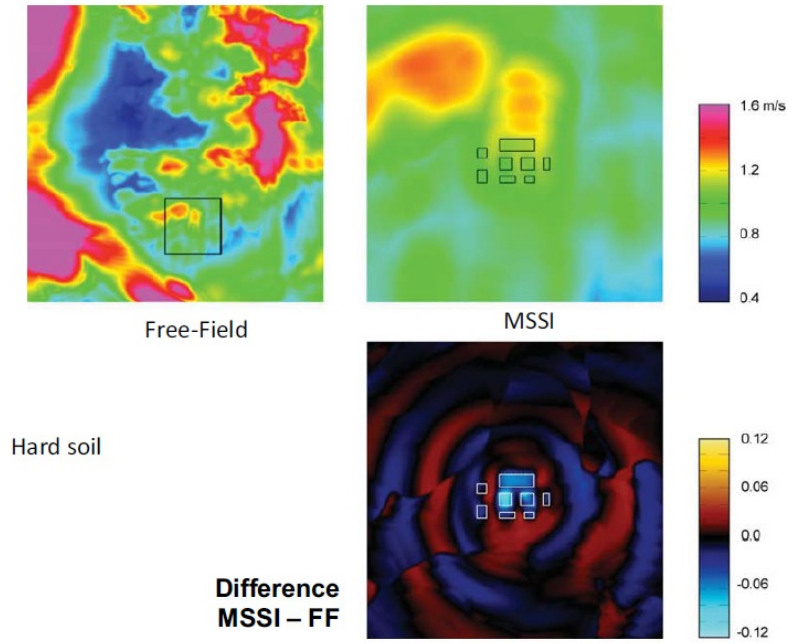
Computational Performance and DRM Advantage

RUN STATISTICS	STEP I	STEP II (HARD SOIL)	STEP II (SOFT SOIL)
Max Freq.	**5 Hz**	**5 Hz**	**5 Hz**
Min Vs	**200 m/s**	**200 m/s**	**100 m/s**
Sim. Time	60s	60s	60s
Min Size Elem.	5m	5m	2.5m
Domain Size	82x82x41 km^3	5.1x5.1x1.6 km^3	5.1x5.1x1.6 km^3
Number of Elem.	2.6 billion	12 million	36 million
Number of Bldgs	0	24	24
Number of Cores	**18,000**	**240**	**240**
Total Running Time	**15 hr 10 min**	**2 hr 30 min**	**6 hr 15 min**
Service Units	**273,000**	**600**	**1,500**
Time For Mesh	334 s	25 s	56 s
Time For DRM	122 s	215 s	128 s

