INL/EXT-16-39195
Revision 1

Light Water Reactor Sustainability Program

Plan to Verify and Validate Multi-Hazard Risk-Informed Margin Management Methods and Tools

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ABSTRACT

This report describes the development plan for verification and validation (V&V) of multi-hazard risk assessment methods and tools developed by Idaho National Laboratory (INL) within the Risk-Informed Safety Margin Characterization (RISMC) technical pathway of the Light Water Reactor Sustainability Program. These methods and tools are used for implementing risk informed margin management (RIMM) methods developed by INL. The V&V plan for the new INL-developed toolkit includes collection and use of unique experimental data sets developed by a new multi-partner collaborative group called the "Experimental Research Group – External Hazards" (ERG-EH) coordinated by INL (Coleman et al. 2016).

The RISMC toolkit includes new tools and methods for advanced evaluation of nuclear facility risk. The external events activity within the RISMC pathway is tasked with developing tools and methods focused on evaluation of risk from multi-hazard external (e.g., seismic and flooding) events, which have been shown to be dominant risk contributors in probabilistic risk assessments performed for operating nuclear power plants (NPPs). The ERG-EH coordinated within the external events activity will provide technical expertise and experimental large-scale testing data needed for further development and validation of tools and methods for external hazard safety evaluations in the RISMC toolkit.

The external events activity within RISMC has two key elements: (1) an organizational and research framework provided by INL and (2) a coordinated group of university and national laboratory partners with the complementary expertise and experimental capabilities needed to conduct large-scale external hazard-focused experiments. This cooperative group, the ERG-EH, will allow INL to leverage a range of existing capabilities to meet the unique needs of RISMC tool and method development. In addition, the capabilities of the ERG-EH could be used to address needs of other national laboratories.

Currently, there is limited data available for development and validation of the tools and methods being developed in the RISMC Toolkit. The ERG-EH will obtain high quality, large-scale experimental data that can be used to validate RISMC tools and methods in a timely and cost-effective way. The ERG-EH is initially formed of INL and six universities. The ERG-EH includes recognized experts in the fields of seismic and flooding hazard assessment. These experts are currently drawn from INL, the University of Buffalo, Purdue University, University of Illinois, North Carolina State University, Idaho State University, and George Washington University. A detailed table of the capabilities of each ERG-EH partner is provided in Appendix A.

The group of universities and national laboratories that will eventually form a larger ERG-EH in later stages (expected to include both the initial participants and other universities and national laboratories that have been identified). This expanded group has the expertise and experimental capabilities needed to both obtain and compile existing data archives and perform additional seismic and flooding experiments. The data developed by ERG-EH will be stored in databases for use within RISMC and will be used to validate the advanced external hazard tools and methods.

The RISMC toolkit under development is composed of analysis tools used to advanced current risk calculation processes and reduce uncertainty in these calculations. To have confidence in the predictive capability of these numerical tools it is important to verify and validate them. To verify and validate numerical tools the user must understand how physics-based approaches are used to represent the problem (e.g., constitutive models used to represent the soil and structural elements), the numerical solver approach used (e.g., finite element), what data already exists that could be used to validate the tools, and what data is needed for validation. A brief discussion of several near term tests to gather data for validation of both seismic and flooding tools is provided in Section 4.

ACKNOWLEDGEMENTS

The Light Water Reactor Sustainability Program at INL commissioned this report. Input on the intellectual and physical capabilities of the external hazards experimental group was provided by each of the six university partners: University at Buffalo, Purdue University, The George Washington University, North Carolina State University, University of Illinois, and Idaho State University.

Plan to Verify and Validate Multi-Hazard Risk-Informed Margin Management Methods and Tools

FIGURES

TABLES

ACRONYMS

BC	boundary conditions
DOE	Department of Energy
ERG-EH	Experimental Research Group – External Hazards
EPRI	Electric Power Research Institute
IC	initial conditions
INL	Idaho National Laboratory
LWRS	Light Water Reactor Sustainability
MOOSE	Multiphysics Object Oriented Simulation Environment
NLSSI	nonlinear soil-structure-interaction
NPP(s)	nuclear power plant(s)
PIRT	phenomena identification and ranking table
PRA(s)	probabilistic risk assessment(s)
R&D	research and development
RIMM	risk-informed margins management
RISMC	Risk-Informed Safety Margin Characterization
SSC(s)	structures, systems, and component(s)
SSI	soil-structure-interaction
V&V	verification and validation

Plan to Verify and Validate Methods and Tools for Multi-Hazard Risk-Informed Margin Management

1. INTRODUCTION

1.1 Report Objectives

This report describes the development plan for verification and validation (V&V) of new multi-hazard assessment methods and tools developed by Idaho National Laboratory (INL) in the Risk-Informed Safety Margin Characterization (RISMC) technical pathway (Smith, Rabiti, and Martineau 2013) of the Light Water Reactor Sustainability Program (INL 2015). These multi-hazard assessment methods and tools are used for implementing risk informed margin management (RIMM) methods developed by INL. The V&V plan for the new INL-developed tool includes collection and use of unique experimental data sets developed by a new multi-partner collaborative group called the "Experimental Research Group - External Hazards" (ERG-EH) coordinated by INL within the RISMC technical pathway.

As described in more detail later in this report, the RISMC pathway is developing a suite of new tools and methods (known as the "RISMC toolkit") for advanced evaluation of facility risk. The RISMC Toolkit is being built using INL's Multiphysics Object Oriented Simulation Environment (MOOSE) High Performance Computing framework (Gaston, Hansen, and Newman 2009). The RISMC toolkit, includes tools and methods focused on evaluation of risk from external hazards (e.g., seismic and flooding events), which have been shown to be dominant risk contributors in probabilistic risk assessments (PRAs) performed for operating nuclear power plants (NPPs).

External hazards are of significant interest for the nuclear energy community, and more research is needed to reduce uncertainty and more accurately quantify the safety margin at existing and new nuclear facilities. The focus is on developing verified and validated tools that can quantify multi-hazard external event risk. The RIMM process will allow nuclear facility owners to better understand and more effectively manage their external hazard risk. Figure 1 illustrates the evolution from today's current approach for quantifying NPP risk to the longer-term goal of quantifying NPP performance using virtual tools. Notice the focus in Figure 1 on external hazards such as seismic and flooding.

As stated above, advanced external hazard capabilities are needed to provide a better understanding of NPP response during and after external hazard events. Advanced external hazard analytical capabilities require research and development in three areas: methods, tools (Numerical Software), and data. This capability can then be used by DOE, NRC, industry, and international partners to manage external hazard risk. Further explanation of the three focuses of capability development areas is provided in Table 1.

Through the ERG-EH, INL will leverage both the intellectual and the physical capabilities maintained by other laboratories, various universities, and international entities. A description of the capabilities that will be leveraged is provided in Figure 2.

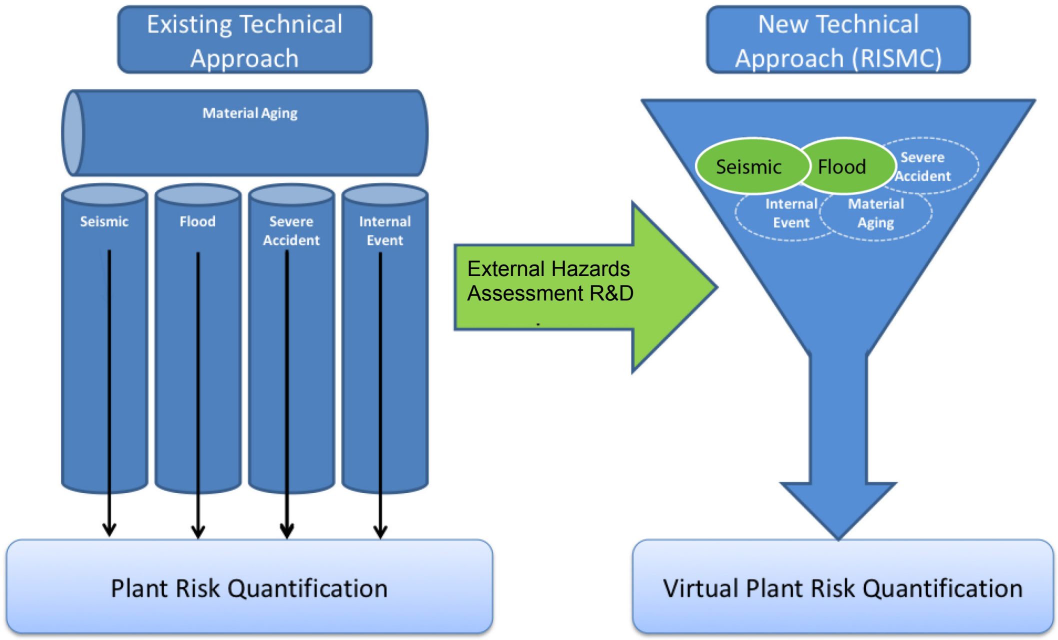

Figure 1. Evolution of NPP External Hazards Risk Assessment and Management

Table 1. External Hazards Areas of Focus

METHODS	TOOLS (Numerical Software)	DATA
Method development includes further developing and documenting acceptable numerical modeling approaches and risk-informed evaluation approaches.	Tools development includes using and integrating existing numerical software and, when necessary, developing new software to support the methods.	Data will be gathered and experimental tests run to validate the methods and tools. Data will be gathered from existing experimental tests and external hazard events at nuclear power plants. Experimental tests will be performed to provide additional validation data.

