INL/JOU-20-58608-Revision-0

MASTODON: An Open-Source Software for Seismic Analysis and Risk Assessment of Critical Infrastructure

October 2020

Changing the World's Energy Future

Swetha Veeraraghavan, Justin L Coleman, Som LakshmiNarasimha Dhulipala, William M Hoffman, Kyung Tae Kim, Efe G Kurt, Robert E Spears, Lynn Brendon Munday, Chandrakanth Bolisetti, Andrew E Slaughter

Idaho National Laboratory

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

INL/JOU-20-58608-Revision-0

MASTODON: An Open-Source Software for Seismic Analysis and Risk Assessment of Critical Infrastructure

Swetha Veeraraghavan, Justin L Coleman, Som LakshmiNarasimha Dhulipala, William M Hoffman, Kyung Tae Kim, Efe G Kurt, Robert E Spears, Lynn Brendon Munday, Chandrakanth Bolisetti, Andrew E Slaughter

October 2020

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

MASTODON: An Open-Source Software for Seismic Analysis and Risk Assessment of Critical Infrastructure

Swetha Veeraraghavan[a], Chandrakanth Bolisetti[b*], Andrew Slaughter[b], Justin Coleman[b], Somayajulu Dhulipala[b], William Hoffman[b], Kyungtae Kim[b], Efe Kurt[b], Robert Spears[b], and Lynn Munday[b]

[a]*Indian Institute of Science, Department of Civil Engineering, Bangalore, India*

[b]*Idaho National Laboratory, Idaho Falls, Idaho*

*Email: chandrakanth.bolisetti@inl.gov

MASTODON: An Open-Source Software for Seismic Analysis and Risk Assessment of Critical Infrastructure

Seismic analysis and risk assessment of safety-critical infrastructure like hospitals, nuclear power plants, dams, and facilities handling radioactive materials involve computationally intensive numerical models and coupled multi-physics scenarios. They are also performed in a strict regulatory environment that requires high software quality assurance (SQA) standards and, in the case of safety-related nuclear facilities, a conformance to the American Society of Mechanical Engineers (ASME) Nuclear Quality Assurance (NQA-1) standard. This paper introduces the open-source finite-element software, MASTODON (Multi-hazard Analysis of Stochastic Time-Domain Phenomena), which implements state-of-the-art seismic analysis and risk assessment tools in a quality-controlled environment. MASTODON is built on MOOSE (Multi-physics Object-Oriented Simulation Environment), which is a highly parallelizable, NQA-1 conforming, coupled multi-physics, finite-element framework developed at Idaho National Laboratory. MASTODON is capable of fault rupture and source-to-site wave propagation using the domain reduction method (DRM), nonlinear site response, and soil-structure interaction analysis, implicit and explicit time integration, and automated stochastic simulations and seismic probabilistic risk assessment (SPRA). When coupled with other MOOSE applications, MASTODON can also solve strongly and weakly coupled multi-physics problems. This paper presents a summary of the capabilities of MASTODON and some demonstrative examples.

Keywords: seismic analysis; probabilistic risk assessment; soil-structure interaction; site response analysis; external hazards

I BACKGROUND

Seismic analysis involves the calculation of seismic loads on the systems, structures, and components (SSCs) of a facility and is a key part of seismic design and risk assessment. Safety-critical facilities, such as hospitals, dams, nuclear power plants (NPPs), and facilities handling radioactive materials, must meet certain seismic safety standards that are typically expressed as an upper limit on the seismic risk. Seismic analysis and risk assessment at these facilities is therefore necessary during their design and also through their life span. The seismic risk at a safety-critical facility depends on the surrounding earthquake faults and site characteristics that determine the seismic hazards on the SSCs of the facility, and the possible accident sequences. The SSCs and the accident sequences together dictate the vulnerability of the facility to a given seismic hazard. Due to the large variability in the local site properties and seismic hazard, when a similar structure is constructed at various sites (such as a specific NPP design), it must be designed and assessed for each site.

Seismic analysis typically involves structural dynamics simulations of the facility. For safety-critical facilities, which often tend to be very large, the seismic loads are calculated from a soil-structure interaction (SSI) analysis. SSI analysis involves the calculation of the seismic response of the structure while accounting for the compliance of the soil and the foundation underneath and for the wave propagation towards and away from the structure. Capturing these phenomena in a single simulation can require large numerical models that are computationally expensive. Several methods with varying levels of complexity and rigor have been developed in the last few decades[1] [2] [3], with two of them implemented in the software, CLASSI[4] and SASSI[5]. Both were groundbreaking when they were developed, while SASSI was the first software to perform three-dimensional SSI analysis for arbitrary flexible foundation geometries and is the most widely used software for seismic analysis in the nuclear industry. However, SASSI and CLASSI are limited to linear analysis and operate in the frequency domain. Consequently, they do not capture the soil, foundation, or structural nonlinearities that are expected during high-intensity earthquakes. With advances in computing, many recent studies have used both open-source and commercially-available finite element software to perform linear and nonlinear soil-structure interaction (NLSSI) analyses in the time domain[6 7 2 8 9 10 11], most of them for civil nuclear applications. These software include the commercial finite-element codes, LS-DYNA[12] and ABAQUS[13], the free and open-source code, OpenSees[14], and the free but closed-source code, MS-ESSI[15].

A common application of seismic analysis in critical facilities is seismic probabilistic risk assessment (SPRA)–the quantification of seismic risk as a probability of an earthquake leading to the occurrence of an unacceptable event (e.g., release of radioactive material outside the facility)–which is required during the design and maintenance of critical facilities. SPRA involves performing probabilistic seismic hazard analysis (PSHA)[16], calculating the probabilistic seismic demands on SSCs for the given seismic hazard, estimating the vulnerability of the facility in terms of seismic fragilities (probability of failure for a given seismic shaking intensity or an engineering demand parameter) of these SSCs, and convolving the seismic hazard and the vulnerability to calculate the risk[17]. In the case of complex facilities like NPPs, all possible accident sequences in the facility are examined and analyzed through an accident sequence analysis involving building and solving fault trees and event trees. In practice, the different elements of SPRA are executed in different software and the results are combined either manually or through customized scripting, which can be cumbersome and introduce errors during the transfer of data from one software to another. In addition to requiring SPRA, seismic analysis of critical facilities often benefits from coupled, multi-physics modeling since they usually comprise diverse physical systems. For example, while structural dynamics and wave propagation in solids are essential to understand the response of an NPP, many of the accident scenarios in an NPP require the capability of modeling the thermomechanical response of nuclear fuels and the dynamic response of the coolant, which is usually a fluid. Another requirement for the seismic (and other safety analyses) of critical facilities is software quality assurance (SQA). Safety analyses of critical facilities such as NPPs are highly regulated and at times require certifications such as the American Society of Mechanical Engineers (ASME) Nuclear Quality Assurance (NQA-1)[18].

While several software exist that can perform either earthquake fault-rupture and source-to-site simulations, or time-domain NLSSI analyses and limited multi-physics simulations (e.g., ABAQUS), or probabilistic risk assessment (e.g., SAPHIRE [19], RISKMAN [20], CAFTA [21]) there is a need for a software that combines all of these capabilities within a framework that scalable to large problems and also enables reliable SQA. To meet this need, Idaho National Laboratory has started developing the open-source seismic analysis and risk assessment application called MASTODON. MASTODON is based on MOOSE (Multi-physics Object-Oriented Simulation Environment[22]), which is a highly parallelizable, NQA-1 certified open-source environment for developing finite-element applications. Being built on the MOOSE framework, MASTODON automatically includes numerous material properties, constraints, boundary conditions, solvers, and stochastic simulation capabilities that are required for SPRA. Additionally, it facilitates easy coupling between MASTODON and other MOOSE-based applications such as BISON[23], which simulates nuclear fuel performance or BlackBear (Spencer *et al.* 2016)[24], which simulates structural material aging and degradation. MASTODON is under active development and as an open-source software, accepts code contributions from all current and potential users. This article presents an overview of MASTODON, its theoretical basis, guidelines for usage and code contribution, and its capabilities with some illustrative examples. This article does not serve as the documentation of MASTODON and readers should refer to the MASTODON website[a] and the source code repository on GitHub[b] for more information.