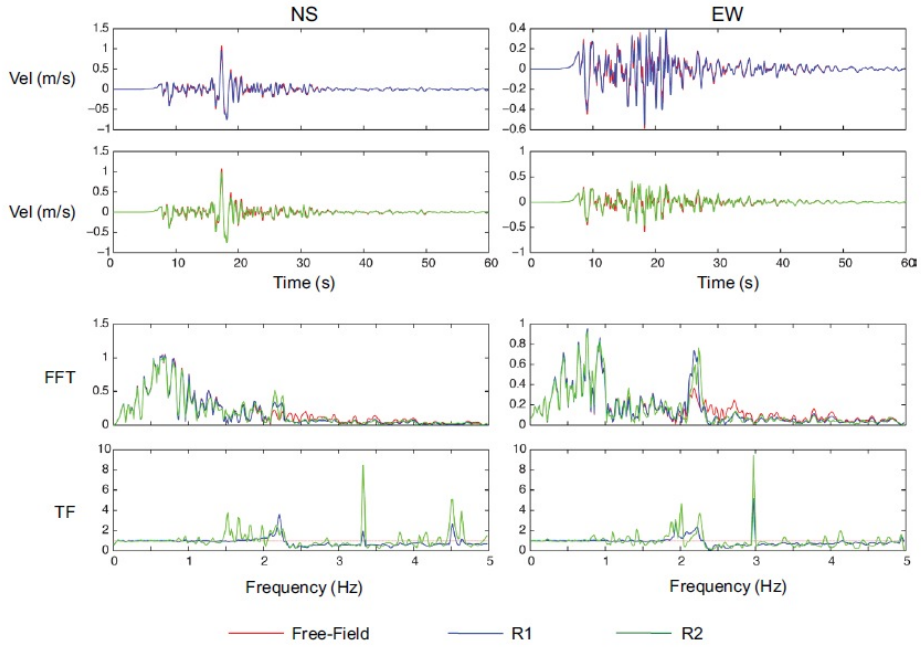
Peak Ground Velocity – Free Field

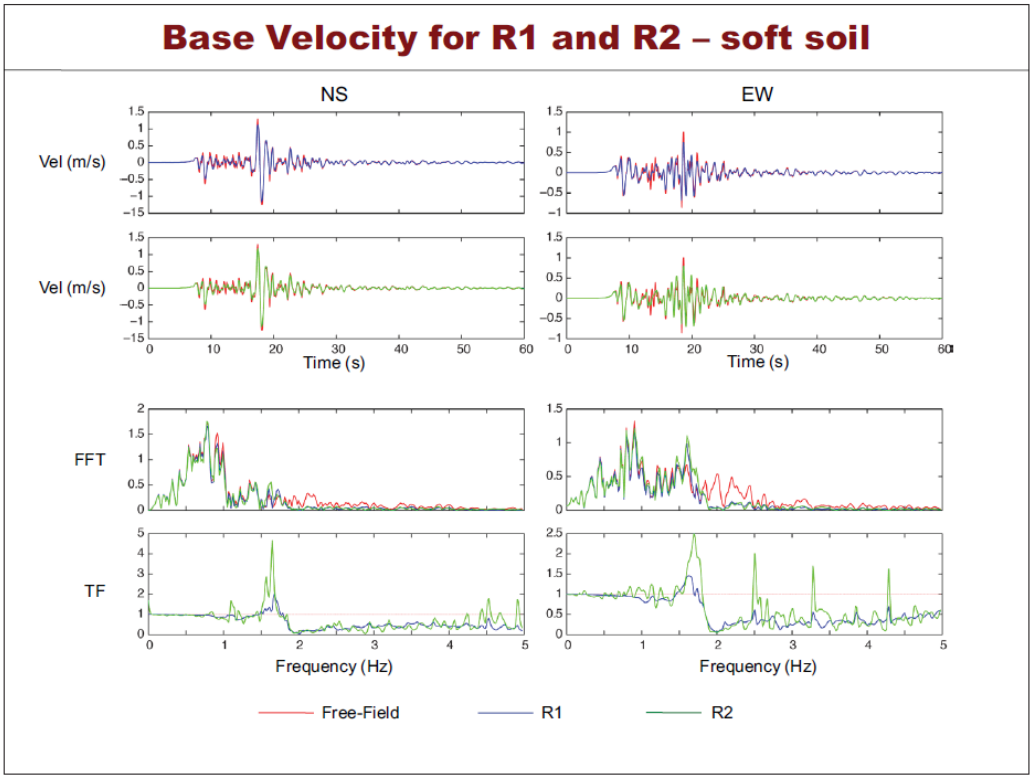


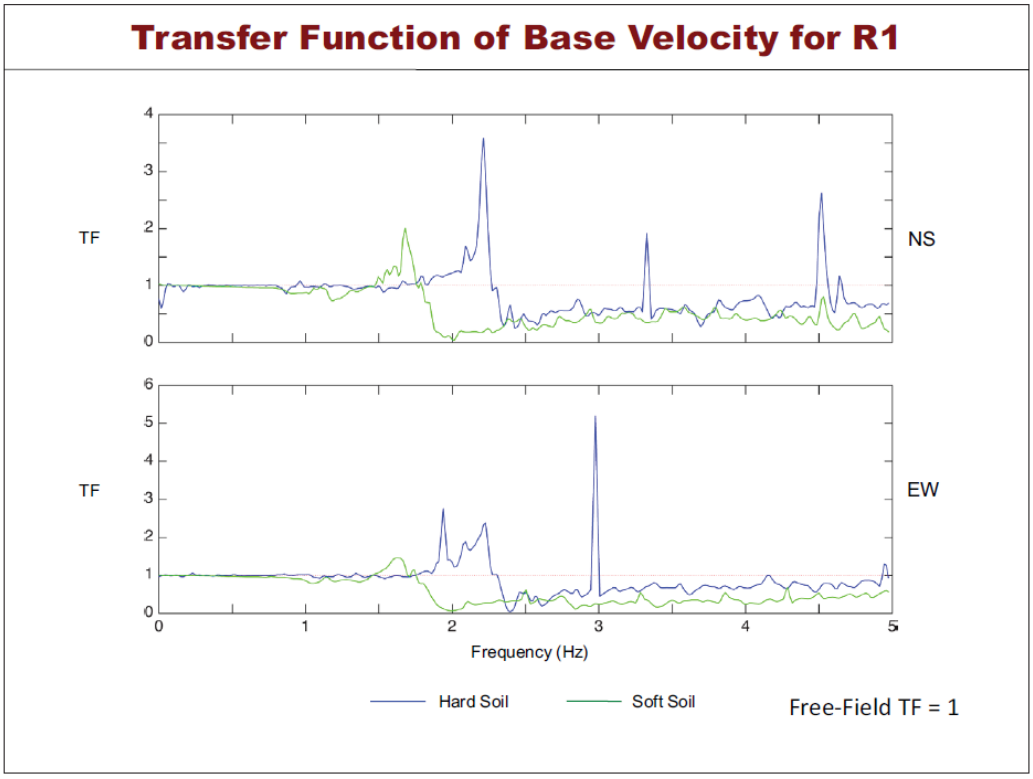
