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Light Water Reactor Sustainability Program

Advanced Seismic Probabilistic Risk Assessment Methodology: Development of Beta 1.0 MASTODON Toolset

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SUMMARY

Design of nuclear power plant (NPP) facilities to resist natural hazards has been a part of the regulatory process from the beginning of the NPP industry in the United States, but has evolved substantially over time. The original set of approaches and methods was entirely deterministic in nature and focused on a traditional engineering margins-based approach. However, over time probabilistic and risk-informed approaches were also developed and implemented in US Nuclear Regulatory Commission guidance and regulation. A defense-in-depth framework has also been incorporated into US regulatory guidance over time. As a result, today, the US regulatory framework incorporates deterministic and probabilistic approaches for a range of different applications and for a range of natural hazard considerations.

Although the US regulatory framework has continued to evolve over time, the tools, methods and data available to the US nuclear industry to meet the changing requirements have not kept pace. Notably, there is room for improvement in the tools and methods available for external event probabilistic risk assessment (PRA), which is the principal assessment approach used in risk-informed regulations and risk-informed decision-making applied to natural hazard assessment and design. Development of a new set of tools and methods that incorporate current knowledge, modern best practice, and state-of-the-art computational resources would lead to more reliable assessment of facility risk and risk insights (e.g., the plant elements and accident sequences that are most risk-significant), with less uncertainty and reduced conservatisms.

Development of the next generation tools and methods for external events PRA is ongoing under the Risk Informed Safety Margins Characterization (RISMC) technical pathway. The RISMC toolkit development centers on integration of the tools and methods under a common framework, MOOSE. These tools and methods make use of existing and newly developed tools and methods, coupled with the experience and data gained in the past decades, to define and analyze more realistic risk assessment models. Specific focus in this report is on the capability to model seismic risk using advanced SPRA methods.

Over the last year, significant capability has been added to the seismic probabilistic risk assessment MOOSE based tool MASTODON. Capability has been added to MASTODON to simulate 3-D wave passage effects through nonlinear soil coupled with nuclear facilities. Verification has demonstrated the capability of MASTODON to model wave passage effects in 1-D, 2-D, and 3-D. Methods have been developed to incorporate probabilistic floor response (demands), calculation of fragilities as functions of local demand parameters (such as floor spectral acceleration at the location of the component) by using the output from stochastic simulations, input event tree and fault tree information, and calculate seismic risk. Also included in MASTODON are web-based verification and user manuals, and web-based software quality assurance documentation and traceability. Additional capability will be added to MASTODON over the next year to implement a robust gapping and sliding element for cyclic shaking, frequency independent damping, and seismic isolation elements. Code development work will complete the dynamic time based risk assessment capability. Verification of all added capabilities continues to occur in parallel with code writing activities. Proposed work for fiscal year 2018 is an application driven methodology for seismically induced fire PRA.

ACKNOWLEDGEMENTS

This report was commissioned by the Department of Energy, Office of Nuclear Engineering under the Light Water Reactor Sustainability Program at INL.

CONTENTS

FIGURES

TABLES

ACRONYMS

1-D	one-dimensional
2-D	two-dimensional
3-D	three-dimensional
ASPRA	advanced seismic probabilistic risk assessment
ATR	Advanced Test Reactor
CDF	core damage frequency
CFR	Code of Federal Regulation
DOE	Department of Energy
DRM	domain reduction method
EMRALD	Event Model Risk Assessment using Linked Diagrams
EPRI	Electric Power Research Institute
ERG-EH	Experimental Rm
GUI	graphical user interface
INL	Idaho National Laboratory
ISRS	in-structure response spectrum
LOCA	loss of coolant accident
LOOP	loss of offsite power
LWRS	Light Water Reactor Sustainability
MASTADON	STOchastic time-DOmaiN phenomena
MAFE	mean annual frequency of exceedance
MLE	maximum likelihood estimate
MOOSE	Multi-Physics Object-Oriented Simulation Environment
NEP	non-exceedance probability
NLSSI	non-linear soil-structure-interaction
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
NUREG	nuclear regulatory report (NRC)
PGA	peak ground acceleration
PRA	probabilistic risk assessment
PSHA	probabilistic seismic hazard assessment
RAVEN	Risk Analysis and Virtual Control Environment

R&D	Research and Development
RELAP5	Reactor Excursion and Leak Analysis Program 5
RELAP-7	Reactor Excursion and Leak Analysis Program 7
RIMM	Risk-Informed Margin Management
RISMC	Risk Informed Safety Margin Characterization
SPRA	seismic probabilistic risk assessment
SSCs	structures, systems, and components
SSI	soil-structure-interaction
TH	thermalhydraulic
UHS	uniform hazard spectrum
U.S.	United States

Advanced Seismic Probabilistic Risk Assessment Methodology: Development of Beta 1.0 MASTODON Toolset

1. BACKGROUND AND OVERVIEW

1.1 Introduction and Motivation

Design of nuclear power plant (NPP) facilities to resist natural hazards has been a part of the regulatory process from the beginning of the NPP industry in the United States (U.S.), but has evolved substantially over time. The original set of approaches and methods was entirely deterministic in nature and focused on a traditional engineering margins-based approach. However, over time probabilistic and risk-informed approaches were also developed and implemented in US Nuclear Regulatory Commission (NRC) guidance and regulation. A defense-in-depth framework has also been incorporated into US regulatory guidance over time. As a result, today, the US regulatory framework incorporates deterministic and probabilistic approaches for a range of applications and for a range of natural hazard considerations. This framework will continue to evolve as a result of improved knowledge and newly identified regulatory needs and objectives, most notably in response to the NRC activities developed in response to the 2011 Fukushima accident in Japan.

Although the US regulatory framework has continued to evolve over time, the tools, methods and data available to the US nuclear industry to meet the changing requirements have not kept pace. Notably, there is room for improvement in the tools and methods available for external event probabilistic risk assessment (PRA), which is the principal assessment approach used in risk-informed regulations and risk-informed decision-making applied to natural hazard assessment and design. Development of a new set of tools and methods that incorporate current knowledge, modern best practice, and state-of-the-art computational resources would lead to more reliable assessment of facility risk and risk insights (e.g., the plant elements and accident sequences that are most risk-significant), with less uncertainty and reduced conservatisms.

Probabilistic seismic hazard assessment (PSHA) and seismic probabilistic risk assessment (SPRA) approaches have been applied and improved for several decades and are now considered to be relatively mature in terms of their conceptual development and application. Unfortunately, the tools currently available for SPRA (of which PSHA is a part) are relatively inflexible and were developed principally for internal event PRAs. As a result, currently available tools are now significantly limiting the development of more advanced SPRA (ASPRA) approaches and methodologies.

Development of "next generation" seismic risk assessment tools and methods, built within the Idaho National Laboratory (INL) Risk Informed Safety Margin Characterization (RISMC) toolkit will lead to significant improvements in industry's ability to address regulatory requirements and make the most of regulatory opportunities (e.g., risk-informed relief) related to natural hazards. An overview of the ongoing development of a new set of ASPRA tools and methods being developed using INL's Multiphysics Object Oriented Simulation Environment (MOOSE) High Performance Computing framework (Gaston, Hansen, and Newman 2009) is shown in Figure 1. These tools are being developed to both integrate the existing large number of available modeling resources and fill in the gaps, as necessary, to address the risk from natural hazard phenomena. A key aspect of this integrated toolset is the use of advanced PRA methods, which represents a significant improvement over current approaches, particularly in its ability to (1) incorporate time dependencies, to (2) incorporate multiple hazards and dependent hazards (e.g., seismically-induced flood), and to (3) quantify and carry uncertainties throughout the analysis.

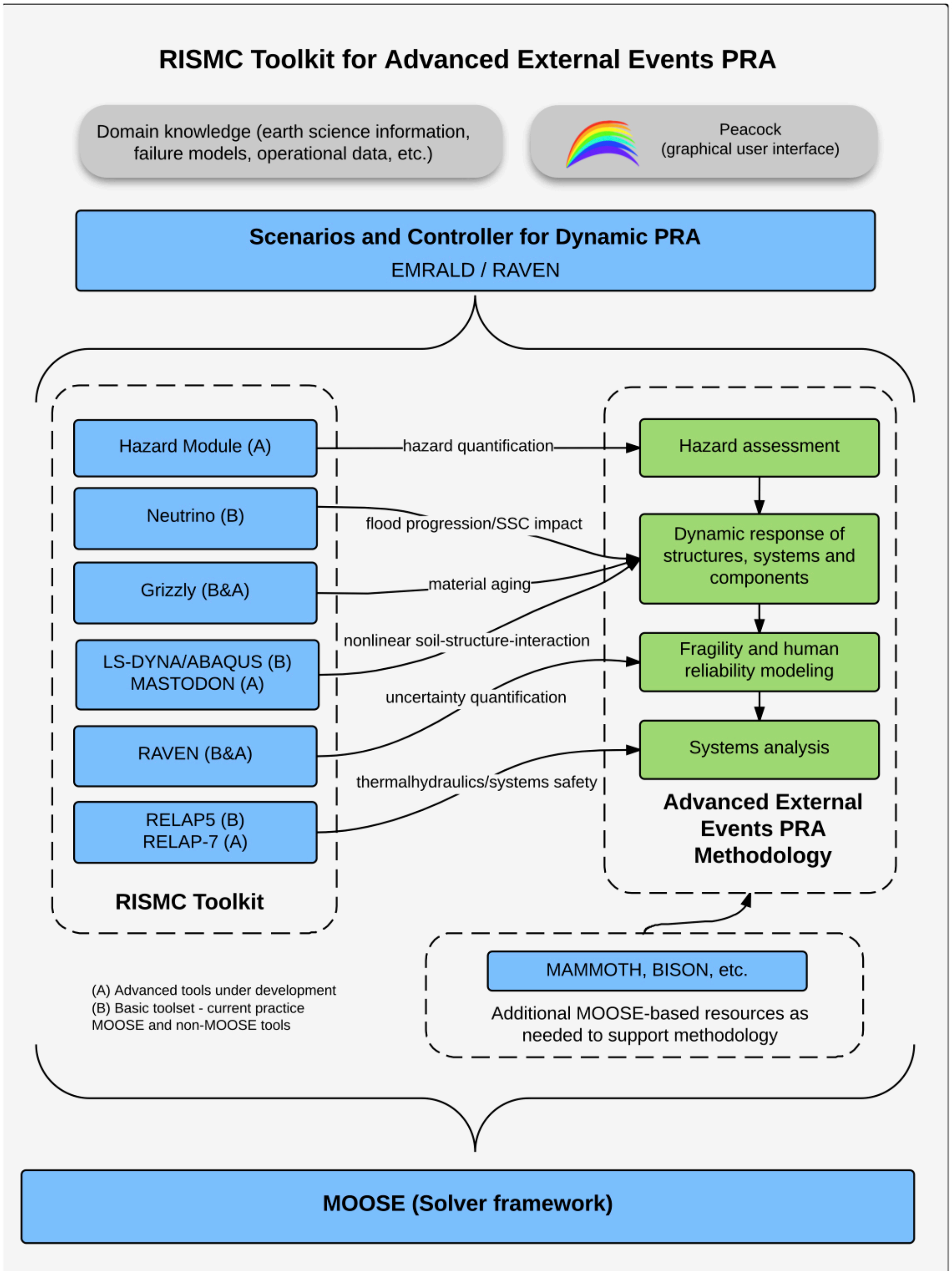


Figure 1. Elements of the RISMC toolkit and their relation to Advanced Probabilistic Risk Assessment for External Events.