II THEORETICAL AND SOFTWARE FRAMEWORK

II.A MOOSE software architecture

Since MASTODON is built on MOOSE, it inherits all of its software design features and advantages. MOOSE is designed to enable the creation of highly parallelizable, coupled multi-physics finite-element applications, which, to date, have been used for applications including nuclear physics and nuclear fuel performance, structural material aging and degradation, geothermal sciences, compressible and incompressible fluid flow, and advanced manufacturing processes[22]. MOOSE

[a] https://mooseframework.inl.gov/mastodon
[b] https://github.com/idaholab/mastodon

comprises various “systems” that can be grouped into three main categories that enable (1) calculation of the partial differential equation terms (e.g., inertia term in the structural dynamics equation of motion), (2) evaluation of material properties (e.g., elasticity tensor), and (3) in-situ post-processing (e.g., evaluating accelerations from the displacement solution or acceleration response spectra from a response history). In addition to these systems, the MultiApp and Transfer systems enable strong coupling between various MOOSE applications and in-situ data transfer between these simulations without the need for additional, external scripting. Decoupling these systems and allowing communication between them through interfaces enables MOOSE to be dimension agnostic (same code can be used for 1D, 2D, or 3D) and downstream applications to be automatically parallelized. More recently, an automatic differentiation (AD) capability has been introduced to MOOSE that eliminates the need for hand-coded Jacobians (equivalent to the tangent stiffness matrix in a static structural system), which can be difficult to evaluate in many cases, and significantly improves convergence for highly nonlinear problems solved with iterative integration schemes (such as implicit Newmark-β). MOOSE also offers a versatile restart analysis capability that can be used for gravity analyses, staged simulations, and also during unexpected interruptions such as a power outage. It includes a robust infrastructure for testing, documentation, visualization, and verification and validation (V&V), collectively termed as the “MOOSE platform”. As a MOOSE application, MASTODON relies on the MOOSE platform and includes numerous tests, documentation, and developing V&V manuals, which are essential elements for SQA[25] and are immensely helpful for users and developers.

II.B MASTODON theory

MASTODON is the MOOSE application for structural mechanics and dynamics developed with an emphasis on earthquake engineering, including seismic analysis and SPRA. MOOSE contains several physics ‘modules’, each of which provides the materials, boundary conditions, constraints, and other tools for a certain class of physics, such as mechanics, heat conduction, fluid flow, etc. Of these modules, MASTODON includes the TensorMechanics, Contact, and StochasticTools modules, which provide the capabilities of solid mechanics and dynamics, contact interface simulation, and uncertainty quantification, respectively. MASTODON also includes another MOOSE application called BlackBear, which simulates the degradation of structural materials like concrete and steel from aging-related phenomena like Alkali-Silica Reaction. In addition to these modules and applications, MASTODON includes other tools that are specific to seismic analysis, such as nonlinear soil materials, seismic protective systems, fault rupture, absorbing boundaries, etc. This section briefly summarizes the theoretical foundations of MASTODON and its capabilities in the context of seismic analysis of critical infrastructure. Full documentation of all the objects and the underlying theory can be found on the MASTODON website.

The strong form of the partial differential equation (PDE) solved by MASTODON is the dynamic equation of motion, or the mechanical wave equation. The PDE and the accompanying displacement and traction boundary conditions are shown in Equation 1 below.

(1)

In this equation, is the spatially and temporally varying density of the domain, , is the stress in the domain, is the external force acting on the domain, either in the form of localized seismic sources (such as a fault rupture) or body forces such as gravity, and is the resultant acceleration, which is the second time derivative of the displacement field, . The first and second terms in Equation 1 are the inertial force (per unit volume) and stress divergence (also the restoring force per unit volume), respectively. The displacement is set to the user-prescribed displacement along boundary of the domain, whereas the tractional forces are set to a user-prescribed traction on boundary of the domain, which are in the general forms of Dirichlet and Neumann boundary conditions, respectively. MOOSE employs the Kernel system to evaluate the different terms in the PDE, and the BoundaryCondition system to evaluate the different forms of Dirichlet and Neumann boundary conditions. Kernel objects evaluate the volume integrals over each finite element in the weak form of the PDE and BoundaryCondition objects evaluate surface integrals over the boundary of the finite element. To solve the equation of motion in MASTODON, the InertialForce kernel object can be used to evaluate the inertia term and the StressDivergence kernel object, along with the corresponding Materials objects, can be used to evaluate the restoring force term (see Figure 1 for the input blocks corresponding to these kernel objects). Several other kernel objects exist, such as the Gravity kernel for applying gravity loads, NodalTranslationalInertia kernel for nodal masses, etc. These kernels, along with the boundary conditions are specified in the input file (described in Section III).

The weak form of the above PDE is numerically solved in MASTODON to calculate the displacement field (which is the solution variable). In the discretized form of the PDE, the residual vector is of the same length as the number of degrees of freedom (DOFs) in the system. Each term in the PDE, when evaluated over a finite element, contributes to the residual of the DOFs corresponding to that element. The residual contributions from all the elements in the domain are then summed to obtain the total residual vector. The solution variable, , is evaluated at each time step such that this total residual vector is close to zero with a certain tolerance. Typically, MASTODON uses an implicit integration scheme, where each time step is solved iteratively to calculate the solution variable. Recently, an explicit integration scheme has been implemented in MOOSE (and is therefore included in MASTODON) and when used, the solution at each time step can be evaluated directly through a linear algebraic equation. These integration schemes, along with the various material models and boundary conditions, are briefly described in the sections that follow.

For discretizing the PDE using finite element method, MASTODON currently includes both continuum elements (solid elements) and structural elements (trusses, beams, and shells) that are in MOOSE. The continuum elements can be modeled in 1D, 2D, or 3D, and the structural elements can be modeled in 2D and 3D. All elements are fully integrated. Typically, simulations are run using first order shape functions, but higher-order shape functions are also available to users for continuum elements. Beam elements can be modeled using both the Euler-Bernoulli formulation as well as a more general, Timoshenko formulation. Shell elements are four-noded and can model both thin and thick plates.

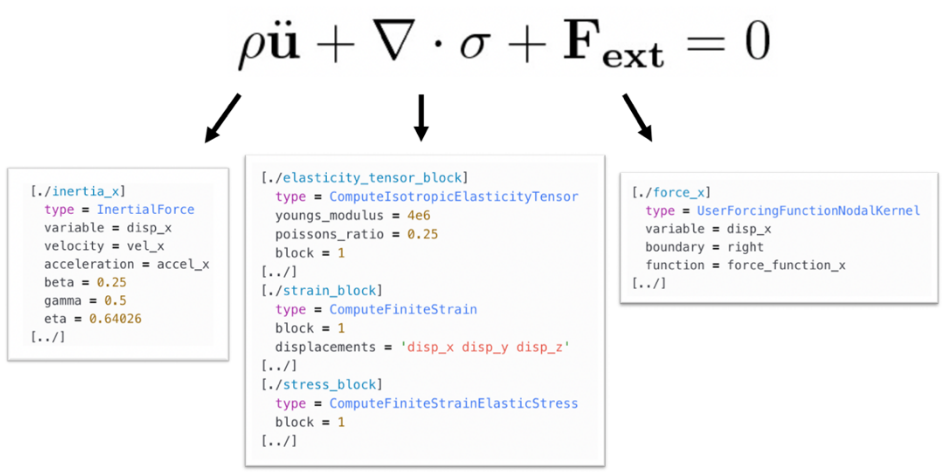


Figure 1: MASTODON architecture

II.B.1 Material models

Material models in MASTODON are defined by a combination of material blocks specified as a block in the input file. For example, a linear isotropic elastic material model with a large strain formulation can be modeled using a combination of the ComputeIsotropicElasticityTensor, ComputeFiniteStrainElasticStress, and the ComputeFiniteStrain objects, which create the linear isotropic elasticity tensor, stress tensor, and a strain tensor, respectively. The StressDivergence kernel object then calculates the divergence of the stress and provides the stress divergence residual in Equation 1. Several other material objects are available for small-strain formulations, non-isotropic elasticity tensors, and nonlinear formulations such as Drucker-Prager and Mohr-Coulomb. Currently, the structural elements (trusses, beams, and shells) are limited to linear materials.

One of the material models available in MASTODON for simulating seismic response of soil is ISoil[26], which is a multi-linear, pressure-dependent material model based on the distributed-element model first proposed by Iwan (1967) [27] and further modified by Chiang and Beck (1994) [28]. The main input for the ISoil model is the shear stress-strain backbone curve. ISoil uses the distributed element model[26] [27] [28] in which, the backbone stress-strain curve is divided into multiple elastic-perfectly-plastic elements that follow the Von-Mises yield criterion. The total stress of the soil element is then calculated as the summation of the stresses from each of the elastic-perfectly-plastic elements (see Figure 2). This soil material model also allows for changes in the yield condition and shear modulus with confining pressure. This pressure dependency property is very helpful in dynamically transitioning the soil backbone stress-strain curve obtained under a given confining pressure in a laboratory setting to confining pressures observed in situ or during the numerical simulation. Pressure dependency can also be used to model the failure of non-cohesive soils under tension. MASTODON provides several options to calculate the backbone curve in ISoil. The `user_defined` option requires the user to input the backbone curve as a CSV file. When multiple soil layers are present, multiple .csv files corresponding to the different layers can be provided. The `darendeli` option auto-generates the backbone curve based on empirical relations obtained from laboratory tests by Darendeli (2001)[29]. The `GQH` option is the General Quadratic/Hyperbolic model proposed by Groholski *et al.* (2016)[30]. It has a unique curve-fitting scheme to account for the mobilized shear strength at large shear strains. This curve fitting is considered an improvement over the `darendeli` model which may under- or over-estimate the mobilized shear strength at large strains.