Capability

Intellectual

INL Expertise

- Leader in DOE-Nuclear Energy (NE) Program
  - Programmatic strategy for future NPP research
- Leader in Nuclear Reactor Safety Nuclear Industry
- Science-Based Modeling
  - Multiphysics Object-Oriented Simulation Environment (MOOSE) based tools
  - Virtual reactor
- Economical Assessments Collaborations
- High Performance Computation (HPC)
- External Hazards and Risk Assessment

Partnerships

- University at Buffalo
  - Hybrid Testing
  - Constitutive model development for SI, soils, concrete, blast
- Oak Ridge National Laboratory
  - Degraded concrete constitutive models
- EPRI
  - SI research, SPRA research, fragility data gathering
- Universities and INL Center for Advanced Energy Studies
- U.S. Manufacturing
  - SI technics
  - Modular construction process
- University of Tokyo
  - Large HPC and capabilities to model nonlinear seismic soil structure interaction from source to site

Physical

INL Facilities

- Center for Modeling and Simulation Structural Dynamics Laboratory
- Hot Cell Tables
- Experimental Research Group
  - Small Scale Seismic Test Facility (proposed for INL) to test Soil-Structure Interaction (SSI), gapping, and sliding
  - Perform small-scale multi-event scenario experiments

National Facilities

- University at Buffalo
  - Two 50-ton, six degree of freedom shaker tables
  - Geotechnical laminar box
  - Linear actuators
- Purdue University
  - Thermal hydraulic shock on shake table
- Oregon State University
  - Tsunami Center
- George Washington University
  - Flow loop for fuel assemblies on shake table
- Idaho State University
  - Flooding fragility testing
- University of Tokyo
- NC State
  - Vulnerability assessment and qualification of systems and equipment
  - Flooding fragility testing
- University of Illinois
  - Geotechnical testing

Figure 2. External Hazards R&D Capability

1.2 Overview of the RISMC Toolkit

A systematic approach to the characterization and assessment of safety margins, and the subsequent margins management, is vital to licensee and regulatory analysis and decision-making. The purpose of the RISMC technical R&D pathway is to develop tools and methods that support plant decisions for RIMM strategies. The aim of RISMC is to improve the economics of aging management while ensuring the reliability and safety of operating NPPs over periods of extended plant operations.

The goals of the RISMC R&D Pathway are twofold:

(1) Develop and demonstrate a risk-assessment method that is coupled to safety margin quantification that can be used by NPP decision makers as part of RIMM strategies.

(2) Create an advanced RISMC Toolkit that enables more accurate representation of NPP safety margins.

The RISMC Toolkit is being built using INL's MOOSE High Performance Computing framework (Gaston, Hansen, and Newman 2009). MOOSE is INL's development and runtime environment for the solution of multiphysics systems that involve multiple physical models or multiple simultaneous physical phenomena. Models built on the MOOSE framework can be coupled, as needed, for solving a particular complex problem, including the assessment of facility performance when impacted by external hazard phenomena (e.g., seismic or flooding events).

The advanced methods and tools in the RISMC toolkit can be used within a RIMM approach to improve decision making by providing a technical basis to assess both the breadth of real world external hazard scenarios and the potential impacts on the NPP based on the hazard. Importantly, external hazards of interest have a primary impact on the nuclear facility. However, as shown in Figure 3, these primary phenomena may also lead to secondary effects, which have not been assessed in a time-based calculation in past practice. Examples of primary impacts of external hazards are seismic shaking, flooding, and high winds. Examples of secondary effects induced by seismic and/or flood events are dam and levy failure, landslide, seismically-induced internal flood, and seismically-induced internal fire. The correlation and temporal relationship of these primary and secondary hazards complicate the determination of safety in any complex facility.

An example of a scenario that RISMC is uniquely capable of assessing is presented in Figure 4. This scenario includes a seismic event that may lead to failure of a flood protection levee, in addition to the direct impact on the safety-related structures, systems and components (SSCs) of the NPP. The scenario involves a primary hazard (seismic shaking) and secondary effects (flooding, both internal and external, and thermal-hydraulic-related effects, including impact to the reactor core). A similar scenario, in which the RIMM approach will be applied at a generic NPP with a flood protection levy and a defined seismic hazard, will be used as a demonstration problem. The analysis will be initiated with potential (i.e., stochastic) seismic events, determined based on a probabilistic seismic hazard assessment, that produce ground motion at the NPP site. These ground motions will be used to calculate probabilities of SSC failures at the NPP and levy. Based on probabilistic models of the conditional failure of piping systems and the flood protection levy, advanced flooding analysis will be run in locations of interest.