1.2 Overview of the report

This report discusses MASTADON tool development for external hazards and provides a demonstration on how the toolkit can be applied to ASPRA for nuclear power plant scenarios. Section 2 of this report provides background on the RISMC toolkit and discusses RISMC toolkit development for external hazards. Section 3 discusses tools in more depth, with a particular emphasis on MASTODON (a MOOSE-based code for NLSSI). Section 4 focuses on new methods and tools for implementing enhanced nonlinear soil-structure-interaction (NLSSI) analysis into ASPRA and its impact on quantifying the impact on fragilities of structures, systems, and components (SSCs). Section **Error! Reference source not found.** describes a SPRA demonstration project. Section 6 discusses software quality assurance efforts and status.

The benefit of the report is describing methods and tools to perform ASPRA calculations in one software platform instead of multiple platforms and excel spreadsheets.

2. SPRA FRAMEWORK AND METHODOLOGY DEVELOPMENT

2.1 Background on MASTODON

Multi-hazard Analysis for STOchastic time-DOmaiN phenomena (MASTODON) is a finite element application that aims at analyzing the response of 3-D soil-structure systems to natural hazards such as earthquakes, and floods. MASTODON currently focuses on the simulation of seismic events and has the capability to perform extensive 'source-to-site' simulations including earthquake fault rupture, nonlinear wave propagation and nonlinear soil-structure interaction (NLSSI) analysis. The unique capability of MASTODON is that as a MOOSE based application it seamlessly couples with other physics based applications such as GRIZZLY, RELAP-7, and BISON. This allows for modeling the response of a nuclear power plant to earthquake scenarios down to the pellet level. MASTODON will stochastically model virtual natural hazards and phenomena at virtual NPPs.

MASTODON is being developed to be a dynamic probabilistic risk assessment framework that enables analysts to not only perform deterministic analyses, but also perform probabilistic or stochastic simulations for the purpose of risk assessment on a single platform. MASTODON performs calculations in effective stress space using a nonlinear hysteretic soil constitutive model (I-soil), and a u-p-U formulation to couple solid and fluid, as well as structural materials such as reinforced concrete. It is also equipped with interface models that simulate gapping, sliding and uplift at the interfaces of solid media such as the foundation-soil interface of structures. MASTODON also includes absorbing boundary models for the simulation of infinite or semi-infinite domains, fault rupture model for seismic source simulation, and the domain reduction method for the input of complex, three-dimensional wave fields.

2.2 Background on the RISMC Toolkit

The RISMC toolkit is a product of the RISMC technical pathway (Smith, Rabiti, and Martineau 2013) of the Light Water Reactor Sustainability (LWRS) Program (INL 2015). The RISMC toolkit provides resources to be used within a technical framework, such as ASPRA, to understand and address real world external hazard challenges, including those posed by the types of scenarios shown in Figure 2 (e.g., a scenario with more than one principal hazard or with secondary effects).

At a nuclear facility, an external hazard is a condition that may cause a deviation in the normal operation. External hazards of interest have a primary impact on the nuclear facility that may also lead to secondary phenomena. Examples of external hazards that cause primary impact are seismic shaking, flooding, and high winds. Examples of secondary phenomena induced by a seismic scenario are dam and levy failure, landslide, internal flood, and internal fire. These types of hazards complicate the determination of safety in any complex facility and often have a strong time-dependency. An example of how an event progresses in time is provided in Figure 3.

An important advancement in the assessment of assessment of risk would be an approach that considers all applicable external hazards together (as shown on the right side of Figure 4), instead the current approach (shown on the left) that calculates the risk from each external hazard separately, even if they have a common cause or other interrelation. An integrated approach provides a technical framework to assess and manage the risk that results from real-world natural hazards events. Tools available for an integrated method include those shown in Figure 1, which each are discussed in more detail in Appendix C. The integrated approach can also make use of a large number additional MOOSE-based tools developed outside RISMC (see Figure 5).

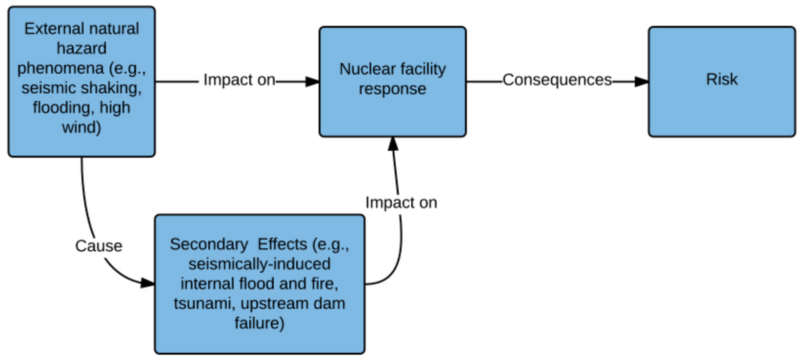


Figure 2. Real world risk propagation at nuclear power plants

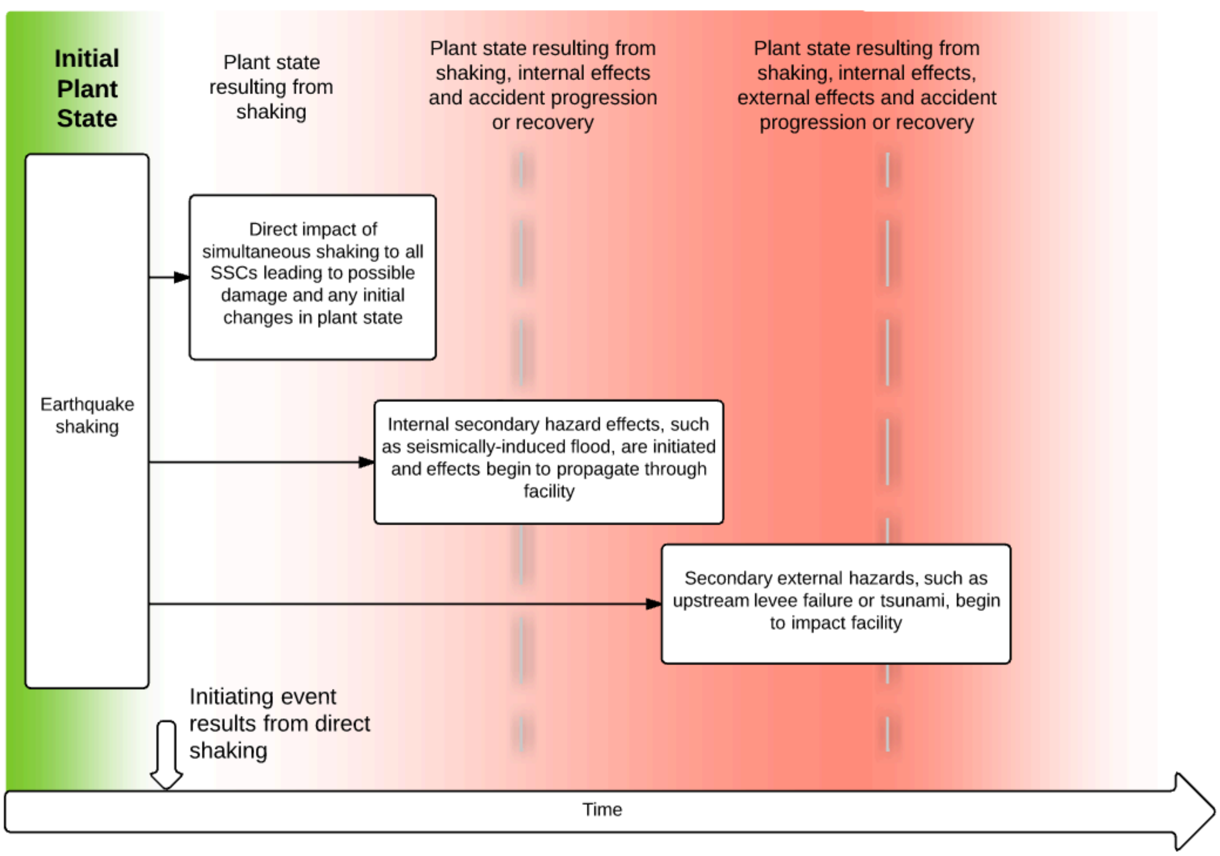


Figure 3. Evolution of an external event over time.

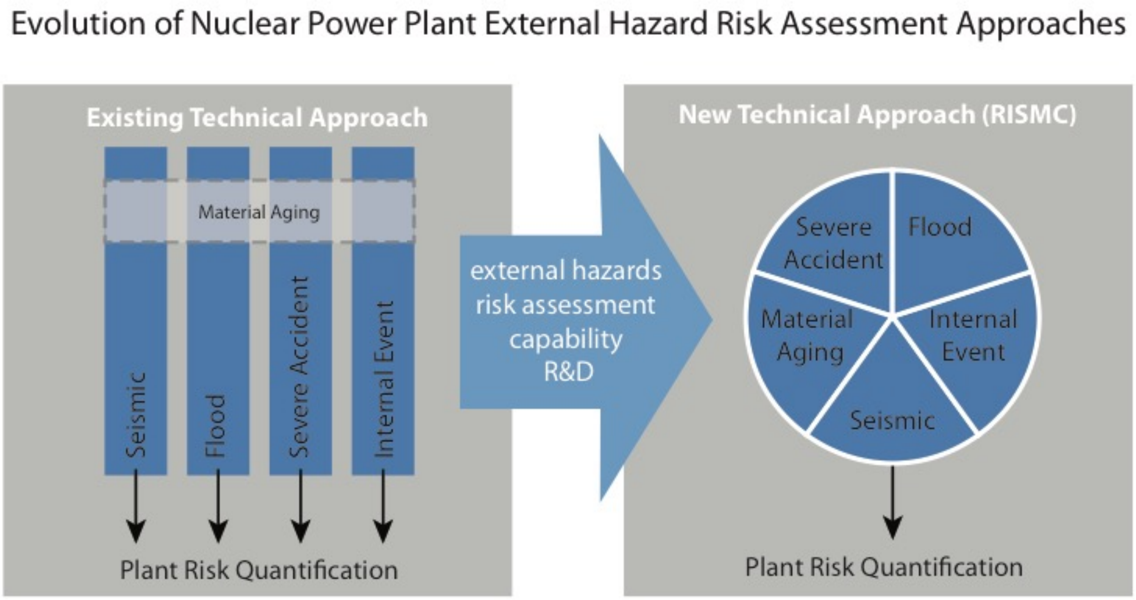


Figure 4. Current risk calculation approach that generally considers external hazards separately versus an integrated approach that considers external hazards together.

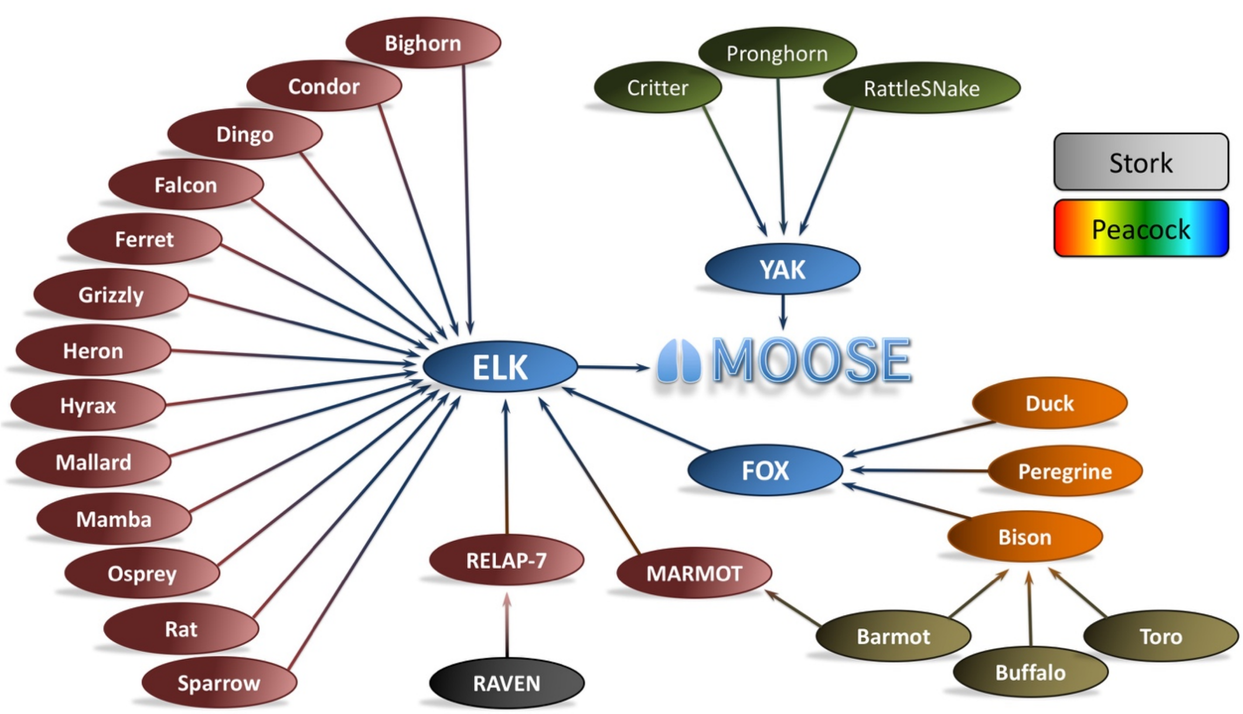


Figure 5. Additional MOOSE resources and tools developed outside RISMC.