Peak Ground Velocity and MSSI Effects

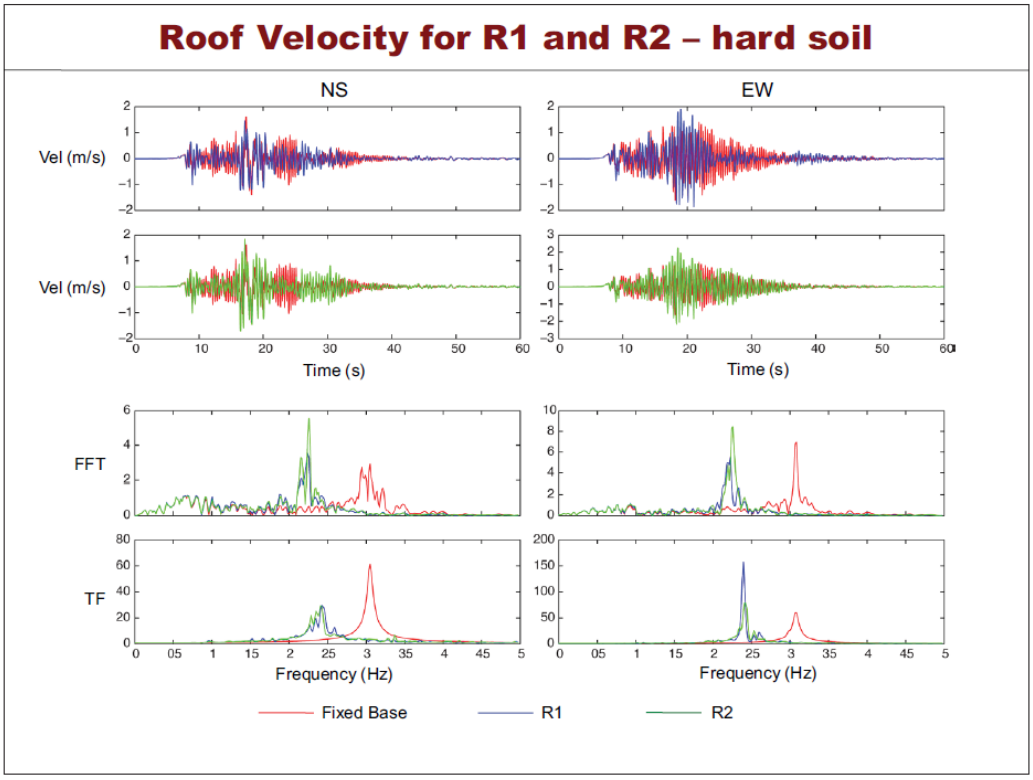


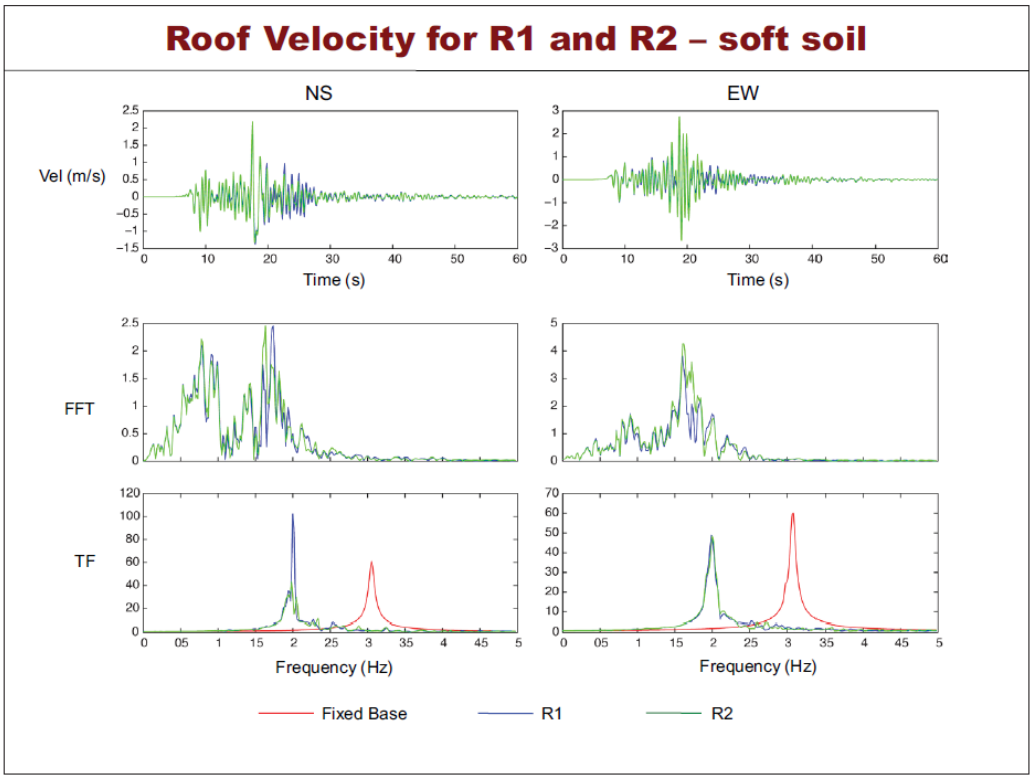
Base Velocity for R1 and R2 – hard soil