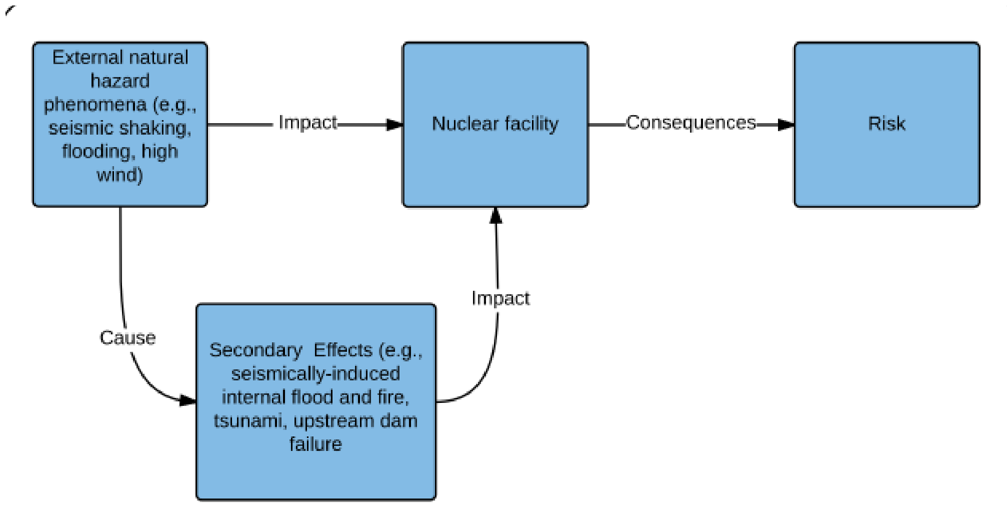

Figure 3: Potential primary and secondary external hazard propagation at an NPP

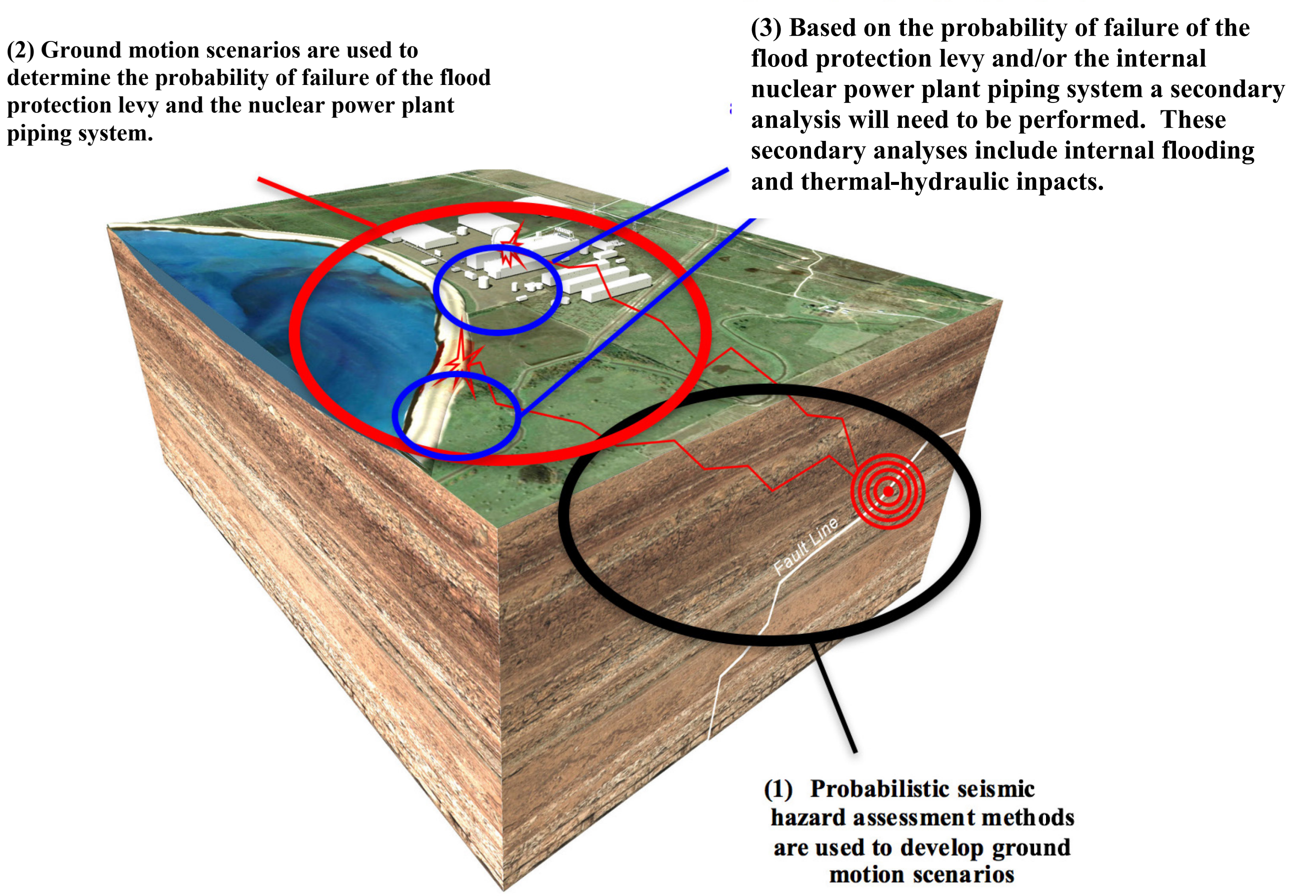

Figure 4. Example multi-hazard problem that can be solved using RISMC computational framework

1.3 The Experimental Research Group – External Hazards

As discussed in Coleman et al. (2016), The external events activity and ERG-EH directly supports RISMIC R&D pathway goal (2), discussed above, and indirectly supports goal (1) by providing experimental data for the verification of tools within the RISMC Toolkit. The external events activity within RISMC has two key elements: (1) an organizational and research framework provided by INL and (2) a coordinated group of university and national laboratory partners with the complementary expertise and physical capabilities needed to conduct large-scale external hazard-focused experiments. This second element, known as the Experimental Research Group - External Hazards (ERG-EH), will allow INL to leverage a range of existing capabilities to meet the unique needs of RISMC toolkit development. In addition, the capabilities of the ERG-EH could be used to address needs of other national laboratories. The initial partners in the ERG-EH are identified in Figure 5, below.

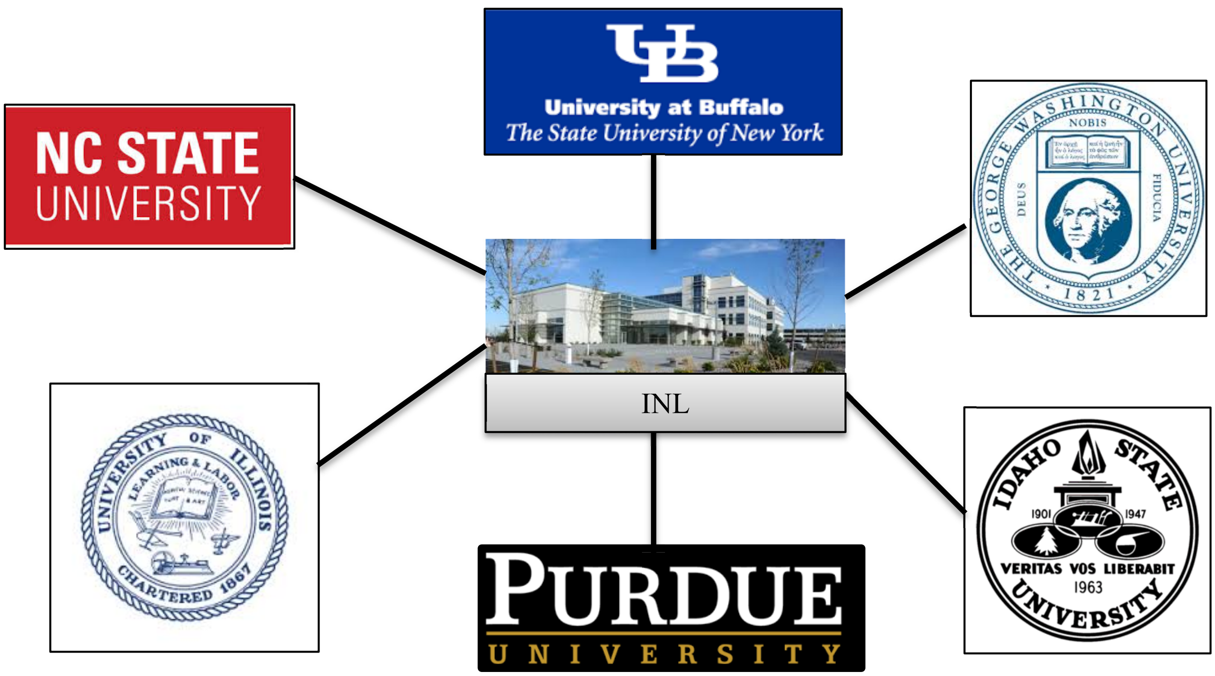

Figure 5: Initial Experimental Research Group - External Hazards partners

1.4 Outline of this Report

Section 2 of this report discusses the need for V&V of toolsets used in the nuclear industry. Section 3 describes the process for V&V planned for the RISMC tools and methods used for external hazard evaluations. Section 4 describes the role of experimental testing in numerical code validation. It also describes some of the testing planned for the ERG-EH.

2. NEED FOR DATA SUPPORTING THE VERIFICATION AND VALIDATION OF TOOLSETS USED IN THE NUCLEAR INDUSTRY

The RISMC toolkit under development is composed of analysis tools used to advanced current risk calculation processes and reduce uncertainty in these calculations. To have confidence in the predictive capability of these numerical tools it is important to verify and validate them and to understand their uncertainties and limits. To verify and validate numerical tools the user must understand how physics-based approaches are used to represent the problem (e.g., constitutive models used to represent the soil and structural elements), the numerical solver approach used (e.g., finite element), what data already exists that could be used to validate the tools, and what data is needed for validation. For example the area of interest for numerical modeling of NPP response due to seismic ground motion is shown as a meshed domain in Figure 6. This figure also shows schematically various numerical modeling tools within the RISMIC toolkit that can be used for analysis of the complex problem.