2.3 External Hazard Applications

The RISMC toolkit ASPRA activity is developing a new set of tools and methods within the RISMC technical pathway to perform ASPRA. These tools and methods would be implemented within the MOOSE solver framework and would make use of existing and newly developed tools and methods, coupled with the experience and data gained in the past decades, to define and analyze more realistic risk assessment models.

New tools and methods are under development as part of the RISMC toolkit and others are being expanded or enhanced. For example, Figure 1, separates tools a "basic" toolset and an "advanced" toolset, denoted by the "B" and "A" notations, respectively. The basic toolset consists of tools that are currently in use and are not expected to be substantially updated as part of the ASPRA efforts, either because the existing tool is sufficient for its purpose within ASPRA (e.g., Grizzly) or because it has been or will be replaced by a new tool (e.g., RELAP5). The advanced toolset are tools that represent a substantial change from past capabilities as it relates to external hazard PRA. These tools can be applied to a variety of problems, including external event hazards.

The technical elements of ASPRA are shown the central box in Figure 1, along with their relationship to other RISMC components. Traditionally, external event PRA has been thought of as being composed of three general elements: hazard assessment, fragility analysis (including analysis of human performance aspects), and systems (plant response) analysis. Advanced external event PRA, as being developed at INL, explicitly recognizes the dynamic response of SSCs (and sometimes human operators) as a critical fourth element. For example, SPRA also has the integrated element of SSI analysis, which couples the rock hazard at the sites to the seismic motions (characterized by in-structure response spectra (ISRS)) experienced by the systems and equipment within the NPP. The fragility of the structure itself is also important for assessment of the potential for early release into the environment. Similarly, flooding PRA must look at how the water flows through a facility and when and how it impacts systems and components. This is parallel to the ISRS in a SPRA because both look at the load on individual SSCs, as opposed to the fragility analysis, which looks at the response of individual SSCs.

The new tools and methods being developed in the ASPRA development program perform the steps in a SPRA using a more integrated approach that could reduce interface issues and more accurately track uncertainties throughout the process. The tools and methods under development are intended move away from the use of peak ground acceleration (PGA) as the fundamental input parameter and instead incorporate parameters of most significance to the SSCs of interest. PGA has been used historically, but is a poor estimator of SSC failure[a] in most cases. By tracking uncertainties more seamlessly and rigorously throughout the process, and using physics-based tools to investigate scenarios of interest that have traditionally been left out of SPRA (e.g., seismically-induced fire and flood), the new tools would provide more accurate models with a clearer view of uncertainties.

Development of a set of tools and methods to replace the existing SPRA toolbox is the first focus area of a multi-phase project. This approach means that a state-of-the-art toolbox (and set of associated methods) will be available at any point in the development process. Focusing on SPRA, which is well understood, will allow the development team to make meaningful comparisons to case studies and to identify gaps and issues. Focus area 2 would develop new tools and methods to address seismically-induced flooding (internal and external). Focus area 2 expands the tools created in focus area 1 by developing methods and protocols to use various physics-based dynamic tools available in the RISMC toolkit to investigate issues and uncertainties in the systems model for facilities being analyzed. Focus area 2 also addresses development of a hazard module that is more integrated in the ASPRA. Activities following these first two phases would identify areas in which efficiencies are found and/or further developing methods based on ongoing use of the tools and methods.

[a] Failure of an SSC for ASPRA purposes is defined as "inability to perform its intended safety function".

Coupled with the development of the tools is an effort to perform verification and validation, which includes a program of small- to large-scale laboratory experiments (Coleman, Smith and Kammerer 2016). The development of the tools is also supported by a new cooperative multi-partner research consortium called the *Experimental Research Group – External Hazards* (ERG-EH) coordinated by INL (Coleman et al. 2016). The ERG-EH is being developed to 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 includes recognized experts in the fields of seismic and flooding hazard assessment. The data developed by ERG-EH will be stored in databases for use within RISMC. These databases will be used to validate the advanced external hazard tools and methods.

3. RECENT ADVANCES THE DEVELOPMENT OF MASTODON

3.1 Introduction

Initially MASTODON was developed as a finite element application to solve the response of 3-D nuclear structures to earthquakes. That concept has been expanded so that MASTODON is now a computation platform for dynamic seismic probabilistic risk assessment. The calculation procedures include: (1) physics for analyzing seismic events with ‘source-to-site’ simulations including earthquake fault rupture, nonlinear wave propagation and nonlinear soil-structure interaction (NLSSI) analysis, (2) pre-processing capability to span off 1000s of simulations based on distributions, and (2) post-processing capability to calculate SSC fragilities and risk. The unique capability of MASTODON is that as a MOOSE based application it seamlessly couples with other physics based applications such as GRIZZLY, RELAP-7, and BISON. This allows for modeling the response of a nuclear power plant to earthquake scenarios down to the pellet level probabilistically. MASTODON will stochastically model virtual natural hazards and phenomena at virtual NPPs.

This section describes recent developments in MASTODONs nonlinear soil constitutive model and verification of the capability. Also described is the development of web based user and theory manuals for the soon to be open-sourced MASTODON.

3.2 Masing Model verification

3.2.1 Brief description of I-soil material model

A piecewise linearized, 3-D soil constitutive model named I-soil (Numanoglu, 2017) has been implemented in MASTODON. The model can be represented by shear type parallel-series distributed nested components (springs and sliders) in one dimensional shear stress space and its framework is analogous to the distributed element modeling concept developed by Iwan (1967). The model behavior is obtained by superimposing the stress-strain response of nested components. Three-dimensional generalization follows Chiang and Beck (1994) and uses von Mises (independent of effective mean stress) and/or Drucker-Prager (effective mean stress dependent) type shear yield surfaces depending on user’s choice. The yield surfaces are invariant in the stress space Figure 6. Thus, the model does not require kinematic hardening rule to model un/reloading stress-strain response and preserves mathematical simplicity.

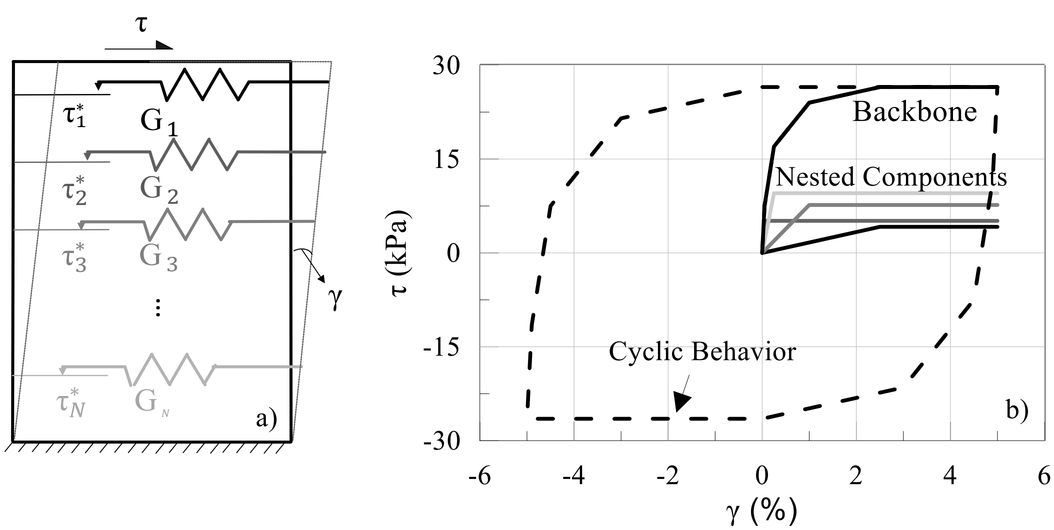


Figure 6 I-soil model details: (a) 1D representation by springs; (b) example monotonic and cyclic behavior of four nested component model (reprinted from Baltaji et al. (2017)).

The Drucker-Prager version of the material model allows the users to modify the stiffness (shear modulus and bulk modulus) and the strength (yield stress) as a function of effective mean pressure (p). The shear modulus (G) of the material as a function of effective mean pressure (p) is given as follows:

$$G(p) = G(p_{ref})\left(\frac{p - p_0}{p_{ref}}\right)^{b_{exp}}$$

where, p_{ref} is the reference pressure at which the experimental data for the backbone curve was obtained, $G(p_{ref})$ is the shear modulus at the reference pressure, p_0 is the tensile pressure tolerance beyond which the shear capacity of the soil reduced to zero, and b_{exp} is a curve-fitting parameter obtained from experimentally observed variation of soil shear modulus with pressure. This variation of the shear modulus with pressure ensures that the soil element fails under tension as in the real world scenario.

The yield stress (τ_y) of the material as a function of effective mean pressure is given by:

$$\tau_y(p) = \tau_y(p_{ref})\sqrt{\frac{a_0 + a_1(p - p_0) + a_2(p - p_0)^2}{a_0 + a_1 p_{ref} + a_2 p_{ref}^2}}$$

where, $\tau_y(p_{ref})$ is the yield stress at the reference pressure, and a_0, a_1 and a_2 are parameters that define how the yield stress changes with pressure. For $a_0 = 0, a_1 = 0$ and $a_2 = 1$, the yield stress varies linearly as a function of pressure.

The backbone stress-strain curve required as input for the soil model (Figure 6(b)) can either be provided by the user or can be auto-generated using the Darendeli (2001) empirical equations or the GQ/H method (Groholski et al. 2016). The backbone curves generated using the Darendeli equations are more suitable for small to moderate shear strain and tend to over or under predict the stress at larger shear strains. The GQ/H method uses modified Darendeli backbone curve that has been corrected for larger shear strains using experiments conducted at large shear strains.

3.2.2 Benchmarking against DEEPSOIL and LS-DYNA

3.2.2.1 Single element test

A single element quasi-static test is first conducted to ensure that the hysteretic backbone curve generated by the soil model is correct. For this test, a single brick element is fixed at the base and a cyclic displacement (Figure 7(a)) is applied at the top of the brick element. The backbone curve used for the I-soil constitutive model is defined using (Darendeli 2001) normalized modulus reduction curves with a unit weight (γ), over-consolidation ration (OCR), lateral earth pressure coefficient at rest (K_0), and plasticity index (I_p) of 20 KN/m^3, 1, 0.4 and 0, respectively. A shear wave velocity (V_s) of 100 m/sec is used to determine small strain shear modulus.