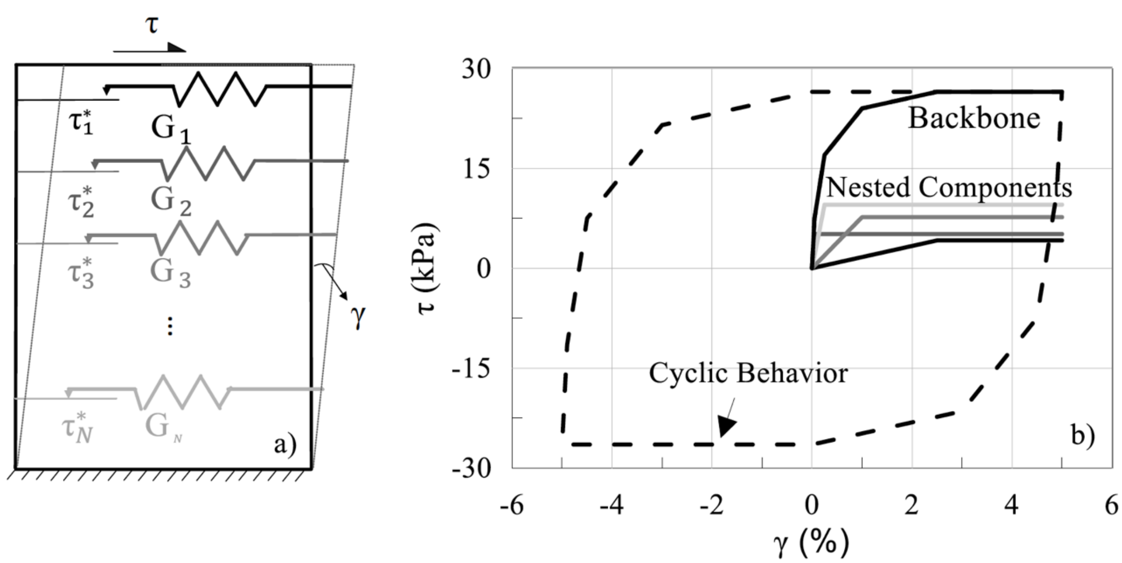


Figure 2: ISoil material model (Baltaji *et al.* 2017)[8]

MASTODON also has the capabilities to simulate seismic protective systems including lead-rubber (LR) and Friction-Pendulum (FP) seismic isolators, and nonlinear fluid viscous dampers (FVD). MASTODON includes macro models of these protective systems and these models are benchmarked with verified and validated models implemented in OpenSees and ABAQUS[31]. These macro models can be created in MASTODON using two-noded line elements in the mesh and creating the appropriate material objects. The LR isolator model is based on Kumar *et al.* (2015a)[32] and can be created in MASTODON using the ComputeLRIsolatorElasticity and ComputeIsolatorDeformation objects. This model is developed specifically for nuclear applications and captures the large deformation behavior of LR bearings such as rubber cavitation and post-cavitation behavior in tension, buckling in compression, interaction between vertical and horizontal stiffnesses, and shear strength degradation due to the heating of the lead core. The FP isolator is based on Kumar *et al.* (2015b)[33] can be created using the ComputeFPIsolatorElasticity and ComputeIsolatorDeformation objects. The FP isolator is also developed for nuclear applications and captures complex behaviors like the dependence of the friction coefficient on pressure, velocity, and contact interface temperature, and the variation of the interface temperature throughout the simulation. Fluid viscous dampers operate on the principle of fluid flow through an orifice that creates a differential pressure across the piston head and develops an internal resisting force in the damper. Reinhorn *et al.* (1995)[34] proposed a simplified expression for the force in the damper as a product of the damping coefficient and a fractional power of relative velocity. FV dampers are typically installed with an in-line brace, which introduces an axial flexibility to the damper assembly. Reinhorn *et al.* (1995)[34] found that capturing the flexibility of this brace is important for the simulation of the damper behavior. The nonlinear FVD model implemented in MASTODON explicitly accounts for the brace flexibility through a Maxwell formulation that models the brace and the damper in series. The damper model can be used through the ComputeFVDamperElasticity object in MASTODON and uses the solution framework proposed by Akcelyan *et al.* (2018)[35] for nonlinear FVDs.

II.B.2 Boundary conditions and constraints

MOOSE includes comprehensive BoundaryCondition and Constraint systems that offer several basic boundary conditions (BCs) such as the Dirichlet and Neumann conditions, and constraints such as the equal value constraint. For seismic analyses, DirichletBC is an essential BC that forces a set of nodes in the mesh to take on a specified value (e.g., simulating a fixed-base condition for a foundation or a soil domain). Earthquake ground motion input can be prescribed using the PresetAcceleration or the PresetDisplacement condition, which apply an acceleration or a displacement history, respectively, at a given boundary. These BCs can be used to directly input a 'within profile' motion for site response and SSI analyses. A 'within profile' motion is a ground motion recorded at depth such as an acceleration, velocity, or displacement history and includes both the incoming and outgoing waves. A 'within profile' input is used when the acceleration at depth is available from a downhole array, or when it is assumed that the bedrock at the base of the soil profile is rigid. When only an 'outcrop motion' is available, the SeismicForce BC, which converts a given ground motion (in terms of a velocity history) into a set of shear forces that are applied at the boundary. An 'outcrop motion' is the ground motion recorded at a rock outcrop in the vicinity of the site and is equal to twice the incoming wave. An 'outcrop motion' input involves converting the ground motion into a shear force history while using a non-reflecting boundary below. 'Outcrop motion' input is typically used when assuming an elastic bedrock at the base of the soil profile[36] [37] [38] [39]. MASTODON also includes an absorbing boundary condition called NonReflectingBC, which is based on Lysmer dampers[40]. Truncating a soil domain and placing this damper at the end of the domain is equivalent to simulating wave propagation in an infinite domain, provided the soil is linear elastic and the wave is almost perpendicular to the boundary. When performing SSI analyses in the time domain using the direct method[6] [2], which involves modeling the structure, the foundation and the soil domain altogether in a single simulation, the lateral boundaries of the soil domain are constrained such that the nodes at each elevation move together in each direction (X, Y, and Z), to simulate a pure shear condition at these boundaries. In MASTODON, this can be achieved using the Periodic BC, which takes the lateral boundaries as inputs and automatically pairs the nodes at each elevation and enforces a pure shear constraint.

II.B.3 Earthquake fault rupture

MASTODON also provides the capabilities of earthquake fault-rupture and source-to-site wave propagation. An earthquake fault rupture is characterized by the fault dimensions, fault's orientation and the slip time history during earthquake. The fault dimensions determine the area of fault rupture, which in combination with the slip history provides the energy released during an earthquake. The seismic moment (equivalent of energy released) is given by: , where is the seismic moment as a function of position and time, is the shear modulus of the soil/rock around the fault, is the area of fault rupture and is the slip history, which is also a function of the position and time. The direction of energy release from the fault rupture is given by the orientation of the fault that is given by the strike (, rake (and dip (of the fault. When this seismic moment is written in terms of the Cartesian coordinate system, with *x* oriented along the geographic north and *z* along the soil depth, a symmetric 3x3 moment tensor (M) is obtained. Each component of M is a force couple with the first index denoting the direction of the force and second index denoting the direction in which the forces are separated (Aki and Richards, 2012)[41].

To model earthquake fault using the finite element method in MASTODON, the fault is discretized into a finite number of point sources and a moment matrix is calculated for each of these point sources using the SeismicSource object. In this case, the moment matrix is defined only at discrete points on the fault instead of being defined at any point *p* within the fault. The total energy released in the discretized scenario is kept the same as that in the continuous fault rupture scenario. The waves generated from these individual point sources interfere constructively or destructively to mimic the rupture of the earthquake fault. Naturally, as the point source density increases, the effect of discretization decreases, and the results converge to those expected from the rupture of a continuous earthquake fault. The advantage of discretizing the earthquake fault using multiple point sources is that complex fault geometries can be easily modeled using this method and it also allows for synchronous and asynchronous fault rupture simulations. In synchronous fault rupture simulations, all the point sources rupture at the same instant generating a quasi-plane wave, whereas asynchronous fault rupture scenarios can be simulated by triggering the point source with a time delay calculated based on the distance of the point source from the epicenter and the fault rupture speed.