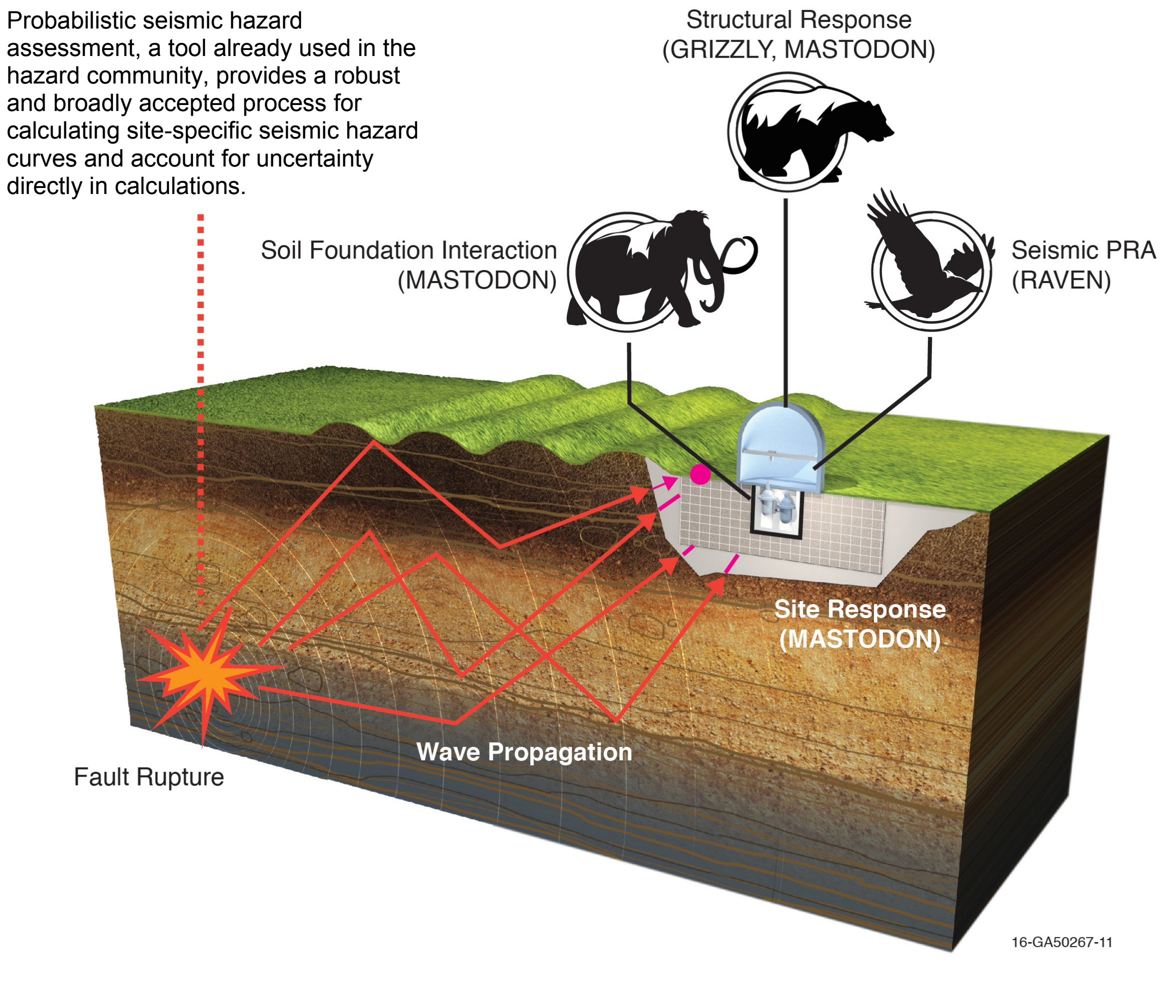

Figure 6. RISMC tools used for evaluation of external event risk

Oberkampf and Trucano (2008) states that verification is "…the process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the mode" and validation is "the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model." An important R&D element of the RISMC Toolkit is the verification and validation of the advanced external hazard (seismic and flood) analysis tools developed. These tools, and their associated methods, are intended to provide best-estimates and ranges of NPP response under a range of hazard inputs in order to gain accurate risk insights and better ensure NPP safety during and after beyond design basis events. The numerical tools must be able to accurately predict the dynamic response of NPPs during earthquakes, as well as the flow of water during flooding. The numerical tools will have physics-based mathematical equations that describe observed physical behavior, such as seismic wave propagation and water flow over complex geometry. Tools that will require validation include those used for predicting nonlinear time domain seismic analysis. One such tool is MASTODON, which is under development in the MOOSE framework. Others include smooth particle hydrodynamic (SPH) analysis codes, such as Neutrino, the flooding simulation tool.

It is important in developing and improving numerical tools, to identify the individual physics-based parameters that contribute the predictive capability of the tool. As discussed in the next section, the V&V start with assessment of the modeling tool at the element or unit level, moves to the benchmark level, and ultimately assesses systems-level model performance. Figure 7 lays out this process for developing and validating the predictive capability in numerical tools intended to perform site response and nonlinear SSI seismic analysis.

Currently, there is very limited data available to perform validation of the tools and methods being developed in the RISMC Toolkit specific to external hazards. This shortage of data applies to all three scales of validation activities discussed above. The ERG-EH is being developed to obtain high quality, small- and large-scale experimental data for validation of RISMC tools and methods in a timely and cost-effective way. The group of universities and national laboratories that will eventually form the ERG-EH (which is ultimately expected to include both the initial participants and other universities and national laboratories that have been identified) have the expertise and experimental capabilities needed to both obtain and compile existing data archives and perform additional seismic and flooding experiments. The resulting databases to be developed will be used to validate the advanced external hazard tools and methods.

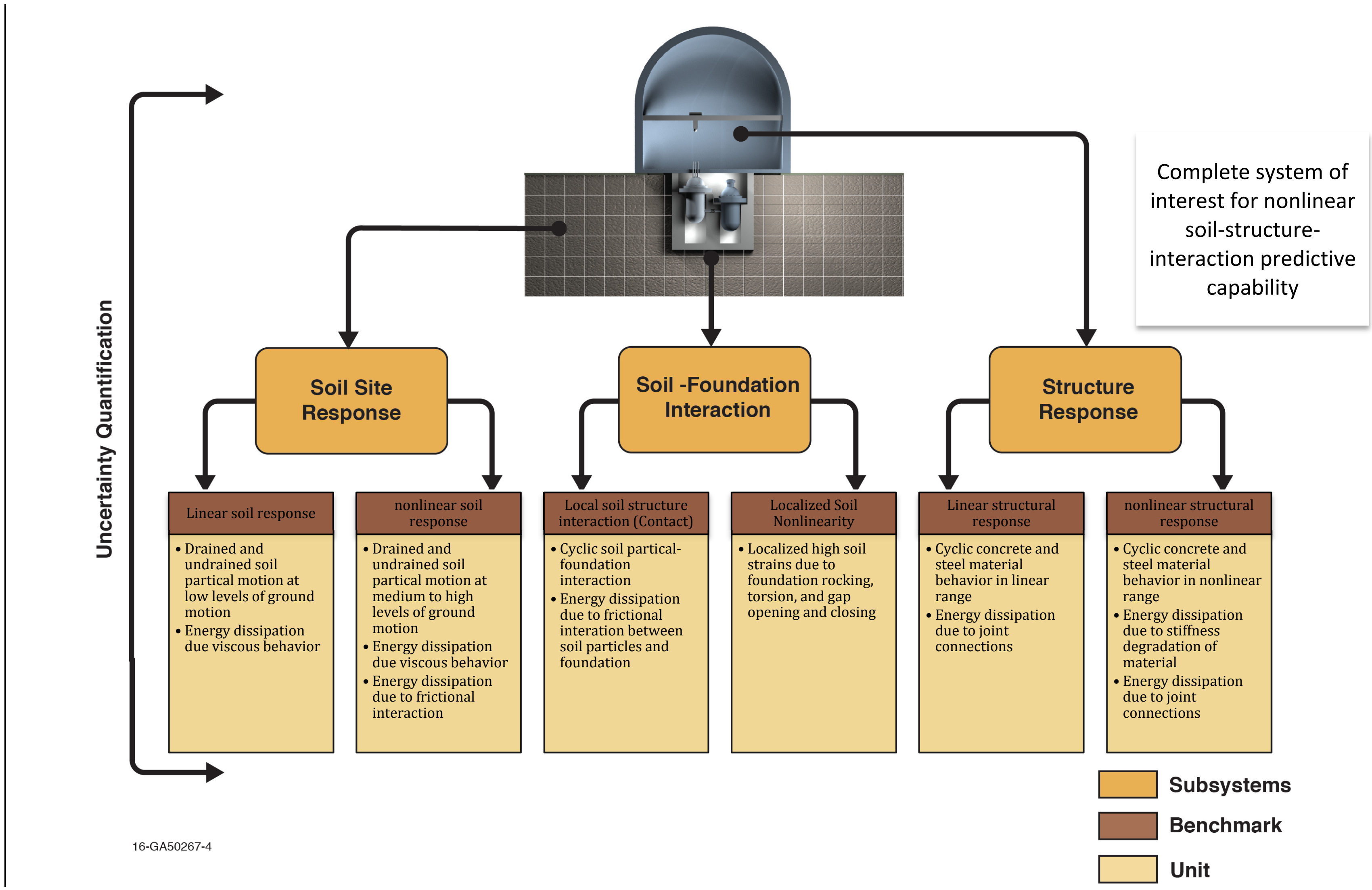

Figure 7: Validation process for developing a predictive capability of site response and SSI numerical tools

3. PROCESS FOR VERIFICATION AND VALIDATION

A V&V process is needed to ensure quality control and to gain confidence the tools have the appropriate predictive capability for the problem of interest. Oberkampf and colleagues (Oberkampf, Trucano, and Hirsch 2004; Oberkampf and Roy 2010) present a process to follow when performing V&V of numerical tools. The verification process compares the computational model and with known mathematical solutions in the range of interest (Figure 8), while the validation process is a process that develops confidence in the predictive capability of computational codes by comparing model results with real world phenomena in ranges of interest. The overall V&V process should address and account for uncertainties throughout the problem, including material property uncertainties, and uncertainties in experimental or field data (e.g., boundary conditions and instrumentation uncertainties).