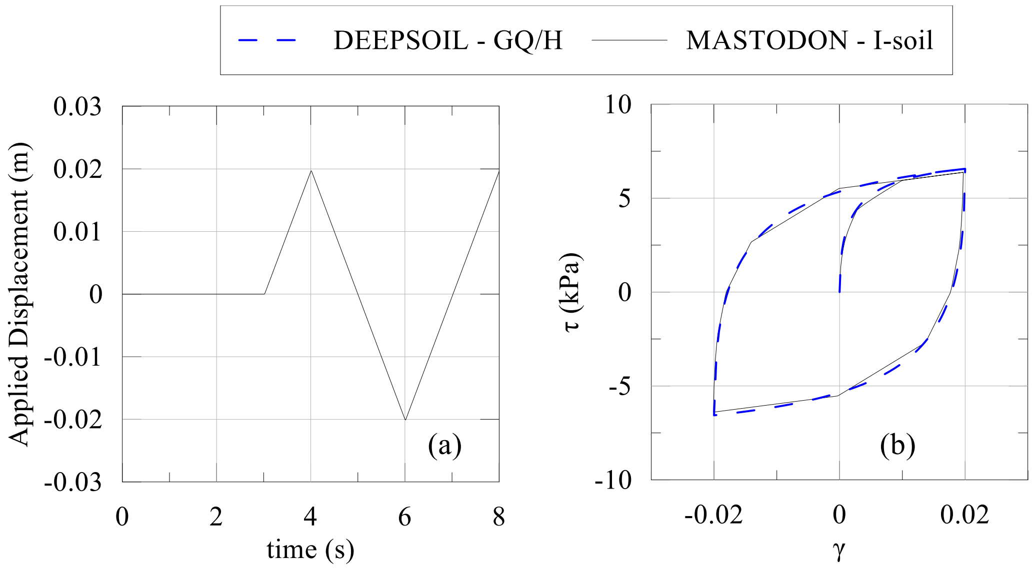


Figure 7 (a) Cyclic displacement applied to the top a 3D brick element, and (b) comparison between shear stress-shear strain curves obtained from MASTODON and DEEPSOIL (reprinted from Baltaji et al. 2017).

For this element level simulation, 9.81 m/s^2 (1g) of gravitational acceleration was activated, and the reference pressure was equated to the effective mean stress ($\sigma_{ii}/3$), which is calculated to be ~6 kPa. The model is set to be pressure independent. The material was assigned a density of 2 ton/m^3. The stresses were initialized to K_0-conditions.

Figure 7(b) compares the nonlinear hysteretic behavior obtained from the GQ/H model in DEEPSOIL(Hashash et al. 2016) and the I-soil model in MASTODON. The cyclic responses of the models are very close. The slight differences are due to the discrete (piecewise linear) nature of the backbone curve used in MASTODON and continuous backbone curve used in DEEPSOIL.

3.2.2.2 Nonlinear 3-D free-field seismic site response test

After conducting single element tests, the next step is to test the response of a 3-D free-field soil model to a base excitation. A 36 m x 36 m x 20 m soil column with 20 1 m thick soil layers is considered for this study. The soil domain and the backbone curves for all the 20 soil layers are shown in Figure **8**.

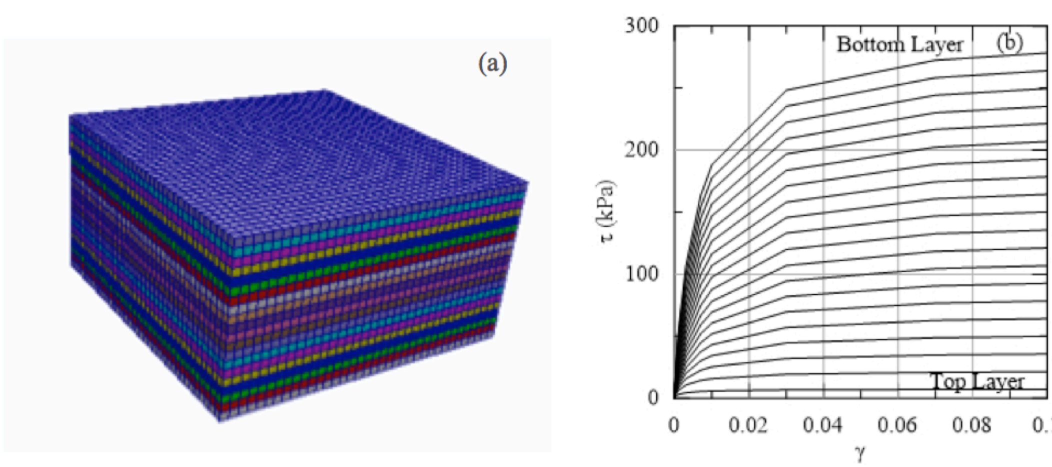


Figure 8: (a) 3-D free-field soil domain with 20 soil layers, and (b) backbone stress-strain curves for the 20 soil layers (reprinted from Baltaji et al. 2017).

A density of 2 ton/m3 is assigned to all layers. In MASTODON, gravity is activated and stresses are initialized to K_0-conditions. Periodic boundary conditions are applied on external nodes, along external edges of the model, of the same elevation in x, y and z directions. Newmark-beta integration parameters, α and β, are set to 0.25 and 0.5. Rayleigh damping is applied to the system. For this model, the mass and stiffness damping parameters, zeta (ζ) and eta (η), are calculated to be 0.000781 and 0.64026 respectively. The same soil profile was utilized in DEEPSOIL to conduct a nonlinear 1-D seismic site response using the GQ/H model.

Finally, the baseline-corrected Chi-Chi-1999 motion, record P1116 (Ancheta et al. 2014), is applied as a rigid base motion in x-direction as a prescribed acceleration.

Figure 9 shows the nodal spectral accelerations and Fourier amplitude spectra resulting from MASTODON, and DEEPSOIL analyses for nodes at 1 m depth, mid-height and bottom. Two analyses have been run: 1) using material backbones defined using 10 points and the original motion of time step (dt) of 0.005 sec; 2) using material backbones defined using 100 points and the input motion is zero-padded to dt of 0.001 sec, corresponding to a sampling rate ten times greater than the maximum frequency considered, 100 Hz, as suggested in (Chopra 2007) and (Phillips et al. 2012). Similar recommendations were suggested in (Coleman et al. 2016). For the first analysis, peak ground accelerations and spectral accelerations throughout the profile match very well for practical purposes except the high frequency content in MASTODON results near 0.02-0.03 sec periods at 10 and 1 m depths which also reveals itself in Fourier amplitude spectra. In the second analysis, it is observed that the high frequency content at 10 m depth vanished. This resulted in a good agreement between MASTODON and DEEPSOIL.

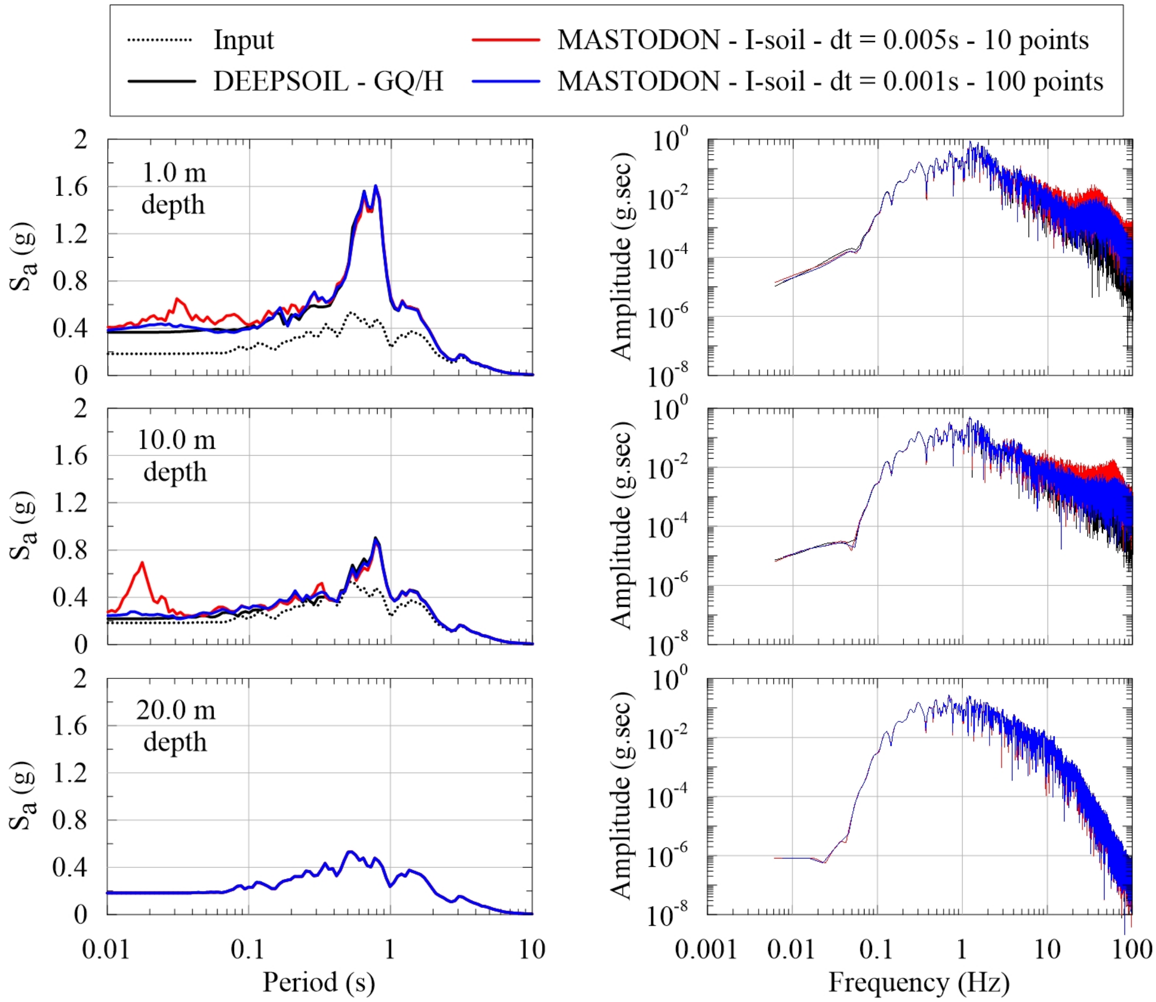


Figure 9 Non-uniform free-field models results: acceleration response spectra and Fourier amplitude spectra at top, middle and bottom of the model (reprinted fromBaltaji et al. 2017).

3.2.2.3 Nonlinear 3-D soil-structure interaction analyses

As a next step, the ability of the I-soil material model implemented in MASTODON to model soil-structure interaction is tested and the results are compared against a similar analyses conducted in LS-DYNA. The model used for this test (Figure 10) is similar to the free-field analyses with 20 soil layers stacked vertically. The soil domain dimensions are 20 m x 20 m x 20 m and the 20 soil layers have the same backbone curve as in Figure **8**(b), but this time yield surfaces are pressure dependent to incorporate the effects of loads induced by the structure. The backbone in both MASTODON and LS-DYNA are discretized using 10 points. A structure of dimensions 4m x 4m x 4m is embedded two meters into the top two layers of the soil profile. A density of 8 ton/m3 is assigned to the structure.

The Coyote 1979 motion, record P0154 (Ancheta et al. 2014), is applied at the base of the model in the x-direction as a prescribed acceleration. Newmark-beta integration parameters, α and β, are set to 0.25 and 0.5. Rayleigh damping is applied to the system. For this model, the mass and stiffness damping parameters, zeta (ζ) and eta (η), are calculated to be 0.000781 and 0.64026 respectively, for a constant damping of 3% applied to all layers.