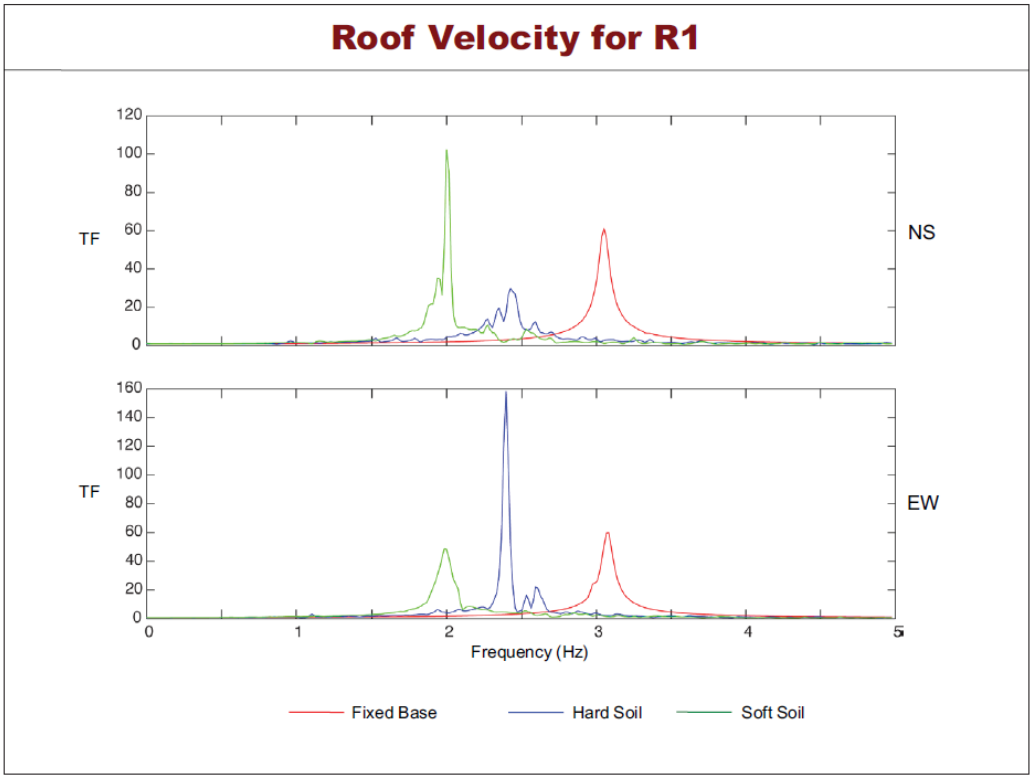



Base Velocity for R1 and R2 – soft soil
NS
EW
Vel (m/s)
Vel (m/s)
Time (s)
Time (s)
FFT
TF
Frequency (Hz)
Frequency (Hz)
Free-Field
R1
R2