MASTODON is also capable of the Domain Reduction Method[42] (DRM), which significantly reduces the domain size of finite-element source-to-site simulations, and also enables the input of complex, 3D wave-fields into a soil domain. DRM is a two-step method developed to model the effect of earthquake ground motion, resulting from earthquake fault rupture, in highly heterogeneous localized regions such as the embedded structure in Figure 3(a). In these models the width of the localized feature such as a structure is usually much smaller (< 50 m) compared to the width of the entire domain including the earthquake fault (~ 15-20 km). In such cases, it is computationally efficient to split this problem into two separate computational domains: (i) larger domain (15-20 km wide) with the earthquake fault, but without the localized feature (Figure 3(b)), (ii) smaller domain (200-300 m wide) with just the localized feature and a small region of soil around it (Figure 3(c)). An equivalent force input from the larger computational domain is transferred to the smaller computational domain along one element layer, termed the DRM element layer (dashed lines in Figure 3 (b-c)). The region of interest (R1) lies within the DRM layer, and the region R2 that lies outside the DRM layer only experiences scattered waves generated due to the addition of the localized feature. When using DRM, the larger model does not have to be re-simulated for any changes in the localized feature, and therefore sensitivity of the different structure parameters on its seismic response can be rapidly assessed using the smaller model. In MASTODON, the DRM method is implemented through the use of UserForcingFunctionNodalKernel or FunctionPointForce objects for injecting the force through the DRM layer, through the use of NonReflectingBC at the outer boundaries of the domain to absorb waves traveling out of the domain.

Figure 3: Schematic describing the domain-reduction method

II.B.4 Solvers and time integration

The 'standard' solution process in MOOSE is through root-finding algorithms, i.e., find the displacement field in Equation 1 that results in a zero residual vector. MOOSE uses the solvers available in the PETSc[43] library for this process, most of which, use a Newton-Raphson type minimization algorithm. Most MASTODON simulations are run using the NEWTON or Preconditioned Jacobian-Free Newton-Krylov (PJFNK) methods for minimizing the residual. While both methods require a Jacobian, PJFNK does not require an accurate Jacobian for convergence and is therefore useful in highly nonlinear analyses where an accurate Jacobian is not available (e.g., ISoil). While performing a linear analysis it is expected that the solution converges in fewer iterations using the NEWTON method and this method is therefore computationally more efficient than PJFNK for linear analyses. The AD capability in MOOSE eliminates the need to code a Jacobian entirely and automatically calculates an accurate Jacobian during the simulation, making it an efficient alternative when an accurate analytical Jacobian is not available. Currently, this option is undergoing testing in MASTODON for seismic applications.

In seismic analyses, minimization algorithms are used with an implicit integration scheme, where the total residual in the weak form of the PDE is minimized iteratively at each time step. Therefore, the standard version of MASTODON involves an implicit integration scheme based on the Newmark-β and Hilbert-Hughes-Taylor (HHT) algorithms, which are commonly used integration algorithms for wave-propagation applications. The HHT scheme is a generalization of Newmark-Beta and reduces to Newmark-Beta when its integration parameter, . It is most useful when there are many degrees of freedom in the system and when it is desirable to dampen the high-frequency noise in the system. More recently, an explicit integration framework with the central difference integration scheme has been implemented in MOOSE. MASTODON can therefore now perform explicit integration using the central difference integration scheme. It is also capable of calculating and enforcing the critical time step to ensure stability in the simulation. At this time, explicit integration is only available for continuum elements, and it will be extended to beams and shell elements in the near future.

II.B.5 Seismic probabilistic risk assessment

Seismic probabilistic risk assessment (SPRA) can be automated in MASTODON using either the intensity-based assessment, or time-based assessment proposed by (Huang *et al.* 2008 and Huang *et al.* 2011)[44 17]. Intensity-based assessment involves calculating the seismic risk for a specific hazard intensity (expressed as PGA or a spectral acceleration at a certain period). Time-based assessment involves repeating the intensity-based risk calculation across a wide range of hazard intensities in the seismic hazard curve and calculating the sum of these risks. It is similar to the Multiple-Stripes approach[45 46 47 48] and has been adopted in FEMA P-58[49]. The time-based assessment for nuclear power plants, as proposed by Huang *et al.* (2011)[17], involves five steps as illustrated in Figure 4. The first step involves a plant system and accident-sequence analysis, which results in the development of accident sequences for the NPP (or any safety-critical facility) in terms of event trees and fault trees. The second step, which characterizes the site seismic hazard involves the development of seismic hazard curves and representative ground motions. The third step involves the simulation of structural response to these ground motions to evaluate the probabilistic demands on the SSCs at various locations in the plant. The fourth step involves assessing the damage to the SSCs from the probabilistic demands and evaluating the conditional fragility curves of the SSCs. The fifth and final step involves propagating these fragilities through the event trees and fault trees of step 1, calculating the overall seismic fragility of the plant, and convolving this fragility with the seismic hazard curve to calculate the risk.

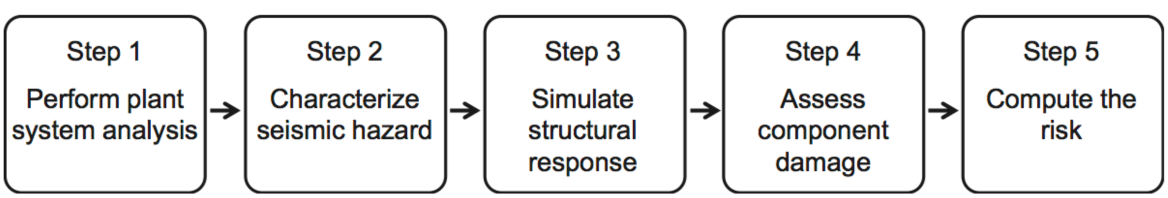


Figure 4: The time-based SPRA methodology[17]

SPRA in MASTODON can be automated from steps 3 to 5 (see Figure 5). By taking the fault trees, event trees, seismic hazard curve, hazard-consistent ground motions, and the finite-element model as inputs, it can perform the probabilistic demand calculation through the MultiApp system and the StochasticTools module either using Monte Carlo or Latin Hypercube sampling. Using these demands, and with the SSCs capacities as inputs, the Fragility object calculates the conditional seismic fragilities of the SSCs. Using the fault-tree and event-tree analysis module, it can then calculate the overall plant fragility and convolve it with the seismic hazard to calculate the seismic risk. The event-tree and fault-tree analysis methods in MASTODON is identical to that used by SAPHIRE[19], which is an INL-developed Nuclear Regulatory Commission (NRC) owned software for PRA of NPPs. In practice, the various steps of SPRA are performed individually using different software tools and custom scripting. By providing all of these tools under one software framework along with the finite-element analysis, MASTODON attempts to make these state-of-the-art methods of SPRA more widely accessible to designers and risk analysts and reduce the risk of error.

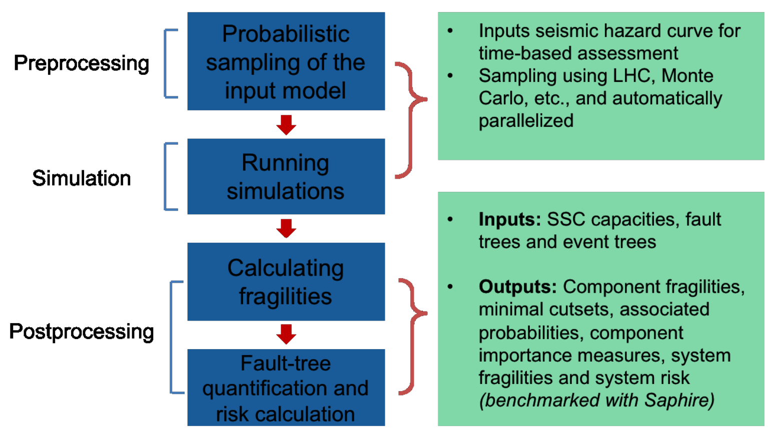


Figure 5: SPRA in MASTODON

III USING MASTODON

MASTODON uses a text input file with a ".i" extension that is organized into "blocks" with each block corresponding to a MOOSE system such as Kernels or Materials. Each block is divided into "sub-blocks" with each sub-block corresponding to an object of the system. For instance, the Kernels block can have different sub-blocks for the InertialForce, StressDivergence, and Gravity kernel objects. For large and complicated models, creating each object in an input file can make the file large and cumbersome to work with. MOOSE provides an Action system for developers to automate the creation of these objects, thereby reducing the burden on the user and making the input file more user friendly. Currently, actions are available that automate the creation of ISoil material objects, StressDivergence kernel objects, etc. Developers can easily extend these actions and create new actions when necessary. Input files can be created using any text editor, but the open source text editor, Atom is recommended since it has a number of useful tools like auto-complete and syntax suggestions that are developed specifically for MOOSE and MOOSE-based applications. Typically, MOOSE and MASTODON input files are not created from scratch, but from modifying other readily available input files from tests, examples, or tutorials. All of these input files are included in the MASTODON repository on GitHub, along with the source code. A detailed tutorial, examples for applications like nonlinear site response and SSI, description of the syntax of all the objects, and several other resources can be found on the MASTODON website. The sections below briefly describe preprocessing and postprocessing in MASTODON. Figure 6 below illustrates the software options available for preprocessing and postprocessing MASTODON simulations.