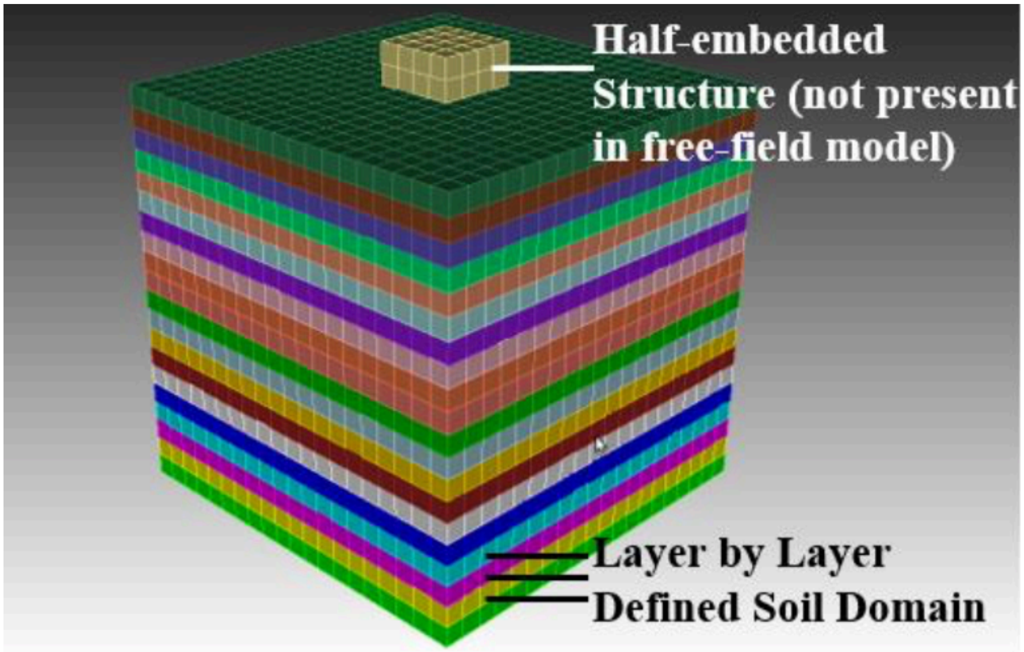


Figure 10 Geometry of the non-uniform free-field model and the SSI model (reprinted from Baltaji et al., 2017).

Figure 11 demonstrates the reasonable agreement between MASTODON and LS-DYNA results in terms of peak ground acceleration and acceleration response spectrum for wide range of periods. For periods below 0.1s, slight differences in the response can be observed particularly for results corresponding to 1.5 m below the bottom of the structure. Fourier amplitude spectra also demonstrate reasonable agreement and shows slight differences at high frequencies. For all practical purposes, MASTODON yields a similar response to LS-DYNA for an idealized soil-structure interaction problem. This demonstrates the capability of MASTODON to be utilized in a 3-D SSI analysis using the direct solution method.

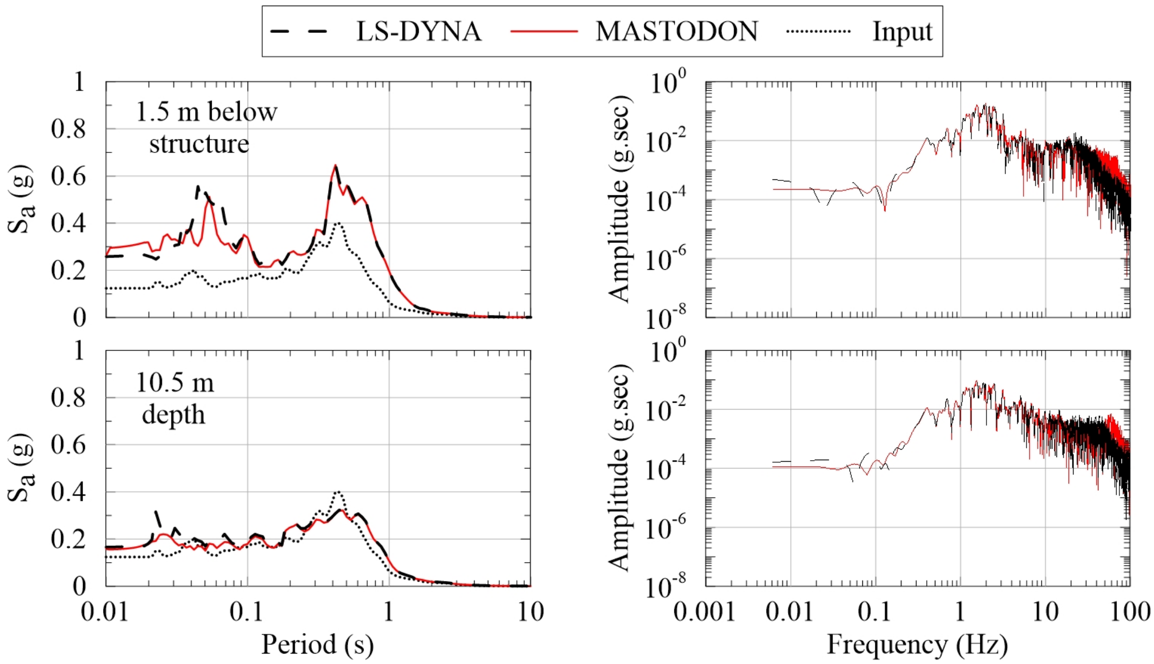


Figure 11 Non-uniform soil-structure interaction models results: acceleration response spectra and Fourier amplitude spectra at top, and middle of the model (reprinted from Baltaji et al. 2017).

3.3 Post-processing

Post-processing is essential to examining the results of the simulation in detail and gain a better understanding of the seismic response of the soil-structure system. Post-processing the raw data from seismic analysis also provides the necessary output for probabilistic risk analysis. While MOOSE contains several post-processing capabilities, the following capabilities have been recently included in MASTODON: (1) generation of response histories, (2) calculation of response spectra, and (3) calculation of Housner Spectruml Intensity. All of these post-processing capabilities are implemented as MOOSE *vectorpostprocessor* objects.

3.3.1 Generation of response histories

Response histories of transient variables can be calculated in MASTODON using the *vectorpostprocessor* called *ResponseHistoryBuilder*. This object outputs the response history of the variable (such as stress, strain, displacement, velocity or acceleration) as a function of time into a csv file. Current implementation requires defining a separate input block for each node or element. This will be extended in the near future to enable the calculation at sets of nodes and elements through a single input block.

3.3.2 Calculation of response spectra

The response spectrum of a signal is defined as the spectrum of peak responses of a hypothetical single-degree-of-freedom oscillator subjected to the signal, at various natural frequencies of the oscillator. In earthquake engineering, response spectra are used both in design, to calculate the expected peak forces or displacements in structures, and analysis, to understand the frequency content of the acceleration, velocity or displacement history. In probabilistic risk analysis, floor spectral acceleration (the value of an acceleration response spectrum at a certain frequency) is commonly used as a demand parameter in the calculation of the probability of failure of structures, systems and components (SSCs). Acceleration, velocity and displacement response spectra can be calculated in MASTODON using *ResponseHistoryBuilder*. The response spectra are calculated as functions of frequency and are output into a csv file. Similar to the generation of response histories, calculation of response spectra for node sets will be implemented in the near future.

3.3.3 Calculation of HSI

Housner Spectrum Intensity (Housner, 1952) is a measure of the intensity of ground motion at a point and is defined as the area under the velocity response spectrum between 0.25sec and 2.5sec. Housner Spectrun Intensity can be very useful response parameter, especially when examining the spatial distribution of ground motion intensity in large areas (e.g., examining topographic effects), where comparing response spectra or response histories can be too cumbersome. Housner Spectrum Intensity is calculated using the *HSICalculator vectorpostprocessor* . Currently, HSI at only one node can be calculated in each input block. This will be extended to node sets in the near future.

3.4 Theory and User Manuals

3.4.1 Documentation Overview

MASTODON utilizes the MooseDocs system for creating documentation. This is a system that is included with MOOSE to generate a website using Markdown format, which is designed to extended and written quickly prior to be converted to HTML. The system is designed to be traceable and testable; documentation is treated as code so it is reviewed, tested, and stored in the repository along with the source code.

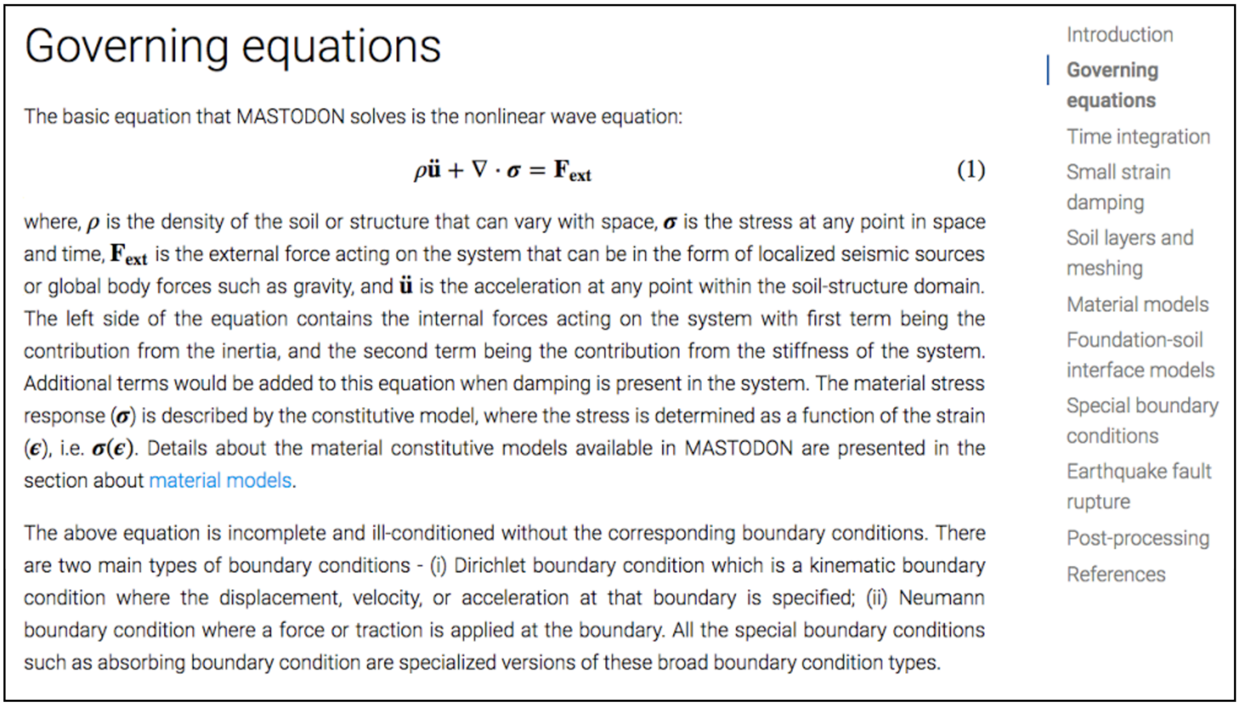
For MASTODON documentation of new objects (i.e., Kernels, BCs) is required and attempts to add objects without documentation will result in a failed documentation tests and not allowed to into the main repository. Additionally, the MooseDocs system includes tools for creating Software Quality Assurance (SQA) documentation using templates and practices defined by MOOSE.

As MASTODON continues to develop all documentation will be created using the MooseDocs system allows for all changes to be tracked and all documentation related to every version of MASTODON to be self-contained within the repository allowing the code and documentation to be accurate at all times.

3.4.2 Theory manual

The theory manual contains the mathematical details of all the objects that are present in MASTODON. The most current theory manual is contained within the repository and available on the MASTODON website (the website is only accessible to individuals that have access to the source code). A screenshot of the current manual is shown in Figure 12. However, there is recent PDF copy of the theory manual available[b], but this will soon be removed as the website version is developed further.