Transfer Function of Base Velocity for R1
TF
NS
TF
EW
Frequency (Hz)
Hard Soil
Soft Soil
Free-Field TF = 1


Roof Velocity for R1 and R2 – hard soil
NS
EW
Vel (m/s)
Vel (m/s)
Time (s)
Time (s)
FFT
TF
Frequency (Hz)
Frequency (Hz)
Fixed Base
R1
R2


Roof Velocity for R1 and R2 – soft soil
NS
EW
Vel (m/s)
Time (s)
Time (s)
FFT
TF
Frequency (Hz)
Frequency (Hz)
Fixed Base
R1
R2


Roof Velocity for R1
TF
NS
TF
EW
Frequency (Hz)
Fixed Base
Hard Soil
Soft Soil

Presentation of Justin Coleman, Expert Panel

ICP

IDAHO CLEANUP PROJECT

Non-Linear Seismic Soil Structure Interaction (SSI)

Method for Developing Non-Linear Seismic SSI Analysis Techniques

Justin Coleman, P.E.

October 25th, 2011

CH2M•WG IDAHO, LLC

SAFELY PLAN • MOTIVATE • DELIVER

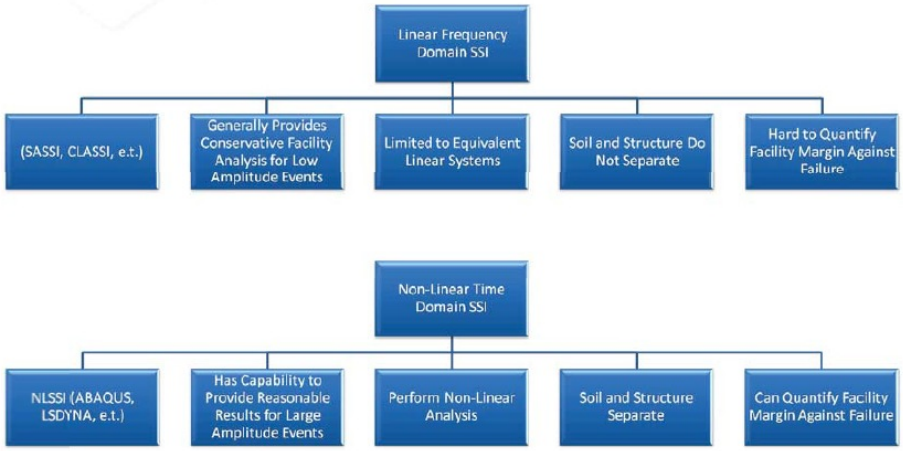
Presentation Outline

- Purpose of Presentation
- Linear versus Non-Linear Seismic SSI
- **N**on-**L**inear seismic **S**oil **S**tructure **I**nteraction (NLSSI) Studies
- The NLSSI Introduction
- SSI Analysis Non-Linearity
- Commercial Software Elements
- Commercial Software Non-Linear Constitutive Models
- Non-Linear Seismic SSI Damping
- Demonstration of Time Domain 2D Model
- NLSSI Validation Approach
- NLSSI Implementation
- Need For NLSSI
- Conclusions

Purpose of Presentation

- The purpose of the presentation is to establish the need for using non-linear analysis software for performing NLSSI analysis
- Propose a method for implementing NLSSI analysis in nuclear facilities

Linear versus Non-Linear Seismic SSI



Non-Linear Seismic SSI Studies

- Studies indicate the need for performing non-linear analysis techniques
  - "EFFECT ON NON-LINEAR SOIL-STRUCTURE INTERACTION DUE TO BASE SLAB UPLIFT ON THE SEISMIC RESPONSE OF A HIGH-TEMPERATURE GAS-COOLED REACTOR (HTGR)" Kennedy, R.P. e.t. all. 1975
  - NUREG/CR-6957, Xu et. all, 2008
  - "Three-dimensional nonlinear seismic ground motion modeling in basins," Xu et all,