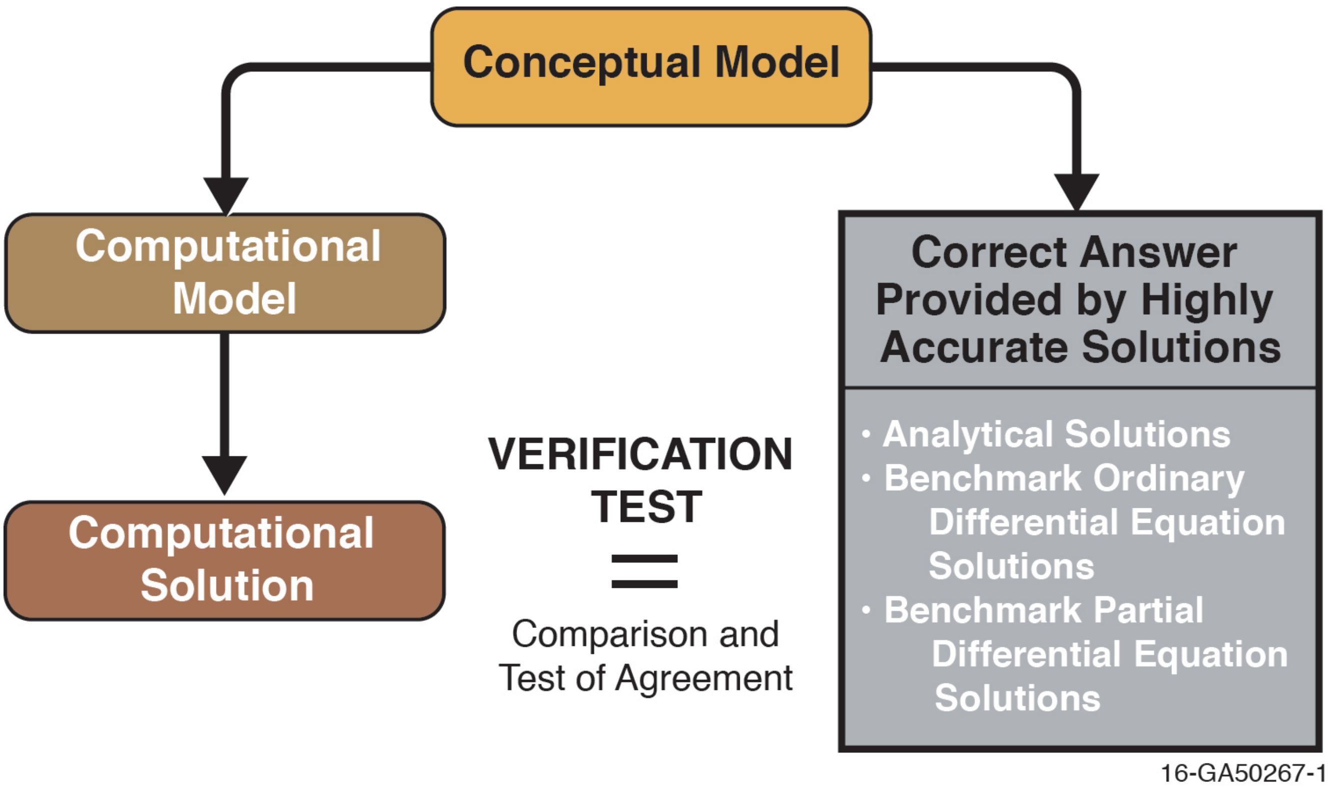

Figure 8: Verification process (Oberkampf, Trucano, and Hirsch 2004)

The validation process includes comparing computation models and solutions with increasingly complex experimental or field data. Each physical parameter can be validated starting at the element or unit level (i.e. the scale at which an element has uniform properties and is exposed to uniform loads). This step can be used to improve the numerical capability of the tools or constitutive models. The next step after element-level validations is to validate tools and model performance at a benchmark tier (or tiers) using a slightly more complex experiment. Finally, system-level experimental tests can be performed and numerically replicated to validate the numerical code's predictive capability. A very well instrumented and well documented field data can also be used for this purpose. Figure 9 outlines this process.

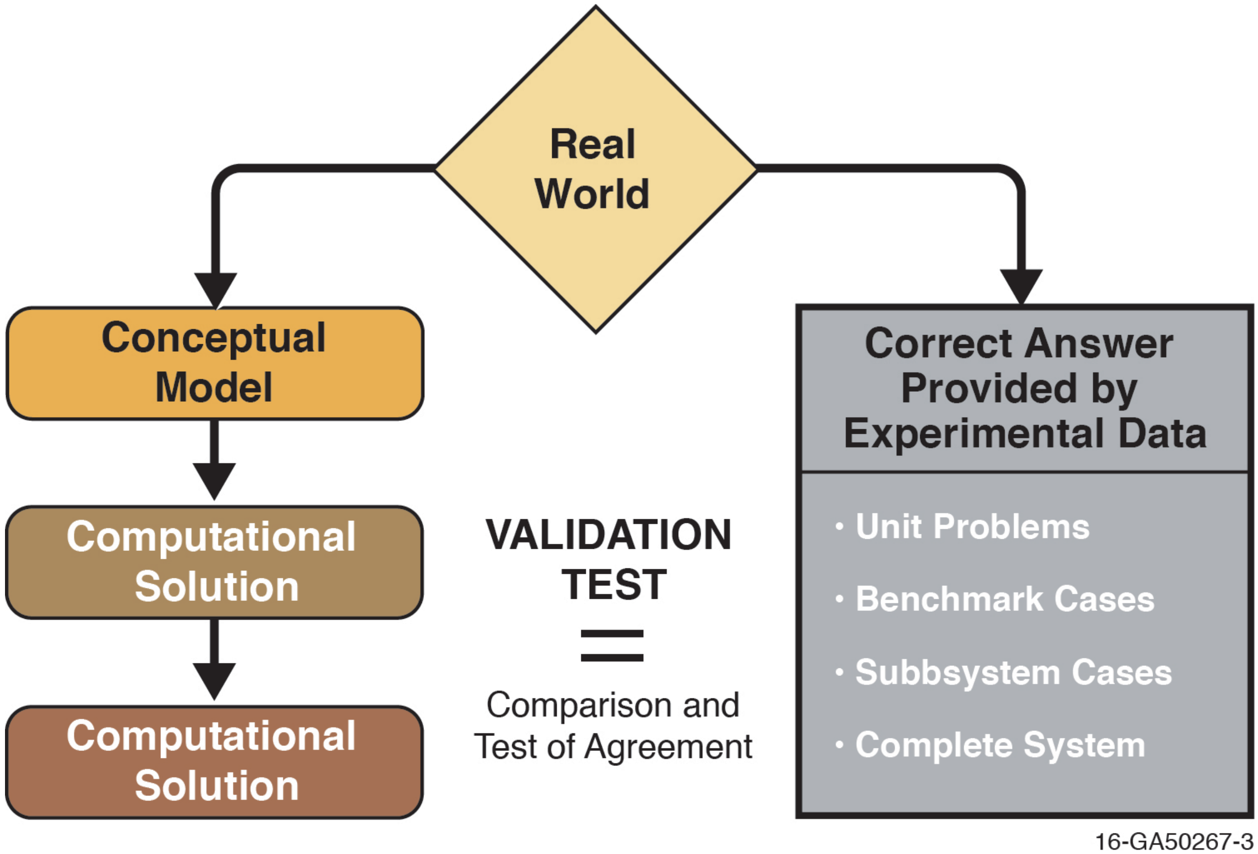

Figure 9: Validation process (Oberkampf, Trucano, and Hirsch 2004)