[b] https://earthquake.inl.gov/Shared%20Documents/MASTODON_theory_manual.pdf



Governing equations

The basic equation that MASTODON solves is the nonlinear wave equation:

$$\rho\ddot{\mathbf{u}} + \nabla \cdot \boldsymbol{\sigma} = \mathbf{F}_{\mathbf{ext}} \quad (1)$$

where, ρ is the density of the soil or structure that can vary with space, $\boldsymbol{\sigma}$ is the stress at any point in space and time, $\mathbf{F}_{\mathbf{ext}}$ is the external force acting on the system that can be in the form of localized seismic sources or global body forces such as gravity, and $\ddot{\mathbf{u}}$ is the acceleration at any point within the soil-structure domain. The left side of the equation contains the internal forces acting on the system with first term being the contribution from the inertia, and the second term being the contribution from the stiffness of the system. Additional terms would be added to this equation when damping is present in the system. The material stress response ($\boldsymbol{\sigma}$) is described by the constitutive model, where the stress is determined as a function of the strain ($\boldsymbol{\epsilon}$), i.e. $\boldsymbol{\sigma}(\boldsymbol{\epsilon})$. Details about the material constitutive models available in MASTODON are presented in the section about material models.

The above equation is incomplete and ill-conditioned without the corresponding boundary conditions. There are two main types of boundary conditions - (i) Dirichlet boundary condition which is a kinematic boundary condition where the displacement, velocity, or acceleration at that boundary is specified; (ii) Neumann boundary condition where a force or traction is applied at the boundary. All the special boundary conditions such as absorbing boundary condition are specialized versions of these broad boundary condition types.

Figure 12. Screenshot showing a portion of the web-based MASTODON theory manual.

3.4.3 User Manual

The MASTODON user manual is also web-based and currently comprised of three main parts: getting started instructions, examples, and system level documentation. The "Getting Started" page explains the basic syntax and usage of the input blocks that are essential for all dynamic simulations. The examples pages provide detailed explanation and demonstrate the use of special capability and input file syntax commonly encountered class of problems such as site response analyses. Finally, as mentioned in the overview section, every system and object within MASTODON is documented. These objects are summarized and linked to detailed pages allowing for advanced users and developers easy access to all the available features and input file syntax for all aspects of MASTODON.

4. RECENTLY DEVELOPED SPRA CALCUATION PROCESS FOR MASTODON

4.1 Preprocessing using MultiApp

Support for stochastic simulations within MASTODON is based on the MOOSE stochastic tools module and utilizes the MOOSE Multiapp and Transfer system. This module was created specifically to support SPRA. It allows for a master application to drive the execution of simulations with parameters perturbed based on arbitrary distributions and sampling schemes. The use of the system may be separated into four steps, as detailed below, with the fourth being optional.

4.1.1 Step 1 - Define Distributions

The stochastic tools module provides the Distribution system for defining distribution functions, which currently includes a uniform and weibull distribution. However, the Distribution system is like all other systems within MOOSE and it is designed to be expanded upon, thus adding any distribution is possible. Distribution objects in MOOSE are function-like in that they have methods that are called on-demand by other objects and do not maintain any state. A custom *Distribution* object is created in the typical fashion, by creating a C++ class that inherits from the Distribution base class. Three functions are required to be overridden: "*pdf*", "*cdf*", and "*quantile*".

To utilize a Distribution object within an input file, first the object must be created and secondly an object must be defined to use the distribution. Distribution objects may be created in the input file within the [Distributions] block. To use a distribution an object must inherit from the *DistributionInterface*, which provides two methods:

- *getDistribution*: This method accepts the name of an input parameter added via a call with the *addParam<DistributionName>* method. In general, application developers will use this method.
- *getDistributionByName*: This method accepts the explicitly defined name of a distribution. In general, application developers will not utilize this method.

Each of these methods return a reference to *Distribution* object, from which you call the various methods on the object as discussed previously.

4.1.2 Step 2 - Sample Distributions

Sampler objects in MOOSE are designed to generate an arbitrary set of data sampled from any number of *Distribution* objects. Samplers operators by returning a vector of matrices (*std::vector<DenseMatrix>)* from the *getSamples* method. The application developer is responsible for creating this output as needed depending on the type of sampler. However, in general, the system is designed such that each row in the matrices represents a complete set of samples that could be passed to sub-applications via the *SamplerMultiApp*.

Currently, two samplers exists within the MOOSE stochastic tools module: *MonteCarloSampler* and *SobolSampler*. The *MonteCarloSampler* generates an arbitrary number of samples for an arbitrary set of distributions, as prescribed in the input file and the *SobolSampler* performs sampling to perform variance-based sensitivity analysis using the SOBOL method. For example, Figure 1 compares 10,000 Monte Carlo samples of a weibull distribution with the exact function.

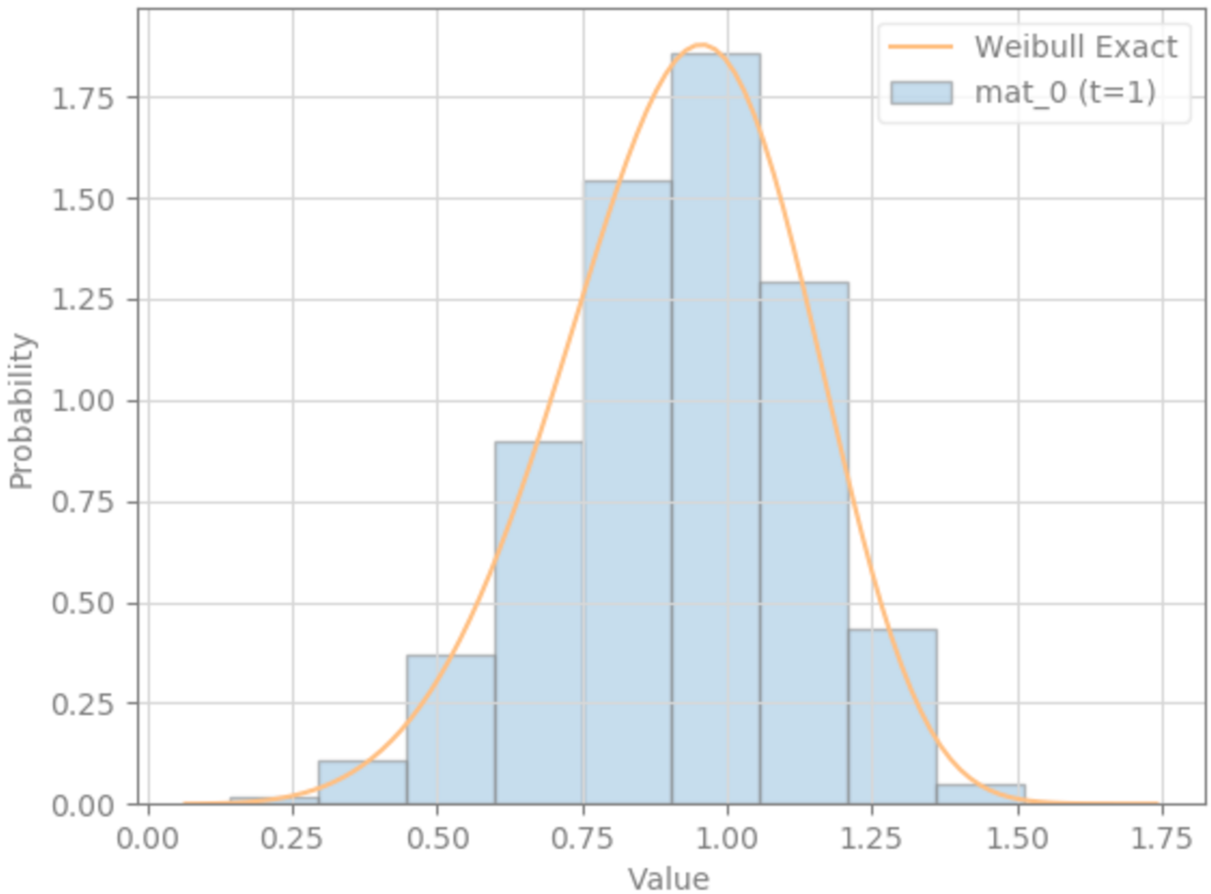


Figure 13. Example Monte Carlo sampling of a weibull distribution.

Again, the *Sampler* system in MOOSE is like other systems, it is design to be customized. A *Sampler* object is created in the typical fashion, by creating a C++ class that inherits from the Sampler base class and the *getSamples* method is overridden, which as mentioned above must return a vector of matrices.

4.1.3 Step 3 - Execute Stochastic Simulations

Execution of the stochastic simulations is done using the MOOSE MultiApp and Transfer systems. Foremost a sub-application input file representing the simulation of interest must be created, for example a seismic soil, structure interaction problem. This input file should work as a stand-alone input file, using sensible default values for the various simulation parameters.

Next, within the master input file, a [*MultiApps*] block is created using the *SamplerMultiApp*, which as eluded to in the previous section will spawn a simulation for each row of each matrix returned by the a Sampler object. The *SamplerMultiApp* simply executes the supplied input file the correct number of times, thus alone will simply run the same simulation many times. Therefore, a Transfer object is necessary to perturb the supplied input file using the supplied Sampler object.

Within the [*Transfers*] block any number of *SamplerTransfer* objects may be used to communicate stochastic samples to the sub-application input file. As shown below in the input file snippet, the parameters that are to be perturbed on the sub-application are listed by name. The *SamplerTransfer* object then substitutes the sampled values for the given parameters for each simulation. For the transfer of data to operate correctly the sub-application input file must contain a *SamplerReceiver* Control object.

```
[Transfers]
  [./sub]
    type = 'SamplerTransfer'
    multi_app = 'sub'
    parameters = 'BCs/left/value BCs/right/value'
    to_control = 'stochastic'
    execute_on = 'INITIAL'
    check_multiapp_execute_on = 'false'
  [../]
[]
```

4.1.4 Step 4 – Post-process Stochastic Simulation Results (Optional)

The previous three steps are adequate to perform stochastic runs with perturbed input values based on distributions. Optionally, it is possible to perform post-processing based on values computed by the stochastic sub-application simulations. To perform such analysis the sub-application must contain some sort of Postprocessor that is computing an aggregate value for the simulation (e.g., the maximum acceleration at a location). The master application, using the *SamplerPostprocessorTransfer* will store these values from each of the sub-applications as a *VectorPostprocessor*. This data can then be used by other tools within MOOSE to perform post-processing as well as on-the-fly processing (e.g., at each time-step) of the data being computed by the stochastic simulations.

4.2 Enhanced fragility calculations

Seismic fragility of a structure, system or component (SSC) is the probability of its failure conditioned upon a given intensity of seismic demand. Currently, in the nuclear industry, seismic fragilities are calculated as a function of the peak ground acceleration (PGA), or other ground motion parameters (such as spectral acceleration of the input ground motion at a certain frequency), although failures of SSCs are better correlated with local demands such as floor spectral acceleration. Additionally, only the uncertainties in the ground motion and the soil properties [only in a deterministic sense, namely, by performing deterministic analyses with upper bound (UB), lower bound (LB) and best estimate (BE)] are considered, and the uncertainties in the structural properties and foundation-soil interface properties are ignored. Current industry practice also involves the assumption of linear soil-structure response, and therefore a linear increase in the seismic demands with ground motion intensity. The Seismic Research Group at INL has made efforts (Bolisetti *et al.*, 2015; Bolisetti *et al.*, 2017; Coleman *et al.*, 2016) to advance this method of fragility calculation to (1) include uncertainties in structural properties and the foundation-soil interface properties, and (2) enable the consideration of nonlinearites in the soil-structure system. This advanced method of fragility calculation is implemented in MASTODON, and the resultant fragilities are termed as enhanced fragilities in this report. Note that the current implementation in MASTODON allows for an intensity-based probabilistic risk assessment, which involves the calculation of unacceptable performance of the system at a single intensity. Therefore only a single point on the SSC fragility curve is required. This will be extended to a time-based assessment by automating the stochastic simulations as well as the fragility calculations at multiple intensities (namely, multiple bins on the hazard curve).