NUPEC Field Test Model of Reactor Building with Embedment

The NLSSI Introduction

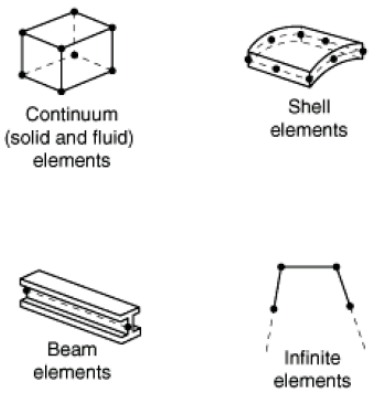
- **N**on-**L**inear **S**oil **S**tructure **I**nteraction analysis method (NLSSI)
- Utilize commercially available time domain explicit software to perform seismic SSI
- Commercially available non-linear analysis software GUI interfaces provide less user error.
- Commercial software packages with robust quality assurance programs provide software control
- Fast computer processors on multiple cores provides reasonable solving times for complex time domain problems.
- The NLSSI analysis approach potentially provides more realistic representation of facility response during earthquake motion
  - Better understanding of margin against failure
  - Provides a more accurate representation of the soil and facility

SSI Analysis Non-Linearity

- Types of non-linearity in SSI analysis
  - Geometric
    - Contact – Sliding and Separation
    - Non-linear springs
  - Material
    - Elastic/Plastic
  - Non-linear soil behavior
  - Non-linear behavior between soil and structure (i.e. the inability of soil to resist tension)
  - Non-linear behavior of the structure (i.e. steel and concrete)

Commercial Software Elements

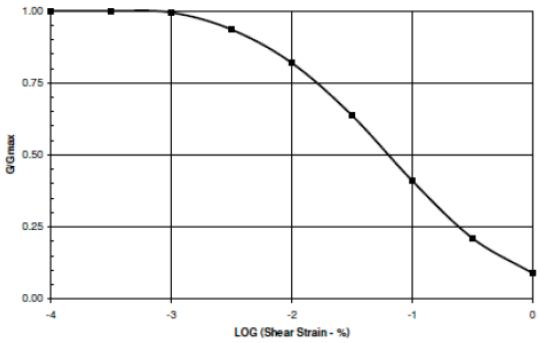
- Commercial software packages provide a large range of suitable structural elements
  - Solid element
  - Shell elements
  - 3D beam
  - Infinite Elements - Passes waves through boundaries.



Commercial Software Non-Linear Constitutive Models

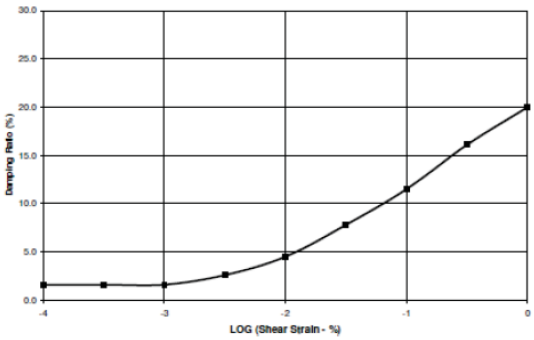
- Material Models for commercially available software:
  - Cracked Concrete Constitutive Models – Developed to match soil shear modulus reduction curve
  - Soil Plasticity Constitutive Models
  - Metal Plasticity Definitions

Soil Shear Modulus Reduction Curve



Non-Linear Seismic SSI Damping

- In the Finite Element model damping is primarily from three sources:
  - Material damping – Choice of constitutive model
  - Numerical damping – Helps with stability of the solution
  - Boundary Conditions- Affect the way in which the numerical model transmits the specific energy of the stress waves.
    - Models the "contact" between the soil and structure



- Validation of the Constitutive models are necessary to assure the appropriate soil and structure response is captured
- Additional structural damping may be required

Demonstration of Time Domain 2D Model

- Demonstration of the explicit time domain capabilities using a 2D model of the Calcine Disposition Project (CDP) process in the existing IWTU cells
- This demonstrates the modeling capabilities of explicit time domain codes to model contact and allow waves to travel through soil and structure during earthquakes.
  - Demonstration Limitations:
    - HIP Unit Mass Not Representative
    - Concrete and Soil are modeled as linear elastic
    - Damping has not been Validated
    - Soil is modeled as on homogeneous layer
    - Cell geometry is simplified

Demonstration of Time Domain 2D Model

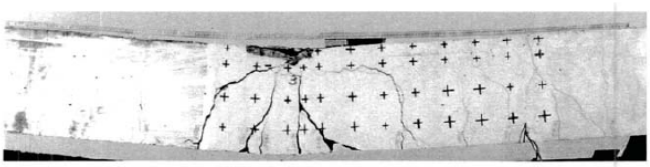
NLSSI Validation Approach

- Validation provides evidence that the correct model is solved.
- Component validation (material modeling, vibration analysis, soil pressures)
  - Constitutive (macroscopic material) behavior
  - Contact/interface behavior
  - Energy dissipation characteristics
- Complete system validation
  - Lotung (1/4 scale containment model) LSST tests
  - Fukushima-Daiichi NPP data
  - Japanese NUPEC tests