The unit tier validation activity should have the following characteristics:

- Physical
  - Simple, non-functional, hardware fabricated
  - Simple geometry
  - No coupled physics
  - Simple physical response measure
- Measured data
  - All model inputs measured
  - Most model outputs measured
  - Many experimental realizations
  - Experimental uncertainty given on all quantities

The benchmark tier validation activity should have the following characteristics:

- Physical
  - Special, non-functional, hardware fabricated
  - Simplified geometry and material properties
  - Little coupling of physics
  - Very simple boundary conditions (BCs) and initial conditions (ICs)
- Measured data
  - Most model inputs measured
  - Many model outputs measured

  - Several experimental realizations
  - Experimental uncertainty given on most quantities

The subsystem tier validation activity should have the following characteristics:

- Physical
  - Functional, system hardware
  - Little or no coupling of subsystems
  - Some physics coupled
  - Simplified BCs and ICs
- Measured data
  - Some measurement of model inputs
  - Some measurements of model outputs
  - Few experimental realizations
  - Experimental uncertainty given on some quantities

The system tier validation activity should have the following characteristics:

- Physical
  - Actual system hardware
  - Actual geometry and material properties
  - Complete coupling of physics
  - Actual BCs and ICs
- Measured data
  - Very limited measurement model inputs
  - Very limited measurements of model outputs
  - Very few experimental realizations
  - Little or no estimate of experimental uncertainty

It is important to identify the physical processes and the associated phenomena elements and physics-based parameters that contribute significantly to the impact of seismic and flooding events at NPPs. A phenomena identification and ranking table (PIRT) is used to identify the physical phenomenon, describe how important the response of the phenomena is to the system, and detail the level of confidence in the current models. As an example, this process to identify important phenomena can be applied to the cyclic response of soils. Some physical phenomena associated with dynamic and frictional effects of soil that need to be investigated experimentally or using field data for validation of numerical models are listed in the PIRT provided in Table 2. This table also shows important to the response of interest and the current level of confidence in available models.

The interaction of soil particles, which is dominated in some soils by frictional effects, is important because this behavior controls relative motions and dissipates energy during shaking. Experimental data has been gathered on frictional interaction of soil particles however little data exists on cyclic frictional interaction and how that interaction dissipates energy. Dilatency or volume change of soil is also important. Volume change of soil can occur during shaking due to compacted soil particles moving on top of one another creating an increase in volume and decreasing shear stiffness. Experimental observations from torsional shear tests and resonant column tests indication that at low levels of soil shear strain that there is a small amount of viscous damping. Direct shear tests on soil are typically performed in 1D. It has been shown that 2D effects are important to the cyclic response of soil (Kammerer, Pestana, and Seed 2002).

Table 2: Phenomena Identification and Ranking Table for identification of behavior need to model soil used in nuclear facility analysis

Phenomenon	Importance to response of interest	Level of confidence in model
Frictional interaction of soil particles	High	Medium
Dilatency of soil	High	Low
Viscous damping behavior of soil at low levels of shaking	Low	Medium
Cyclic Multidirectional effects of soil	High	Low
Soil saturation	Medium	Low
Wave passage effects in soil	High	Low

4. EXPERIMENTAL TESTS FOR NUMERICAL CODE VALIDATION

There are several near term tests planned and underway to gather data to validate both seismic and flooding models. This information will be used to validate numerical seismic and flooding tools under development.

4.1 Seismic Testing

As discussed in Coleman et al. (2016) two tests are currently being planned to validate nonlinear seismic behavior. These include tests to acquire data with (1) nonlinear soil behavior (site response) and (2) gapping and sliding between the foundation and the soil. The testing to address element (1) will use a large-scale geotechnical laminar box to experimentally capture wave passage effects. The large-scale geotechnical laminar box at the University at Buffalo will be used for experiments designed to provide the appropriate large-scale test data. Once performed, this laboratory-controlled study will provide an important comprehensive new data set that can be used for validation of site-response analysis and NLSSI tools. Tests are scheduled to be performed in the summer of 2016.

Gapping and sliding can significantly affect SSC response in nuclear structures, but these phenomena are currently not well understood. The Seismic Research Group at INL will be conducting experiments to provide (1) insight into the physics of gapping and sliding between soil and concrete and (2) data that will be used to calibrate the soil-foundation contact models used in nonlinear SSI simulations.

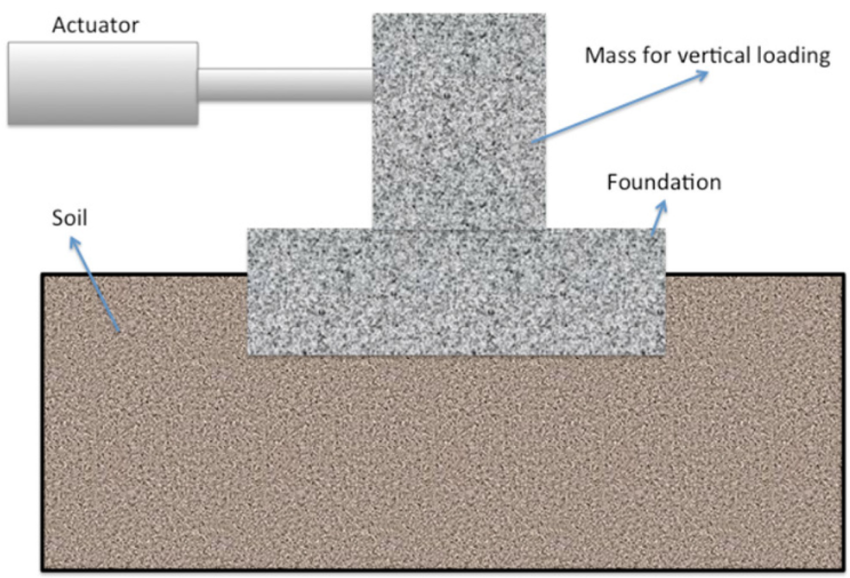

Figure 10: Proposed gapping and sliding experimental test setup

Figure 11. Large-scale laminar box at the University of Buffalo

4.2 Flooding Testing

For flooding tests, initial tests of simple components will be run and the complexity of the experiments increased over time to include more prototypic components. The first phase focuses on the initial application and includes modifications such as instrumentation specific to the needs of flooding data collection and expansion of an existing water reservoir. These modifications will allow tests for water rise and spray scenarios. The later phase of testing will focus on wave impact testing. While the first phase is underway, research is being conducted into wave impact event generation and simulation.

Programmatic testing-related research is also being conducted in parallel with the testing described above. The program strategy will be to begin with conducting a large number of simple tests using simple components utilizing existing or easy to procure components and testing infrastructure. The goal of these tests will be to develop a qualitative understanding of how different kinds of components such as structural, mechanical, and electrical components behave in various flooding scenarios. As the testing capability increases, the testing methodology and sophistication will increase, building on the experience gained in early testing. Testing with actual NPP components will carry certain higher costs and the testing protocol must be highly refined prior to conducting these tests to ensure the quality of the data is sufficient for use in assessing NPP risks. The program will solicit participation from industry and regulatory stakeholders and procure more complicated and prototypic NPP components. Figure 12, showing damage from Fukushima Tsunami event, provides an example of the damage states of in-situ systems and components that the testing is intended to better understand and quantify.

Figure 12 Flooding Damaged Doorway Example

After the qualitative understanding of component failure is developed in the early stages, fragility curves can begin to be developed that quantitatively describe the failure. A key part of this task is to identify the flooding variable which drives the failure and ought to be distributed in the fragility curve. Depending on the component and nature of flood, water height may not always be the strongest variable to consider. Research should be conducted looking at how other factors play a role in failure. Other variables that may be important factors are the hydrodynamic (impulse) loading, and time of submergence. Determining when a component can resume its function after the water has receded may also be an important factor to consider. Once the fragility curves for critical components in the NPP have been developed they can be used to help inform plant stakeholders about the risk posture of the plant to various flooding scenarios. In order to be of use however, this data will need to be tied in with the codes in the RISMC Toolbox (as well as potentially new codes) to model risk informed safety margin.