The enhanced fragilities are calculated as functions of local demand parameters (such as floor spectral acceleration at the location of the component) by using the output from stochastic simulations described in the previous section. The calculation of enhanced fragilities in MASTODON is carried out in the [FragilityCalculation] block of the input file. The calculation is performed in the following steps:

1. The seismic capacities of the SSCs are assumed to be lognormally distributed and are input in the [FragilityCalculation] block as a median and lognormal standard deviation, along with other properties of the SSCs including the natural frequency, location of the SSC (currently input as a single node), and the damping ratio. Current implementation in MASTODON only uses spectral accelerations as demand parameters. This will be extended to other demand parameters in the future.
2. The seismic responses calculated from the stochastic simulations are assembled and the demand parameters for each SSC are calculated for each sample. These demands are assumed to be lognormally distributed and the median and lognormal standard deviation are calculated for each SSC.
3. The probability of failure of the SSC at each intensity is calculated as the probability that the demand is greater than the capacity. This probability is numerically calculated using the following convolution integral

$$P\left(\mathrm{D}>\mathrm{C}\right)=\int_0^\infty\int_0^{\mathrm{d}} P_{\mathrm{D}}(\mathrm{d})\cdot P_{\mathrm{C}}(\mathrm{d})\cdot d\mathrm{c}\cdot d\mathrm{d}$$

where C and D are the variables corresponding to the capacity and demand distributions, respectively.

4.3 Plant response model quantification using enhanced fragility calculations

The enhanced fragilities (or conditional probabilities of failure) calculated in the previous section are used as inputs to the plant response model consisting of event trees and fault trees. This section describes the fault tree and event tree analysis implemented in MASTODON. This analysis includes the evaluation of minimal cutsets, namely the possible accident sequences that lead to unacceptable performance, and also identify the critical components in these scenarios. Current implementation in MASTODON includes the analysis of a single fault tree, and this will be extended to multiple fault trees and event trees in the future. This fault tree analysis (FTA) code is also capable of calculating the system fragilities for a time-based PRA.

4.3.1 Fault tree analysis

The fault trees are input as two csv files containing the logic of the fault tree and log-normal distribution parameters (median and lognormal standard deviation) of basic events. The first file is the *logic file* containing the descriptions of the events. The events are described using the event name, the logic gate (AND, OR, etc.) and the corresponding dependent events. The first row of the file always represents the top event of the fault tree. A sample logic file is shown in Figure 14 below.

```
TOP, AND, GATE1, GATE2
GATE1, OR, FT-N/m-1, FT-N/m-2, FT-N/m-3
GATE2, OR, B1, B3, B4
GATE3, OR, B2, B4
FT-N/m-1, AND, GATE3, B3, B5
FT-N/m-2, AND, GATE3, B1
FT-N/m-3, AND, B3, B5, B1
```

Figure 14: Sample logic input file for fault tree analysis

The second input file, called the *basic event file*, contains the probability distributions of the basic events, namely, the enhanced fragilities of the SSCs. Currently, this file needs to be manually created using the enhanced fragilities calculated as described in the previous section. An automatic transfer of the enhanced fragilities for fault tree analysis will be implemented in the future. The basic event file describes one basic event in each row. These events are described using the basic event name (e.g., B1), type of probability distribution (e.g., LNORM for lognormal distribution), and the distribution parameters (e.g., median and lognormal standard deviation for the lognormal distribution). A sample basic events file is shown in Figure 15 below. In addition to the two files, the FTA code also takes the lower and upper bounds for the intensity measures (such as PGA) in the hazard curve, as well as the number of bins in the hazard curve for time-based risk assessment, as input. Current FTA code is applicable for coherent fault trees with ‘AND’ and ‘OR’ gates only. More logic gates will be added in the future.

```
B1,LNORM,1.88,0.5
B2,LNORM,3.78,0.79
B3,LNORM,2.33,0.76
B4,LNORM,3.66,0.45
B5,LNORM,0.60,0.28
```

Figure 15: Sample basic events file for fault tree analysis

The fault tree analysis is carried out in three steps: (1) calculating the cutsets using the MOCUS algorithm, (2) removing redundancies in the cutsets and calculating the minimal cutsets using the idempotence and absorption laws, and (3) calculating the probabilities of minimal cutsets. These steps are similar to those followed in the systems analysis code, Saphire (USNRC, 2011) and are described below:

1. The cutsets of the fault tree are calculated using the MOCUS algorithm, which is based on the fact that the AND gate increases the size of a cutset and the OR gate increases the number of cut sets. The algorithm is implemented using a top-down approach. First, the top event is replaced by its dependent events using the following rules:
    - Rule 1: An AND gate generates new elements (columns) in the matrix of cut sets.
    - Rule 2: An OR gate generates new sets (rows) in the matrix of cut sets.
2. After generating all the cut sets, the following two rules are used to remove redundancies and obtain the minimal cut sets:
    - Idempotence law ($A \cap A = A$): Remove same elements in a cut set and remove same cut sets in the matrix of cut sets. If set data structure is used, this rule is automatically satisfied.
    - Absorption law ($A \cup (A \cap B) = A$): Remove non-minimal cut sets.
3. After calculating the minimal cutsets, two approximations are used by PRA software to reduce the computation time. An exact calculation is also possible, and is implemented in MASTODON. These calculation methods are described below:
    - Rare-event probability: This is calculated by adding the probabilities of all the minimal cut sets. This approximation is appropriate when the probabilities of the individual cut sets are small, and the cut sets do not share many of the same basic events. The rare-event probability is calculated using the equation:

$$P_{f_{rare_{event}}} = \sum_{i=1}^{m} P_{C_i}$$

where $P_{f\_rare\_event}$ is the probability due to rare event approximation P_{C_i} is the probability of the i^{th} minimal cut set, and m is the number of minimal cut sets.

- Upper bound probability: This approximation calculates the probability of the union of minimal cut sets and is appropriate when the fault tree contains only AND and OR gates. The results produced can be conservative when the fault tree contains NOT gate, or complementary events. The upper bound probability is calculated using the equation:

$$P_{f\_upper\_bound} = 1 - \prod_{i=1}^{m} \left(1 - P_{C_i}\right)$$

where $P_{f\_upper\_bound}$ is the upper bound approximation of the minimal cut set probability, P_{C_i} is the probability of the i^{th} minimal cut set, and m is the number of minimal cut sets.

- Exact probability: The FTA code in MASTODON also provides the capability of calculating the exact probability for the fault tree, given the probabilities of basic events. The calculation is implemented using the inclusion-exclusion rule as follows:

$$P_{f\_\min\_max} = \sum_{i=1}^{m} P(C_i) - \sum_{i<j} P\left(C_i \cap C_j\right) + \sum_{i<j<k} P\left(C_i \cap C_j \cap C_k\right) - \cdots + (-1)^{m-1} P\left(\bigcap_{i=1}^{m} C_i\right)$$

where $P_{f\_\min\_max}$ is the exact probability, and m is the number of minimal cut sets.

4.3.2 System fragility calculation

The system fragility is calculated by obtaining the failure probability for each bin of the hazard curve using any of the calculation approaches (rare-event, upper bound or exact) described above. A lognormal CDF fit is then obtained for the system failure probabilty points. This is currently done in MASTODON using the least square fit method. A sample system fragility curve calculated using this approach is presented in Figure 16 below. The final system risk in a time-based PRA is calculated by convolving the system fragility curve with the hazard curve. This calculation will be implemented in the future.

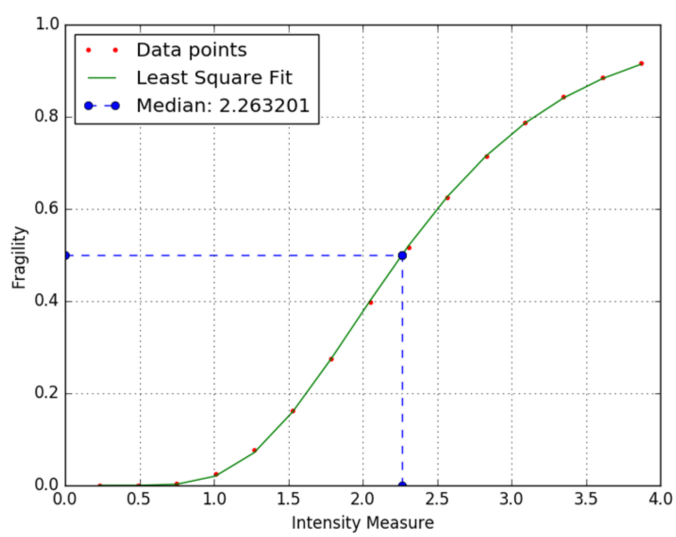


Figure 16: System level fragility for the given fault tree using the exact calculation

4.4 Future work

The beta version of MASTODON currently has the basic framework to perform an intensity-based SPRA calculation for small systems comprising of a single fault tree. This process is almost fully automated and involves little manual intervention. An immediate priority in the SPRA implementation in MASTODON will be the full capability to perform an automated time-based PRA. This includes automation of the binning of hazard curve into several intensity bins as requested by the user, running a stochastic simulations and calculating conditional probabilities of failure of SSCs at each intensity, and fitting a lognormal CDF through these probability points to calculate the enhanced fragility. The enhanced fragilities will be input into the FTA code and the system fragility will be calculated using a Monte Carlo simulation. The system fragility will be convolved with the hazard curve to calculate the final risk. This process will provide the basic framework to perform a time-based PRA. Apart from these capabilities, a calculation of importance factors (such as risk-reduction ratio, risk-increase ratio, etc.) of various basic events in the fault tree will be implemented. This will enable importance analysis of the basic events and examine the relative importance of the SSCs, which can be critical information for owners and decision makers.

5. DEMONSTRATION OF SEISMIC PRA IN MASTODON

This section demonstrates the newly implemented seismic PRA capabilities in MASTODON. The demonstration involves an idealized four-story fixed-base shear wall building structure with a natural frequency of vibration of 12Hz. Probabilistic properties are assigned to the shear stiffness of the building, and the density of the material. The shear stiffness of the building is assumed to be lognormally distributed with a median of 1280kip/ft and a lognormal standard deviation of 1.5 The density of the material is also assumed to be lognormally distributed with a median of 2000kcf and a lognormal standard deviation of 1.3. This building is populated with a hypothetical pump, battery and switchgear. These components are assumed to have spectral capacities that are lognormally distributed. These capacity distributions, along with the natural frequencies of the compoenents are shown in Table 1 below. The locations of these components is shown in Figure 17 below. An idealized fault tree is also developed with these components. This fault tree is shown in Figure 18 below. A simple seismic PRA is performed to calculate the probability of the top even shown in the fault tree.

Table 1: Hypothetical spectral capacities of the components in the building used for SPRA demonstration

Component	Natural frequency (Hz)	Median capacity (g)	Aleatory uncertainty	Epistemic uncertainty
Pump	10	2.1	0.11	0.11
Battery	2.8	2.8	0.20	0.10
Switchgear	3	3.8	0.10	0.20

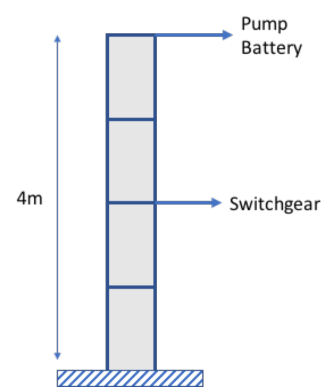


Figure 17: Illustration of the idealized building and components used in the SPRA demonstration

The building is excited with a pulse of a PGA of 0.6g and a stochastic seismic analysis is performed with Monte Carlo sampling. This stochastic simulation is performed using the MultiApp, as described in Section 4.1. Thirty samples are used and the probabilistic demands are calculated at 2m elevation and 4m elevation. The results of these simulations are processed using the Fragility class as described in Section 4.2 and a single point in the enhanced fragility curve is calculated. The probabilistic demands and failure probabilities are presented in Table 2 below.