Slide from, **Jeremi´c, High Performance, High Fidelity Modeling and Simulation of Earthquake-Soil-Structure Interaction for Nuclear Power Industry Quake Summit 2011, NEES & MCEER Annual Meeting, Buffalo, NY, June 9-11, 2011**

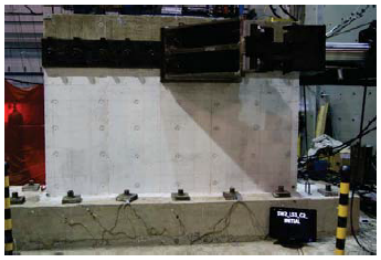
NLSSI Validation Approach

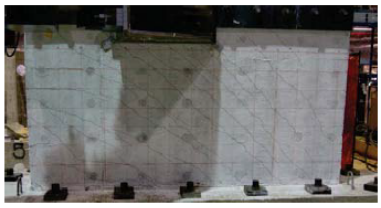
- Analyze simple models to validate the soil constitutive model and the structural constitutive model against experimental results
- Analyze the coupled SSI system and benchmark against experimental or actual results



NLSSI Validation Approach

- Validate the structure constitutive model by validating it against known results.
  - Performed impact modeling in non-linear software package
  - Use shear wall testing data from "Seismic Response of Low Aspect Ratio Reinforced Concrete Shear Walls,"
- Model and analyze coupled SSI system and benchmark against experimental and known results





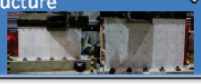
NLSSI Proposed Development Approach

Model and Analyze Simple Linear Soil Columns
- Compare to Hand Calculated and Experimental Results

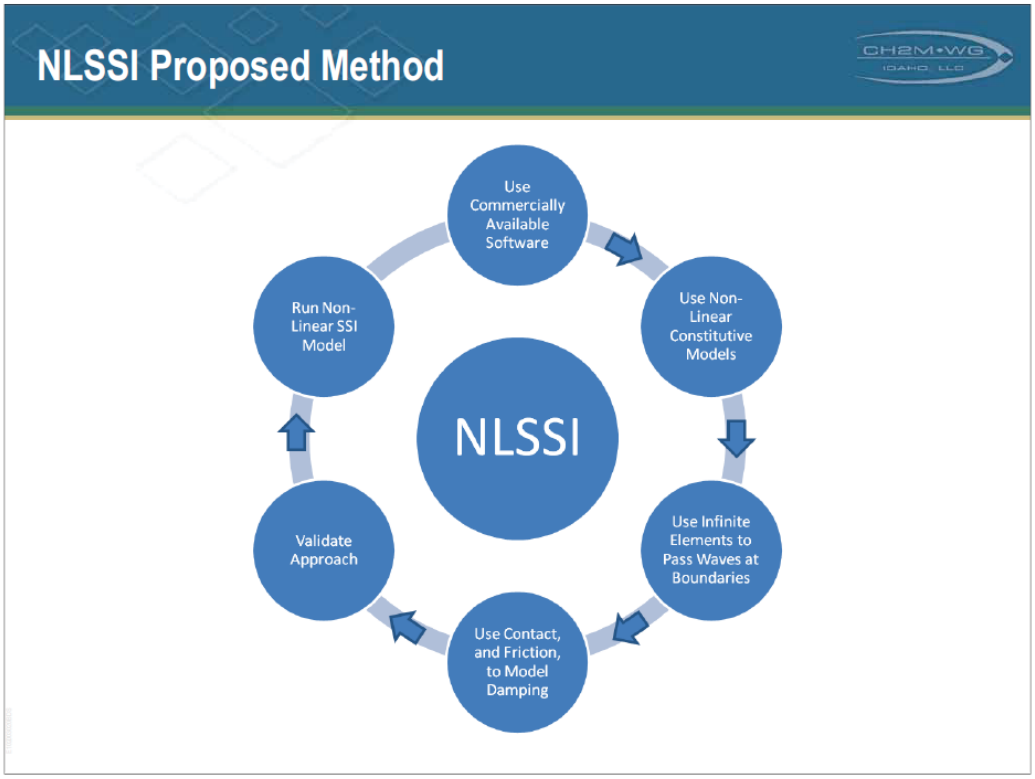
Model and Analyze Lotung SASSI Benchmark Problem as Linear SSI
- Compare Results to Experimental and SASSI