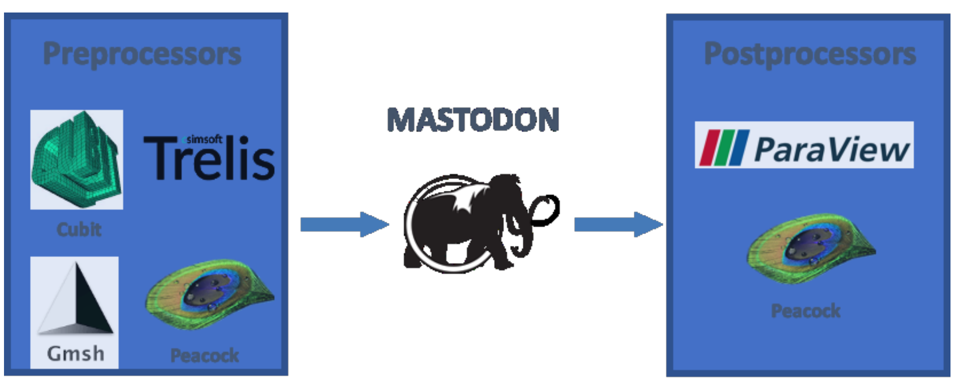


Figure 6: Preprocessing and postprocessing options for MASTODON

III.A Preprocessing

MASTODON can be used with the MOOSE graphical user interface (GUI), Peacock (Figure 6). Peacock is a dynamic GUI that works for all MOOSE-based applications. During pre-processing, it is used to create or modify the input file, and visualize the mesh, mesh blocks, boundaries, node sets, etc., for verification. Peacock provides the option to execute the input file after preprocessing, in addition to executing the file directly from the terminal. During post processing, Peacock is used for preliminary verification of the data in the output objects including Postprocessors and VectorPostprocessors. For seismic analyses, Peacock is used to create and edit the input file, verify the mesh, run the analysis, and verify outputs like response histories, stress contours, and response spectra.

MASTODON supports reading meshes from a large number of formats, but it most reliably reads the Exodus II format (.e or .exo extension) and the Gmsh ASCII format (.msh) as illustrated in Figure 6. CUBIT[50] is the most widely-used meshing software amongst MASTODON users and developers and creates meshes in Exodus II format. CUBIT is available for free for United States government users. Trelis[51] is the commercial version of CUBIT and has licensing options available for non-government users. The ".msh" files are created using Gmsh[52], which is a free and open-source meshing software. For creating and editing simple meshes, MOOSE also provides mesh generation objects through the MeshGenerator system, which is used directly through the input file without the need for an external file mesh.

MASTODON provides various features to increase ease of usage and more features can be added by developers. For example, in simulations where the soil layers are non-horizontal and non-planar, MASTODON can process image files (.jpg, .png, etc.) of the soil profile and create a soil layer mesh, where material blocks are based on the colors in the image. For creating 3D soil domains, multiple 2D images with soil profiles at different 2D cross sections of the soil domain can be provided as input. MASTODON can also automatically ensure that the soil mesh density is adequate for wave propagation of a certain frequency. If the mesh is too fine, the simulation will be very slow. If the mesh is too coarse, the waves beyond a certain frequency will be filtered by the mesh. The maximum element size depends on the type of element used for meshing (8-node or 20-node solid elements, etc.), cut-off frequency () of the wave and the shear wave velocity () of the soil layer. A minimum of 10 elements is required per wavelength of the wave to accurately represent the wave in space[6 53]. The minimum wavelength is calculated as:

(2)

where is the number of elements per wavelength. For linear analyses and with QUAD4 or HEX8 elements, an value of 10 is recommended. If quadratic elements such as QUAD9 or HEX27 are used, an value of 5 is recommended. Using the minimum element size information, MASTODON refines the mesh such that the element size criterion is met and at the same time the layer's separations are visible. An example of this meshing scheme is presented in Figure 7, where a 2D soil domain is divided into 3 soil layers and these soil layers are meshed such that the element size criterion is satisfied. A denser mesh is created at the interface between different soil layers. Note from the figure, that an Octree mesh is used. MOOSE, and therefore MASTODON, is capable of Octree meshing and adaptive re-meshing. Given the versatile and modular nature of the MOOSE systems, several such features can be developed in MASTODON (such as an Action object for NLSSI analyses) to improve the ease of input model creation.

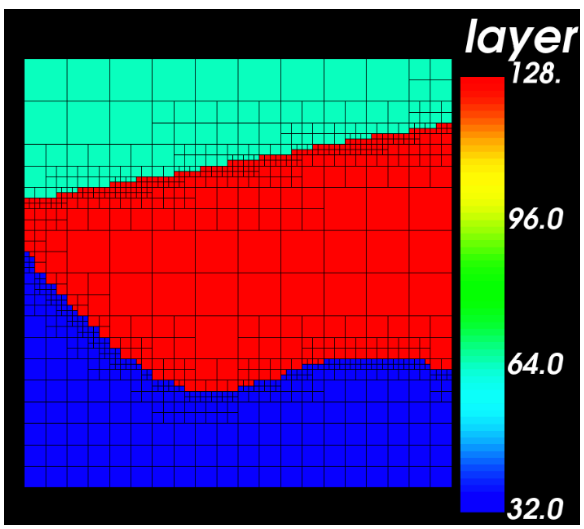


Figure 7: Auto-generated mesh for a soil domain with three non-horizontal non-planar soil layers.

III.B Post-processing

MASTODON is equipped with a wide variety of useful post-processing tools (Figure 6). Spatial data is written to an exodus file (.e) for each timestep of the simulation. However, this output exodus file, which contains the mesh as well as solution fields, is different from the input exodus file that contains only the mesh. By default, regardless of the filename of the input exodus file, if a file 'ssi.i' is executed and an exodus file is requested, an exodus file called 'ssi_out.e' containing the mesh and the solution fields will be created. For large meshes with many timesteps, the data can be written at fewer timesteps in order to reduce file size. Users can visualize results stored in this file using Peacock, the MOOSE graphical user interface (GUI), or using an external viewer such as ParaView[54]. The variables output to this file are setup within the input file, specifically in the Variables and AuxVariables blocks.

MASTODON also utilizes the PostProcessor and VectorPostprocessor systems in MOOSE, which are objects designed to be simple and modular, allowing users to output a single calculated value or vector of values at each instance of the calculation. An example of a postprocessor would be a displacement history at a node in the X direction for the whole duration of the simulation. Similarly, an example of a VectorPostprocessor would be the history of X displacements at all intersecting nodes along some user-defined line—a vector of values for each timestep. Another example of VectorPostprocessor objects is the ResponseSpectraCalculator, which outputs the acceleration, velocity, and displacement spectra at a specific node. In general, the PostProcessor and VectorPostprocessor data is output in comma separated value (CSV) files. There are a wide variety of postprocessing options available within MASTODON and MOOSE, and because the system is simple and modular, creating custom PostProcessor and VectorPostprocessor objects is relatively straight-forward.

IV CAPABILITIES AND DEMONSTRATIVE EXAMPLES

IV.A Earthquake fault rupture and source-to-site wave propagation

In many scenarios, the seismic safety of structures is assessed under the assumption of vertical seismic wave propagation[55,56,57,58,59,60]. While this assumption is valid for sites that are far from the earthquake fault, the near-fault (< 25 km) wavefields are significantly more complex due to the presence of body waves (S- and P-waves) of different incidence angles, and also due to the presence of surface waves[61,62]. The earthquake fault rupture capability in MASTODON allows the user to model these complex wavefields and the response of the structure to these wavefields.