An effort is also currently underway to test full scale doors using an existing water reservoir. For later tests, it is proposed to use a new larger setup. Flood testing will take on a variety of different forms. The water rise rates in the tank are likely to be a critical variable in understanding how the components fail. For the spray testing and later wave impact testing, large volumes of high velocity water coming from a bank of pressurized nozzles will impact the sides of the flooding chamber.

Additional testing will be conducted to assess the ability to simulate the hydraulic loads from high velocity waves using new approaches. Most open channel wave impact machines utilize a ram and even large facilities are only capable of simulating waves in the 5 foot range. An effort is underway using numerical models to determine if water transients can be developed in a *closed* channel system that simulates the hydrodynamic loading of a 10 foot by 10 foot section of a 20 foot tsunami wave. The effort is currently using a computational fluid dynamics code to map pressure forces to rigid bodies interacting with waves. One closed conduit concept being evaluated is depicted in Figure 13 and involves the rapid introduction of a large item (grey in color) to a reservoir which would generate the impulse necessary for the wave simulation.

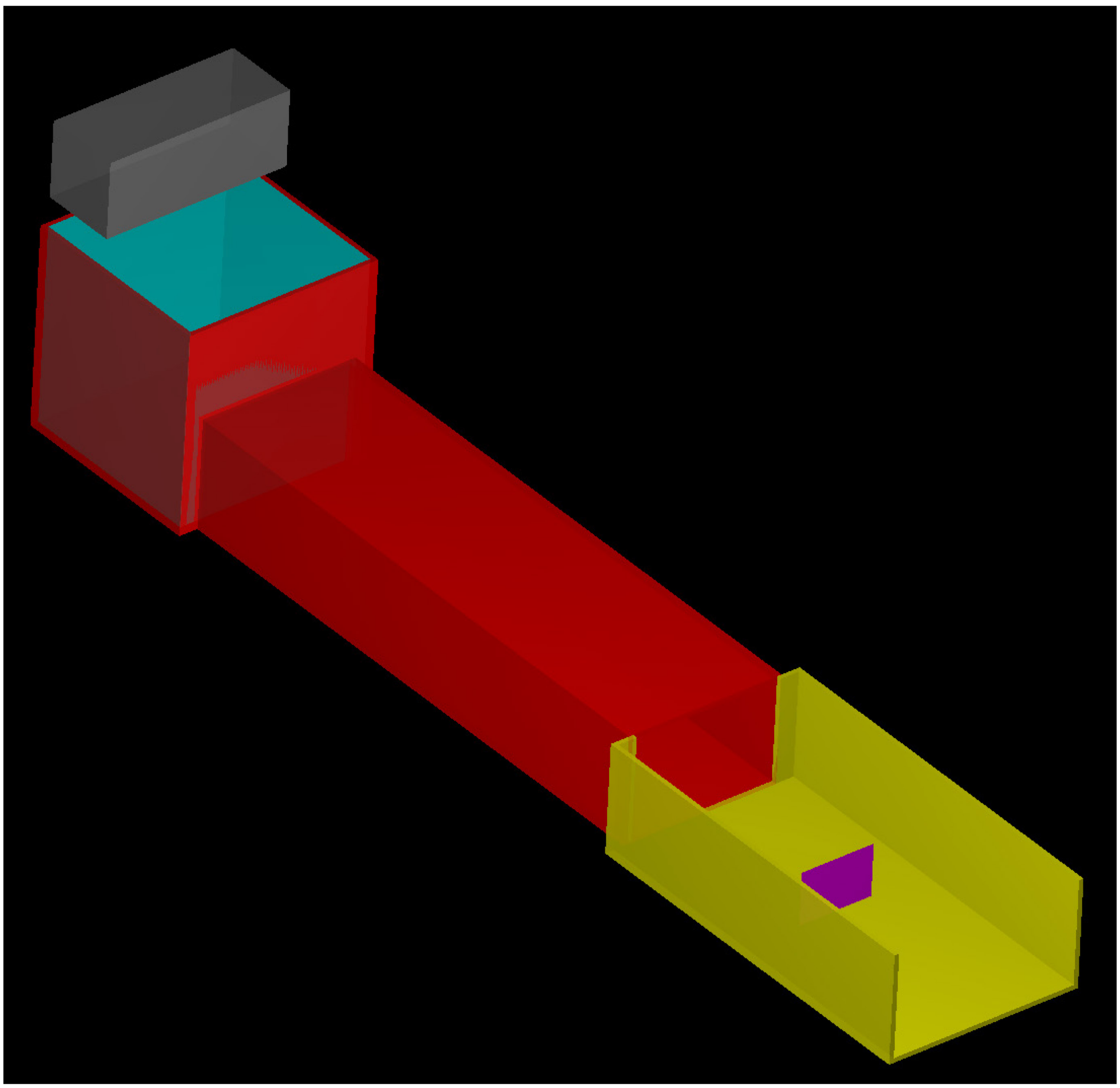

Figure 13. Closed Conduit Wave Generation Concept

Numerical simulation results will be compiled and used as the input to the design effort of the wave generation machine. A small scale prototype of this machine will be built and tested to verify its functionality. In more advanced tests, the wave impact machine will supply a short duration, high pressure slug of water, which will be capable of failing a component. An instrumentation and control system for this machine will be required as it will be desirable to monitor and vary the conditions of the wave impact tests.

Figure 14 illustrates the types of tests that will be performed for the flooding fragility experiments. In this test, a door is tested to failure (due to water building up behind the door). Information is collected (e.g., time of failure, height of water, type of component, nature of the failure, leakage rate of water prior to failure) during the experiment in order to later determine probabilistic fragility models for various component types.

Figure 14. Example of Door Flooding Fragility Test Outcome

5. SUMMARY

This report describes the development plan for verification and validation (V&V) of new multi-hazard assessment methods and tools developed by Idaho National Laboratory (INL) in the Risk-Informed Safety Margin Characterization (RISMC) technical pathway of the Light Water Reactor Sustainability Program. These methods and tools are used for implementing risk informed margin management (RIMM) methods developed by INL. The V&V plan for the new INL-developed tool includes collection and use of unique data sets collected by a new multi-partner Experimental Research Group - External Hazards (ERG-EH) coordinated by INL.

The RISMC pathway is developing a suite of new tools and methods for advanced evaluation of facility risk. The external events activity within the RISMC pathway is tasked with developing tools and methods focused on evaluation of risk from multi-hazard external (e.g, seismic and flooding) events. These events have been shown to be dominant risk contributors in probabilistic risk assessments performed for operating nuclear power plants (NPPs). The ERG-EH coordinated within the external events activity will provide technical expertise and experimental large-scale testing data needed for V&V and further development of tools and methods in the RISMC toolkit for external hazard safety evaluations.

Currently, there is limited data available for development and validation of the tools and methods being developed in the RISMC Toolkit for external hazards. The data developed by ERG-EH will be stored in knowledge bases within the RISMC Pathway. These knowledge bases will be used to validate the advanced external hazard tools and methods.

6. REFERENCES

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APPENDIX A – INTELLECTUAL AND PHYSICAL TESTING CAPABILITIES OF ERG-EH PARTNERS

Partner	Existing/ Future Capabilities	Capabilities	Description
Intellectual			
INL	Existing	Nonlinear seismic soil structure interaction method development	Using commercial time-domain codes to run sensitivity seismic sensitivity studies to further NLSSI R&D activities
	Existing	MASTODON	MASTODON will have the capability to perform stochastic nonlinear soil-structure interaction (NLSSI) in a risk framework coupled with virtual NPP. These NLSSI simulations will include structural dynamics, time integration, dynamic porous media flow, hysteretic nonlinear soil constitutive models (elasticity, yield functions, plastic flow directions, and hardening softening laws), hysteretic nonlinear structural constitutive models, and geometric nonlinearities at the foundation (gapping and sliding).
	Existing	Advanced SPRA methods development	Developing a method for evaluating multi-hazard risk including seismic and flooding
	Existing	Time-based stochastic analysis	
	Future	Virtual external hazards at virtual reactors	Evaluate the risk of multiple hazards impact virtual nuclear power plants including all applicable physics to model the nuclear core response to those hazards.
University at Buffalo	Existing	Numerical analysis of seismic isolation systems	Significant experience with both testing and analysis of seismic isolation components and systems. Under NRC funding, developed isolator unit elements for multiple NLSSI codes.
	Existing	Advanced SPRA methods development	Developed new techniques for SPRA approaches for isolator and umbilical systems in isolated facilities.
	Existing	Nonlinear seismic soil-structure interaction analysis	Extensive experience with NLSSI analysis. With INL staff, authored non-mandatory appendix on NLSSI for ASCE 4-16.
George Washington University	Existing	Diagnostics development for time based analysis and code validation	Experimentalist team that has track record of developing custom diagnostics that are deployed on earthquake shake table. Extensive experience in computer model benchmark and validation.
Purdue University	Existing	Nonlinear seismic soil-structure interaction analysis	Capability to perform NLSSI evaluations
University of Illinois at Urbana-Champaign	Existing	Nonlinear seismic soil-structure interaction; Soil constitutive modeling; Discrete Element	Developed widely used numerical code for performing fully non-linear site response analyses. Under NRC funding, developing new soil constitutive model for implementation in NLSSI codes.