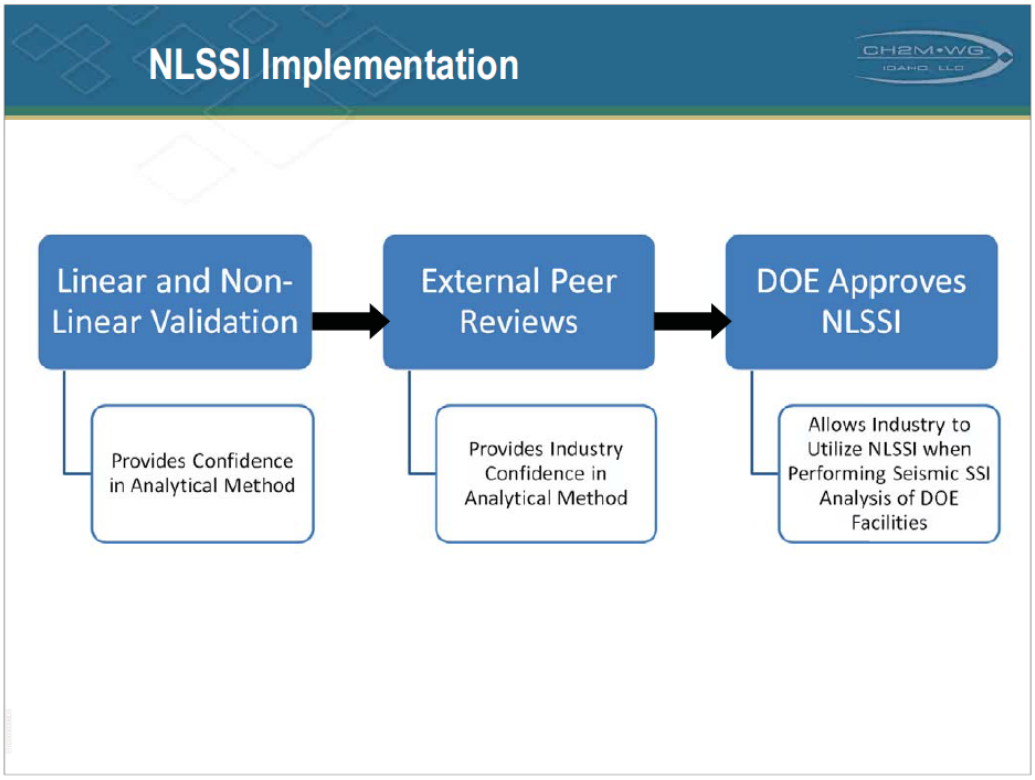
Release the tie between soil and structure and note difference

Model and Analyze Simple non-linear soil and structure experimental problems



Implement non-linear constitutive models in Lotung problem
- Drive model with larger amplitude time histories and note the difference
- Compare to large amplitude event data, Japan Kishiwazaki, Japan Fukishima


NLSSI Proposed Method
NLSSI
Use Commercially Available Software
Use Non-Linear Constitutive Models
Use Infinite Elements to Pass Waves at Boundaries
Use Contact, and Friction, to Model Damping
Validate Approach
Run Non-Linear SSI Model


NLSSI Implementation
Linear and Non-Linear Validation
External Peer Reviews
DOE Approves NLSSI
Provides Confidence in Analytical Method
Provides Industry Confidence in Analytical Method
Allows Industry to Utilize NLSSI when Performing Seismic SSI Analysis of DOE Facilities

Need For NLSSI

- Provides more accurate representation of seismic Soil Structure Interaction
- Increases DOE confidence in facilities margin against failure
- Potentially saves cost of construction
- Eliminates the need to utilize multiple software packages to perform the analysis; only one is needed

Conclusion

- Commercial software packages have capabilities for performing non-linear SSI methods
- Commercial software packages with robust quality assurance programs provide software control
- Commercial software packages provide user friendly Graphical User Interface that minimize input errors and maximize post processing capabilities
- NLSSI provides a more accurate representation of soil structure interaction during earthquake events
- NLSSI improves confidence in predicting nuclear facilities margin against failure
- DOE standardizes the NLSSI for Nuclear facility seismic analysis
- NSR&D funding needed for development of the NLSSI