One of the recent studies using this capability focused on simulating the effect of surface topographical features, such as the mesas and canyons present in the Los Alamos region, on the ground response at that location during an earthquake[63]. The earthquake faults near this region have an inclination between 45^{o} and 65^{o} from the horizontal and are located within 5 km from these topographical features. To get a complete understanding of the effect of topography, the response of the considered 2D soil domain was analyzed under various earthquake fault configurations including different fault inclinations, homogenous versus random spatial slip variations along the fault, and synchronous versus asynchronous fault rupture scenarios. Figure 8 presents snapshots of the vertical velocity at three different time instants from two of the simulations involving the rupture a 65^{o} fault, modeled using 501 point sources. The results present on the left column are from the synchronous fault rupture scenario, where all the point sources rupture simultaneously resulting in an inclined quasi-plane, whereas those on the right column are from the asynchronous scenario, where the rupture initiates at a hypocenter and propagates up and down the fault. The nature of the wavefields generated in these two scenarios are very different and affect different regions of the soil domain. This study demonstrated that the presence of mesas and canyons cause significant disturbances in the near-surface wavefield and extends the duration of ground motion. This study also found that even small mesas (height < 100 m) can amplify the response by a factor of 2. These earthquake fault rupture simulations use absorbing boundary conditions, modeled using Lysmer dampers [40] on the left, right and bottom boundaries.

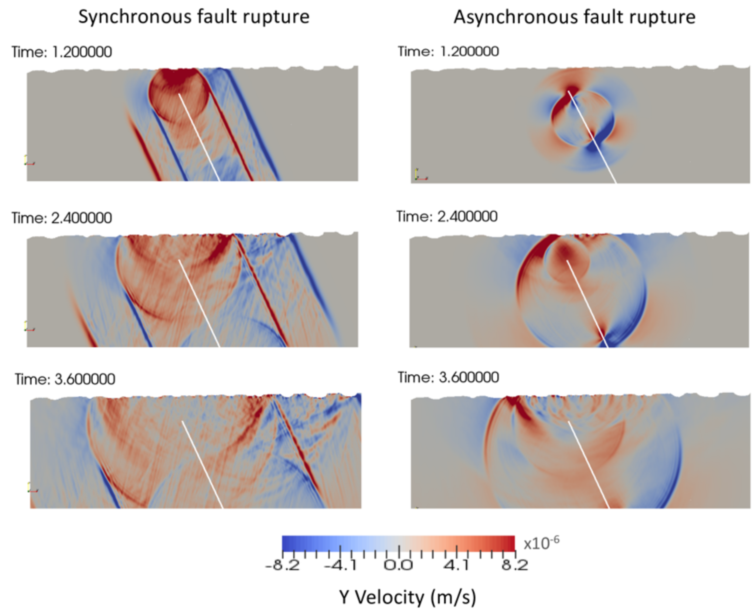


Figure 8: Snapshots of vertical velocity contours at three different time instants demonstrating the wavefield generated in the case of synchronous fault rupture (left) and asynchronous fault rupture (right). The scattering of the resulting wavefield due to the surface topographical features can also be observed in these figures. This figure is reprinted from Veeraraghavan *et al.* 2020[63].

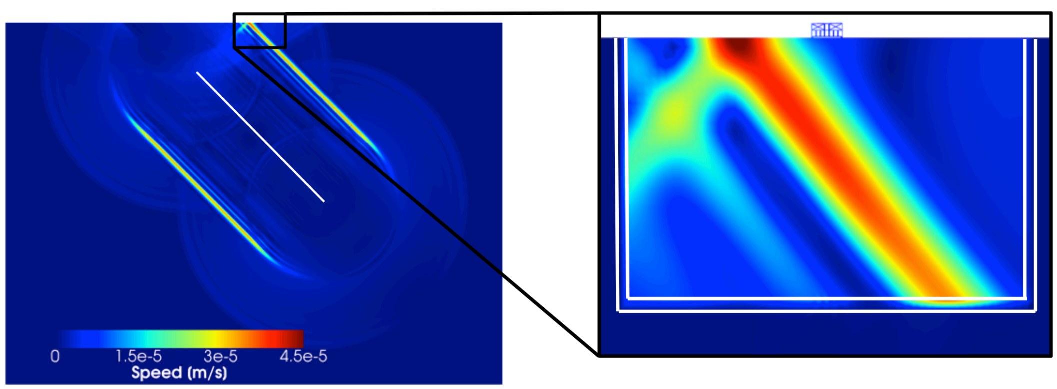


Figure 9: Snapshot of free-field earthquake fault rupture simulation showing the particle speed. The white line represents the earthquake fault with 45 dip. The yellow contour lines represent the SV wavefront generated from the fault rupture. The zoomed inset shows the smaller soil domain containing the structure and part of the soil around it, modeled using the DRM method. The seismic forces from the free-field simulation are transferred to the smaller soil domain along the DRM element layer marked in white.

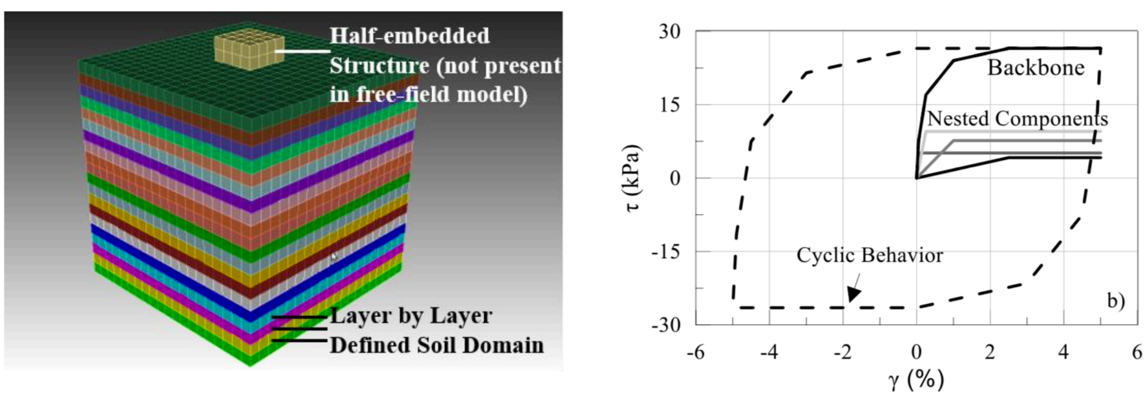
In the structure design process, it is computationally expensive to re-run the source-to-site wave propagation analysis for every small change in structural design as the structure dimensions are much smaller (< 50 m) than the dimensions of the soil domain (~15-20 km) required to simulate earthquake fault rupture. DRM can be used in MASTODON to overcome this problem by transferring the input from the free-field source-to-site simulations (left panel of Figure 9) to a much smaller domain that contains the structure and the soil around the structure (right panel of Figure 9). This transfer of input forces occurs along one element layer near the outer boundary of the smaller soil domain (element layer between white solid lines in the right panel of Figure 9). With the use of DRM, computationally expensive calculations such as modeling of material and geometric nonlinearities can also be performed within this smaller soil domain without any loss in accuracy. To date, the source-to-site wave propagation and DRM capabilities of MASTODON has been used to investigate the effects of topography on the seismic hazard[63] and assess the effect of inclined waves on deeply embedded structures[64].

IV.B Nonlinear site response and soil-structure interaction

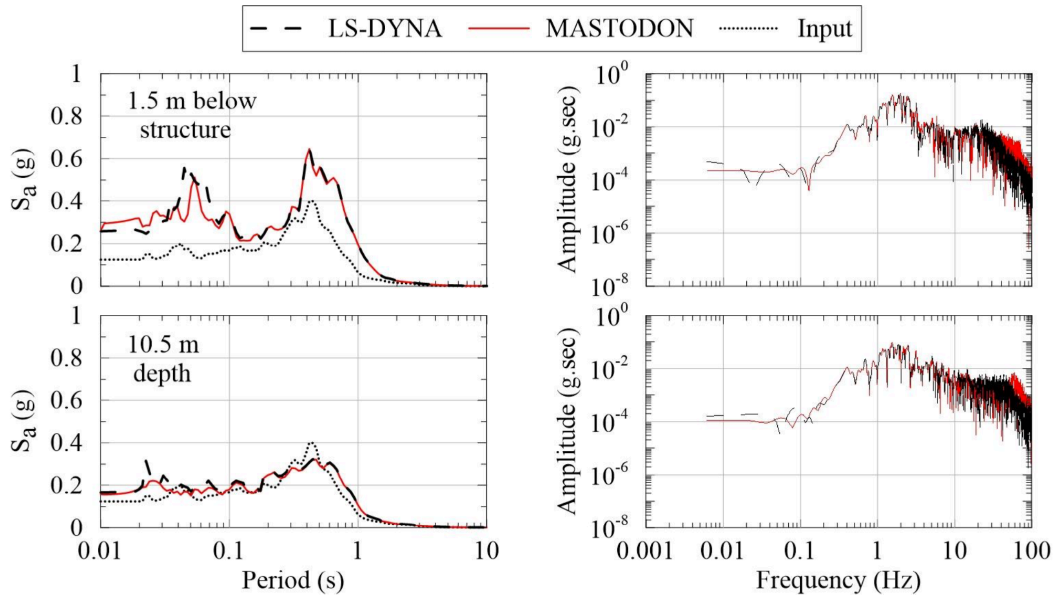
Equivalent-linear analysis codes such as SASSI[5] have been widely used to calculate the seismic SSI response of safety-critical nuclear structures[65] [66] since the 1980s. After the Fukushima Daichi NPP incident[67], seismic demands for beyond design basis events have been a growing concern[68]. With the advent of efficient computational tools in the last few decades, NLSSI analysis techniques have been developed to capture nonlinear mechanisms, particularly to assess the seismic performance of NPPs[2] [6] [15] [69] [70] [71] [72] [73].