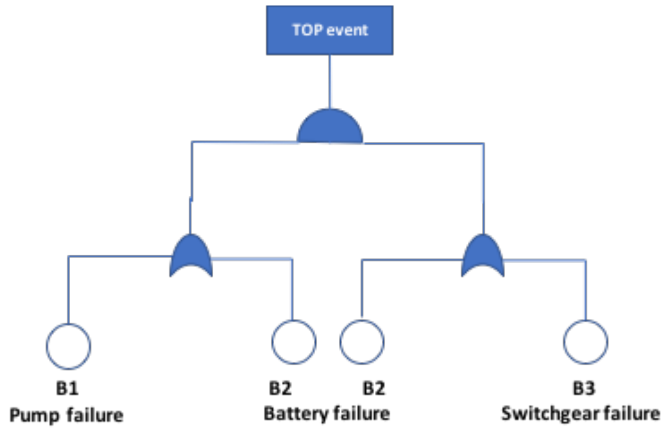


Figure 18: Fault tree used in the SPRA demonstration

Table 2: Probabilistic demands and failure probabilities calculated using the [Fragility] vectorpostprocessor in MASTODON

Component	Median demand (g)	Beta demand	Conditional probability of failure
Pump	1.45	0.14	0.039
Battery	2.5	0.23	0.055
Switchgear	1.27	0.60	0.043

The probabilities of failure of the components are used as the probabilities of the initiating events in the fault tree. A fault tree analysis is performed as described in Section 4.3 and the probability of the top event is calculated using the exact, upper bound and rare-event solutions as described in Section 4.3. these probabilities are listed in Table 3 below. Given the simplicity of the fault tree and the small number of events, these failure probabilities are almost identical.

Table 3: Results of fault tree analysis

Method of calculation	Probability of top event
Exact	0.05658
Battery	0.05658
Switchgear	0.05667

6. SOFTWARE QUALTIY ASSURANCE

Software quality assurance (SQA) is an important aspect of MASTODON development. SQA will allow for deployment of MASTODON as a production NLSSI seismic PRA software. The MASTODON application is a highly agile software development project that uses the MOOSE framework. SQA will insure: (1) Software configuration management including configuration identification, change control, configuration status accounting, and configuration audits; (2) reviews to ensure design traceability and assurance of satisfactory completion of software development activities including acceptance testing (these reviews are outlined in PLN-4005); (3) Control of records, currently being addressed by storing them in GitHub/GitLab record keeping systems; (4) Software requirements specification document that outlines the technical and functional requirements of the software; (5) Testing, a significant strength of the MOOSE and MOOSE-based application environment.   shows the documentation status of MASTODON SQA.

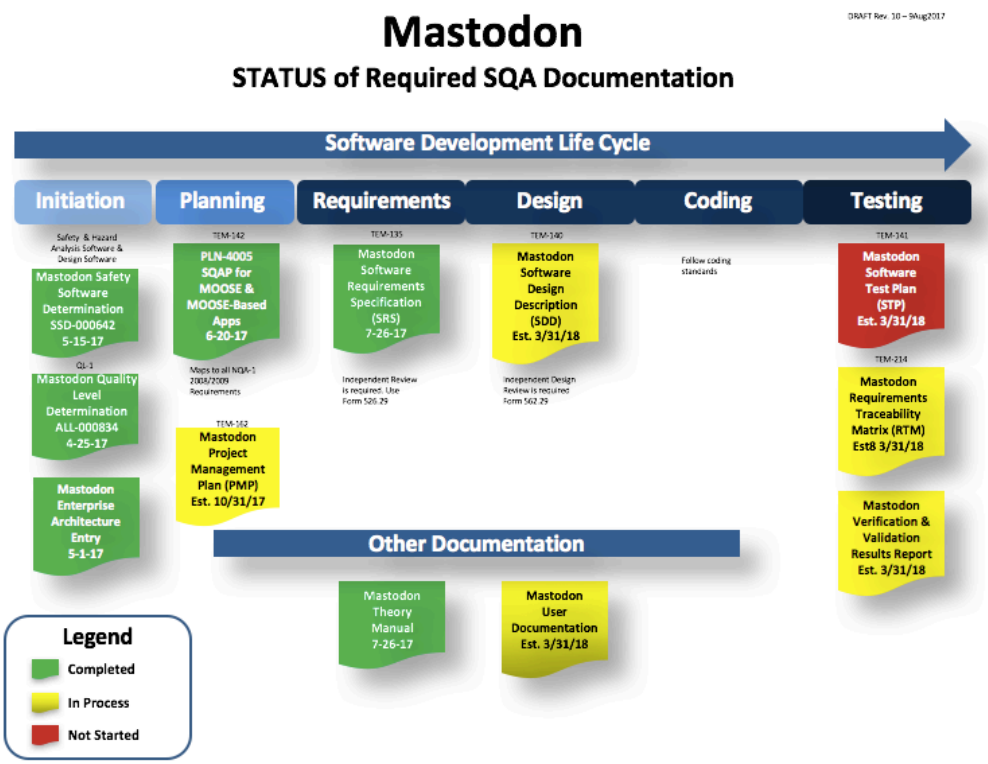


Figure 19. Overview of quality assurance process and status for MASTODON

A software quality assurance assessment on MASTODON was performed on August 3rd 2017 The assessment provided recommendations on continued SQA documentation and development. The assessment stated that:

The MASTODON project is a highly agile design and analysis software development project using the MOOSE framework. The MOOSE and MASTODON staff are competent in their knowledge of INL SQA program requirements. Modeling and Simulation management is very supportive and ensures that the proper quality and engineering practices are implemented. Together these key traits place INL as a leader in software engineering and quality assurance.

MOOSE and MASTODON are well-managed projects and effective in implementing the INL SQA program requirements. MOOSE and MASTODON projects are highly successful in implementing *a DOE O 414.1D and ASME NQA-1 compliant program. The MOOSE and MASTODON projects are considered examples for the DOE complex and software industry in the implementation of an agile development environment while meeting industry standards.*

The SQA assessment identified two areas of improvement, (1) the team needs to develop a project management plan and (2) software requirements definition document. MASTODON is managed by Project Management Office (PMO) personnel and is being controlled adequately for its life cycle stage. However, the SQA assessment stated that several future key activities need to be described and documented in a project plan.

Testing of MASTODON-specific components is performed through the use of the Continuous Integration, Verification, Enhancement and Testing (CIVET) automated build and testing system. Four types of testing are performed including component, integration, system, and deployment. Coding standards are enforced through CIVET. Test coverage and performance are monitored by the responsible Project Manager. Test coverage analysis is performed during the code review and the development team is automatically notified if coverage falls below 80%. Performance is also monitored through "test timing" data collected by CIVET. Coverage and performance results are available on the MOOSE framework website. Testing is performed for all supported configurations.

Model Validation/Theory Manual In accordance with ASME NQA-1, the model validation activity has two primary purposes:

1. Verification that the computer program produces correct solutions for the encoded mathematical model within defined limits for each parameter employed

2. Verification that the encoded mathematical model produces a valid solution to the physical problem associated with a particular application. As part of the final MASTODON V&V report, journal articles and technical reports need to be referenced to show validation of the models as defined in the theory manual. It is recommended that ASME V&V 10-2006, Guide for Verification and Validation in Computational Solid Mechanics, concepts be considered to support MASTODON's model validation efforts. Model validation for MASTODON differs from the various INL testing activities in that the results of the BU experiments are being peer reviewed and are considered to be scientific analysis. If these results were to be considered design inputs, ASME NQA-1 Part I, Requirement 11 would be applicable.

7. SUMMARY

Development of the next generation tools and methods for external events PRA is ongoing under the Risk Informed Safety Margins Characterization (RISMC) technical pathway. The RISMC toolkit development centers on integration of the tools and methods under a common framework, MOOSE. These tools and methods make use of existing and newly developed tools and methods, coupled with the experience and data gained in the past decades, to define and analyze more realistic risk assessment models. Specific focus in this report is on the capability to model seismic risk using advanced SPRA methods.

Over the last year, significant capability has been added to the seismic probabilistic risk assessment MOOSE based tool MASTODON. Capability has been added to MASTODON to simulate 3-D wave passage effects through nonlinear soil coupled with nuclear facilities. Verification has demonstrated the capability of MASTODON to model wave passage effects in 1-D, 2-D, and 3-D. Methods have been developed to incorporate probabilistic floor response (demands), calculation of fragilities as functions of local demand parameters (such as floor spectral acceleration at the location of the component) by using the output from stochastic simulations, input event tree and fault tree information, and calculate seismic risk. Also included in MASTODON are web-based verification and user manuals, and web-based software quality assurance documentation and traceability. Additional capability will be added to MASTODON over the next year to implement a robust gapping and sliding element for cyclic shaking, frequency independent damping, and seismic isolation elements. Code development work will complete the dynamic time based risk assessment capability. Verification of all added capabilities continues to occur in parallel with code writing activities. Proposed work for fiscal year 2018 is an application driven methodology for seismically induced fire PRA.

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Appendix A

RISMC TOOLS

Table 4. RISMC Toolkit advanced tools for dynamic probabilistic risk assessment

Advanced Tool	Capabilities
RELAP-7	RELAP-7 is a component-based integrated tool that simulates NPP energy and fluids systems behavior in normal, off-normal, and postulated accident scenarios. RELAP-7 builds upon the well-established and validated capabilities of nuclear systems codes (RELAP, TRAC, etc.), but also provides high-fidelity, multi-physics capabilities for new insights into NPP safety. Implementing state-of-the-art numerical methods and coupled multi-physics capabilities (via the MOOSE framework), enables the advancement of modern techniques for risk reduction and margin characterization, such as safety systems classification, thermal limit margin and fuel life cycle optimization, and maintenance program savings.
Grizzly	Grizzly simulates component ageing and damage evolution events for LWRS specific applications. Grizzly provides simulation capability for: • Reactor metals (embrittlement, fatigue, corrosion, etc.), such as Reactor Pressure Vessel (RPV) and core internals • Weldment integrity • Integrity of concrete containments subjected to a neutron flux, corrosive environment, or high temperatures and pressures.
MASTODON	MASTODON has the capability to model stochastic NLSSI in a risk framework coupled with virtual NPPs. These NLSSI simulations include structural dynamics, time integration, dynamic porous media flow, hysteretic nonlinear soil constitutive models, hysteretic nonlinear structural constitutive models, and geometric nonlinearities at the foundation (gapping, uplift, and sliding).
EMRALD/ RAVEN	EMRALD and RAVEN are tools for dynamic probabilistic risk analysis, event sequence control, and probabilistic evolution of accident scenarios. These tools use reduced order modeling for uncertainty quantification.
Neutrino	Neutrino is a mesh-free, smooth particle hydrodynamics-based solver which also uses advanced boundary handling and adaptive time stepping. Neutrino is an accurate fluid solver and is being used simulate coastal inundation, river flooding, and other flooding scenarios. Neutrino models friction and adhesion between solid/fluid boundaries and various adhesive hydrodynamic forces between fluid/fluid particles.
Integrated dynamic PRA Hazard Module	The hazard module takes as input the logic tree, parameter distributions, and underlying data developed by a probabilistic hazard assessment (e.g., a model defined in a PSHA Hazard Input Document, as described in NUREG-2115 (NRC 2012a) and NUREG-2117 (NRC 2012b)). Directly incorporating the hazard model into the PRA, rather than handing off only the final hazard results, maintains the complete set of hazard model information, including the complete characterization of uncertainties, in a form that can be queried by EMRALD or RAVEN. The hazard module, which is in the planning stages of development, will sit within the EMRALD or RAVEN tool.