Partner	Existing/ Future Capabilities	Capabilities	Description
Intellectual			
		Modeling; Visualization	
North Carolina State University	Existing	Multi-Hazard Risk Assessment	Seismically induced internal flooding due to leakages in pipes and tanks. Evaluation of piping vulnerabilities and integration with thermal hydraulic PRA for severe accident management particularly for beyond design basis events. Simulation of coastal storm surge flooding and storm wind effects for multi hazard PRA. Identification of previously unidentified critical paths due to correlated external/internal hazards. Consideration of Bayesian networks.
	Existing	Vulnerability Assessment for SSC	Integration of component and subsystem level experimental data into system-level models for simulation of seismic performance of building-equipment-piping systems to include the effects of interactions among them. Uncertainty quantification in constitutive models for reinforced concrete and for steel. Propagation of uncertainty through system level simulations.
	Existing	Fragilities of Flood Defense Structures	Uncertainty quantification and assessment of fragility surfaces for concrete protection structures such as walls, weirs, dams, and levees subjected to flooding and seismic loads. Consideration of structural as well as foundation failures.
	Existing	Equipment Qualification	Reconciliation of experimental and simulation results for electrical cabinets and control panels. Characterization of uncertainty in mounting arrangement. Effect of high frequency ground motions on amplifications in the electrical cabinets and control panels.
Idaho State University	Existing	Flood/tsunami numerical modeling	SPH fluid modeling experience. Research into modeling of hydraulic structures and flood control structures.

Partner	Existing/ Future Capabilities	Capabilities	Description
Physical			
INL	Existing	Geotechnical Centrifuge	Could be used to perform small scale soil experiments. Some modifications are necessary to a 1D shake table.
	Future	Small scale structural dynamics lab	Used to perform small scale structural dynamics experiments. The main goal is to allow INL researchers developing numerical code to also get experience in a physical environment and gather data used to frame larger scale experiments.
University at Buffalo	Existing	Two high-performance, 6 DOF shake tables	Tables can be relocated to adjacent positions or placed up to 92 feet apart (center-to-center). Together, the tables can support specimens of up to 100 metric tons and as long as 115 feet. When operated together, the tables can be programmed with identical or uncorrelated dynamic motions. Each shake-table surface has plan dimensions of 12 ft. x 12 ft. Two 23 ft. x 23 ft. shake-table extension platforms are available for both shake-tables. Use of the table extensions extends the footprint available for test specimens.
	Existing	Nonstructural Component Simulator (NCS)	The NCS is a modular two-level testing frame for experimental performance evaluation of nonstructural components and equipment under realistic full scale floor motions. The NCS can provide the dynamic stroke necessary to replicate full-scale displacements, velocities and accelerations in the upper levels of multi-story buildings during severe earthquake shaking. The system can test nonstructural components and equipment at up to 3 g horizontal accelerations with specimen capacity of up to 6.9 kips per level. Vertical accelerations can also be included in an experiment by mounting the NCS on one of the shake-tables.
	Existing	Large-scale geotechnical laminar box	Designed for soil-foundation-structure interaction studies near full scale. The laminar box comprises 39 rings or laminates built of welded I-beams, stacked vertically to form a rectangular box. Each laminate is supported by ball bearings that are fixed to the laminate below. The laminates are separated by a 0.2 in. gap. The stacked laminates are mounted on a sliding steel base assembly that is supported by 288 ball bearings. The sliding base is installed on a steel plate that is bolted to the strong floor. Two 110-kip dynamic actuators are connected between dedicated reaction blocks and the sliding base. When subjected to periodic

Partner	Existing/ Future Capabilities	Capabilities	Description
Physical			
			or simulated seismic motions, the laminar box and the soil contained within deform in a manner that simulates free ground response. The laminar box has a maximum height of 19.7 ft. The nominal internal dimensions are 16 ft. long x 9 ft. wide. The enclosed volume can be filled with a saturated sand or soil to a maximum capacity of 100 cubic yards, using a hydraulic slurry pump and distribution system. A supply of Ottawa (F-55) sand is stored in three (65.4 cubic yards each) outdoor storage containers and is available for use in sponsored projects. Use of other soil materials is possible.
	Existing	Hybrid simulation systems	Two hybrid simulation systems are available, both of which are connected via SCRAMNet shared-RAM access to the shake-table and structural test controllers, data acquisition systems, and dedicated real-time control computer hardware. The hybrid platforms can be deployed on experiments using the east shake-table, the NCS or any of the structural actuators. The hybrid simulation platforms are typically programmed using MathWorks MatLab and Simulink, for which SEESL has licensing and maintenance agreements.
George Washington University	Existing	Modal and Tensile Testers	Modal Teste: Vibration Research system. 0-3,000 Hz, 80 lbf Tensile Tester: 10,000 lbf
	Existing	Dedicated high-bay space with strong floor	25' ceiling, 1,340 sqft, 26'x10' strong floor, 1 MW of electrical power, 4 tons crane, 75 Hp Hydraulic Pump
	Existing	Large, polyvalent, and transportable suite of advanced diagnostics proven on shake table	27 cameras total, including cameras able of exposure down to 10 ns and single photon detection, speed of 1.3×10^6 frames/second, recording time of several hours; light sources ranging from lasers (0-100 kHz from UV to IR), strobe LEDs (0-100 kHz), Flood lights, etc.; in-house and commercial Digital image correlation, particle image velocimetry codes
	Future	1D 10'x10' shake table	MTS , 0-50 Hz, 6 Mtons
	Future	1D 5'x5' shake table	MTS, 0-100 Hz, 1 Mtons
University of Illinois at Urbana-Champaign	Existing	Illinois Multi-Directional Cyclic Simple Shear Device for soil testing.	Multi-directional simple shear device capable of performing both drained and fully saturated testing on element-level specimens of sand and clay materials. Most appropriate testing methods for development of soil constitutive models.

Partner	Existing/ Future Capabilities	Capabilities	Description
Physical			
	Existing	Monotonic and Cyclic Triaxial soil testing	Testing device used for consolidation and strength testing of geotechnical materials.
	Existing	Resonant Column soil testing	Testing device appropriate for determination of appropriate V_S and G_O properties of geotechnical materials to be used in site response and SSI analyses
Purdue		Wykeham Farrance unsaturated dynamic hollow cylinder device capable of testing hollow or solid specimens	Testing device appropriate for determination of appropriate V_S and G_O properties for unsaturated soil materials to be used in site response and SSI analyses
		Automated triaxial testing (CKC) system for cyclic or monotonic loading with user-defined stress paths, equipped with bender elements	Testing device capable of determining V_S and G_O properties of geotechnical materials. Also, commonly used for consolidation and strength testing of geotechnical materials.
		Automated MTS programmable load frame for stress- or strain-controlled dynamic or monotonic testing, allowing testing of geotextiles, and independent control of pore water pressure or confining stresses	Testing device capable of determining properties of geotextiles and other laminar materials. Of use for testing materials used to represent vapor barrios in gapping and sliding testing.
		Small- and large-scale direct shear boxes, ring shear device and pull-out box	Testing device used for strength testing of geotechnical materials. Capable of assessing crushing of particulate materials under load.
		Hydraulic static and cyclic actuators with upto 1000 kip capacity	Can perform dynamic soil-foundation interaction analysis
Idaho State University	Existing	Water flume and associated water storage/pumping	Used to develop flooding fragilities of SSCs