Two types of nonlinearity are often important when simulating the seismic response of NPPs: material nonlinearities and interface nonlinearities. Material nonlinearity encompasses deviations from the linear stress-strain behavior of the soil and also energy dissipation due to hysteretic stress-strain behavior. Material nonlinearity in the soil can be simulated using the ISoil model in MASTODON. Interface nonlinearity at the foundation-soil interface arises from gapping, sliding and uplift of the structure from the soil. This form of nonlinearity can be modeled using node-to-face contact models available in MOOSE or by adding a thin nonlinear soil layer at the soil-structure interface as illustrated by[74], where the backbone shear stress-strain curve of the interface soil element can be tuned to simulate Coulomb friction. Additionally, when the pressure dependency is switched on, the yield stress varies linearly with confining pressure similar to Coulomb friction. In addition to frictional sliding, gapping between the soil and structure can be also modeled without much additional effort using this nonlinear soil material model since it can simulate zero strength in tension.

As an illustration, Figure 10(a) shows the SSI domain including a half-embedded linear structure and a 20 m deep nonlinear soil domain with 20 different soil layers[8]. For each soil layer, a different backbone stress-strain curve is used. This SSI model is excited by prescribing the ground acceleration at the base of the soil domain. The results obtained from MASTODON compare well with those obtained from a similar analysis using LS-DYNA in terms of peak ground acceleration and acceleration response spectrum for a wide range of periods (Figure 10(c)).



(a) (b)



(c)

Figure 10: (a) A soil-structure interaction analysis model with 20 m deep nonlinear soil and partially embedded linear structure with ground motion prescribed at the base of the soil domain. (b) Example of a backbone stress-strain curve, the division into multiple elastic-perfectly plastic stress-strain curves, and the hysteretic behavior corresponding to the given backbone curve. (c) Spectral acceleration as a function of time period at a point 1.5 m below the structure obtained from MASTODON and LS-DYNA. This figure is reprinted from Baltaji *et al.* (2017)[8].

In the past, geotechnical laminar box testing has been performed at University at Buffalo, and the data was used to validate nonlinear site response analysis in MASTODON using the ISoil material model[75]. The ISoil material model has also been used to simulate the seismic site response at the Lotung site using nonlinear site response analysis and has been benchmarked with LS-DYNA and ABAQUS, which also use a similar soil model[38]. More experimental studies are being carried out both at the Structural Dynamics Laboratory (SDL) at INL and the University at Buffalo, to gather data from small and medium-scale models of concrete foundations placed on soil and subjected to static and dynamic loading. Another effort is currently underway to validate NLSSI simulations (Figure 11(a)) in MASTODON with experimental data obtained from shake table testing, where a 1/9 scale tunnel was fully embedded in the soil using a laminar soil container[76]. The testing model was densely instrumented to measure dynamic response of both the soil and the tunnel under earthquake excitation (Figure 11(b)). Particular attention is paid to matching soil displacement histories at different depths and the tunnel deformation (Figure 11(c)). This model employs the ISoil material model for the soil, with the foundation-soil interface being tied and not simulating interface nonlinearities.

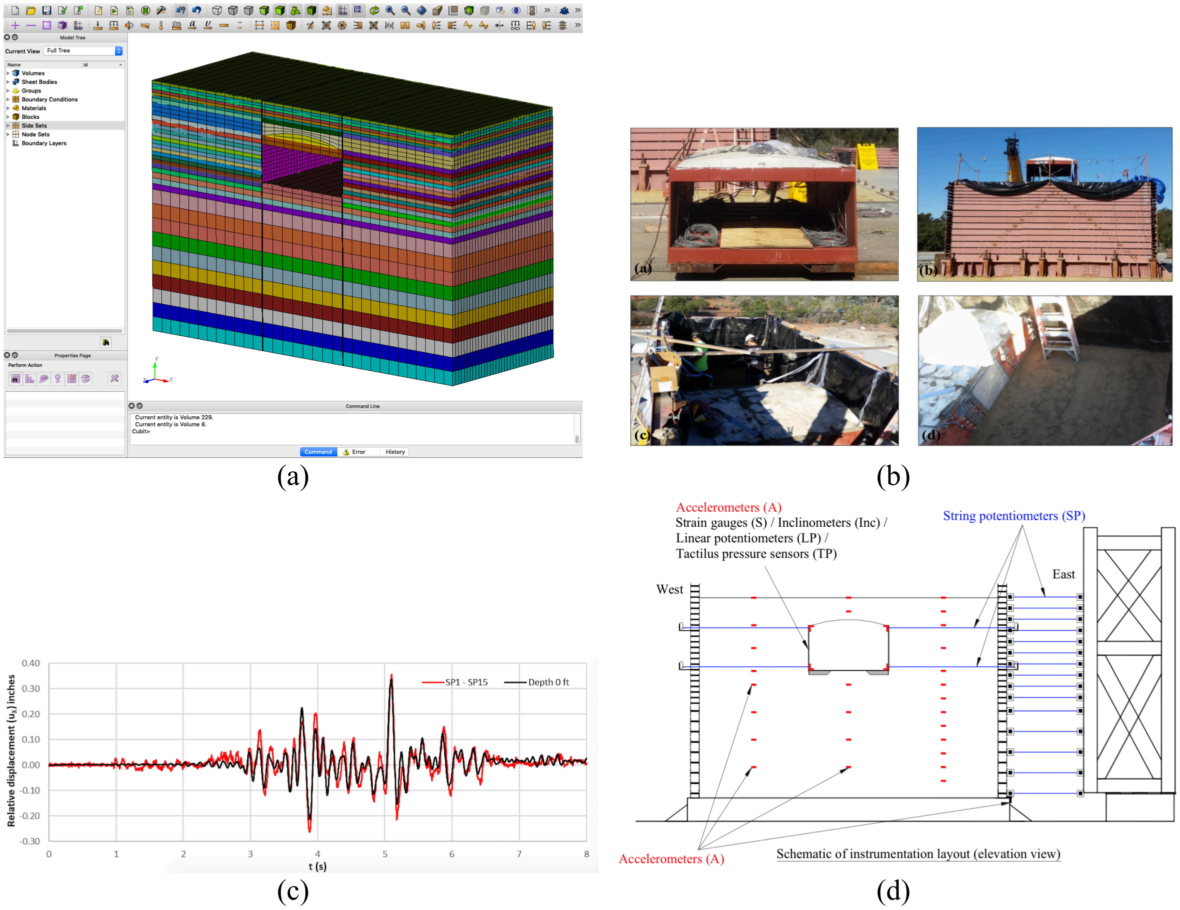


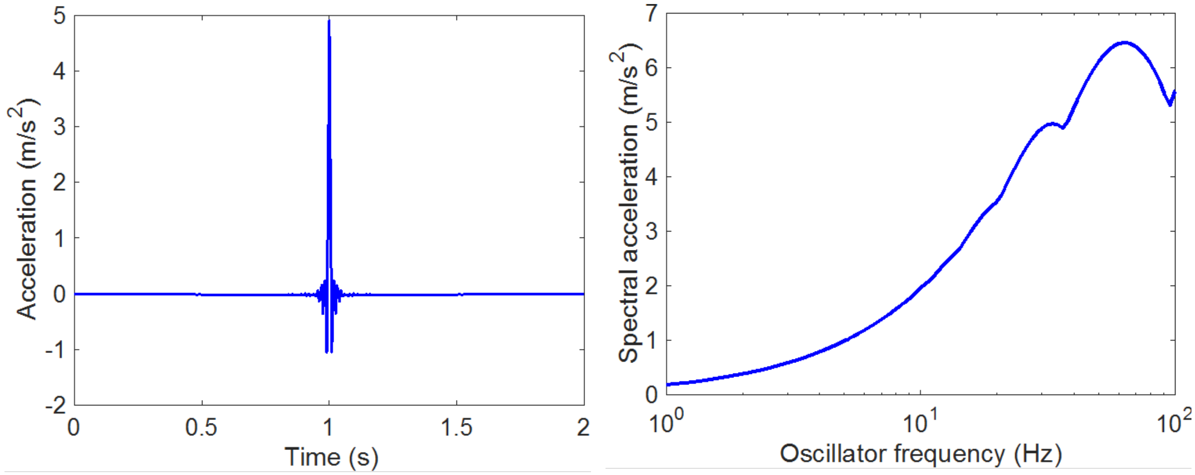
Figure 11: MASTODON modeling validation with experimental data: (a) Nonlinear soil-structure interaction model created in CUBIT. (b) Large-scale shake table test model for shallow tunnel[76]. (c) Soil displacement response histories at different depths and the tunnel deformation. (d) Instrumentation layout for the shake table test [76].

IV.C Stochastic analysis

More often than not, the input parameters of a model are not known deterministically, i.e., the input model parameters can be uncertain, and this uncertainty is characterized by probability distributions. For example, the parameters that drive a soil/structural material model, the Rayleigh damping parameters, or the dynamic inputs to the system can be uncertain in nature. Adequately characterizing the system's response given these uncertainties is a critical step in the SPRA of critical infrastructure. MASTODON includes the StochasticTools module of MOOSE and is capable of performing stochastic simulations under random values of the input parameters. MASTODON randomizes the input parameters by performing either Monte Carlo, Latin Hypercube, or Sobol sampling for effective exploration of the input parameter space, and automatically parallelizes these simulations. Currently, MASTODON can explicitly model uncertainties in the material properties and geometry (to a certain extent) but other uncertainties like aleatory uncertainty, effect of modeling simplifications, etc., can only be captured using approximate methods in the fragility analysis. However, since it is an open source software, users can easily add more sources of uncertainty as needed.

Performing stochastic simulations requires two input files. A "master" file sets up the stochastic simulations by sampling the input parameters according to their distributions and the number of samples. The master file transfers the input parameter samples to a "sub" file that performs the finite-element simulations. The master and sub files interface with each other through the MultiApp system to perform the stochastic analysis. Stochastic analysis capabilities enable MASTODON to also perform probabilistic risk assessment and design optimization circumventing the use of an external uncertainty quantification and stochastic analyses software.

Significant uncertainties can dominate the site response results not only due to input motion uncertainties[77], but also due to uncertainties in the soil properties. Below, a site response analysis example is used to demonstrate MASTODON's stochastic analysis capabilities by randomizing a site's properties. The site is composed of a single layer that is 5 meters thick with linear soil properties. Model parameters such as the shear modulus and the density define the site dynamic behavior. An Ormsby wavelet with a peak ground acceleration of 0.5 g and which has a constant Fourier amplitude between 0.2 Hz and 20 Hz is used as an input. Figure 12(a) presents the acceleration history of the Ormsby input motion and Figure 12(b) presents the corresponding spectral acceleration. Shear modulus and density are treated as uncertain by assuming that they follow an Uniform distribution with bounds [100, 200] MN/m^2 and [1000, 2000] Kg/m^3, respectively. Fifty sets of shear modulus and density are drawn and the site response analysis for each set is performed. Figure 13 presents the peak ground acceleration at the soil surface versus the site frequency scatter plot. Figures 14(a) and 14(b) present the mean and 3 deviation response spectrum at the soil surface and the amplification spectrum, respectively.



(a) (b)

Figure 12: (a) Ormsby wavelet in time domain; (b) response spectrum of Ormsby wavelet.

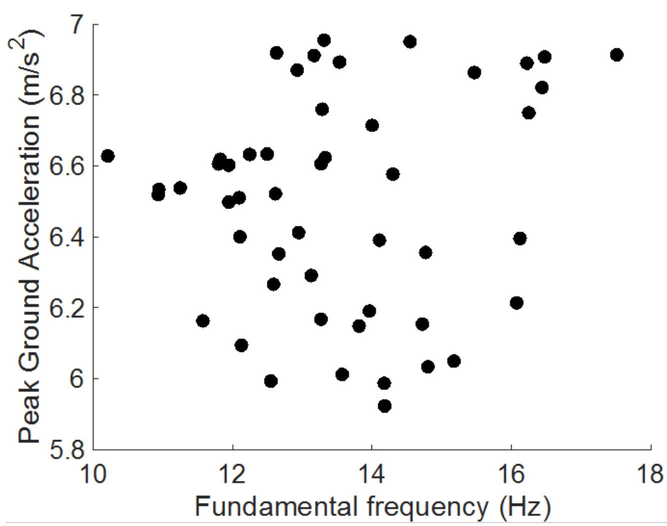
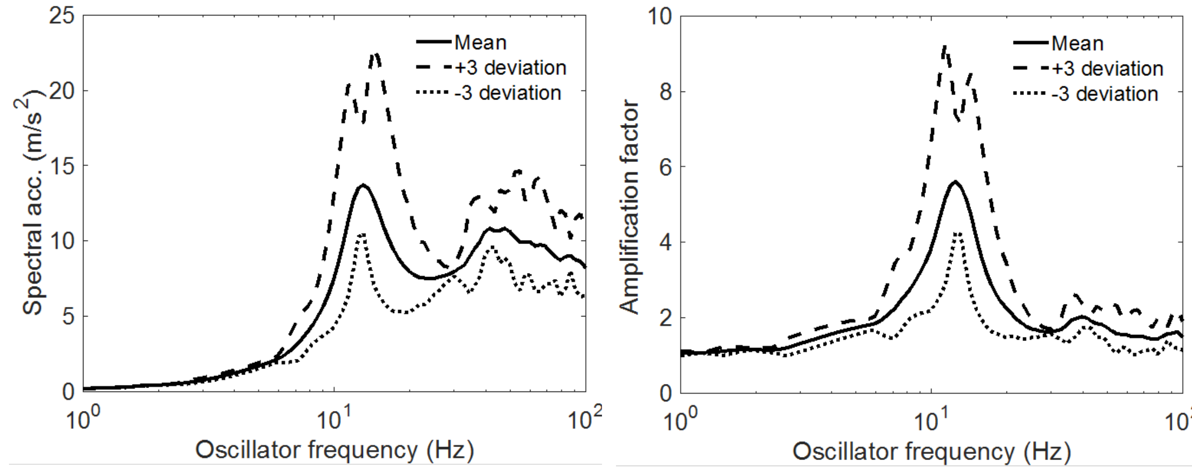


Figure 13: Peak ground acceleration at the soil surface versus site fundamental frequency.



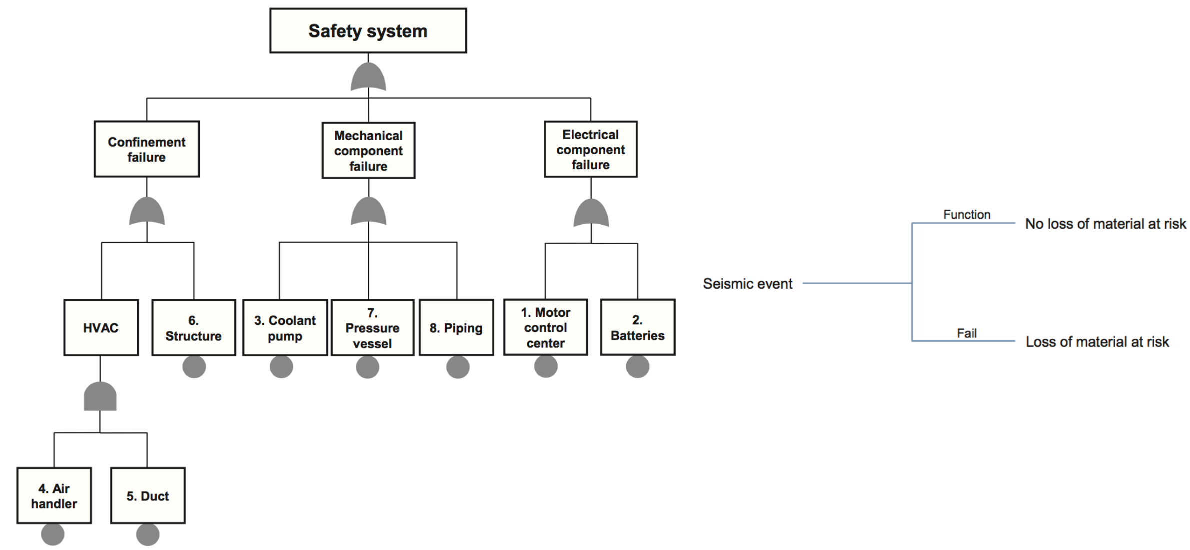
(a) (b)

Figure 14: Mean and 3 deviation of: (a) soil surface response spectrum and (b) amplification spectrum.

IV.D Seismic probabilistic risk assessment

The stochastic analyses described in the previous section can be used to calculate probabilistic demands from structural analyses, per step 3 of SPRA as described in Section II.B.5. If these demands are calculated at the locations of safety related SSCs in the facility, the Fragility object can process these demands, along with SSC capacities input by the user, to calculate the seismic fragilities, which are the estimates of the probability of failure of the SSC, given an intensity of seismic shaking. In SPRA, these fragilities are typically expressed as a log-normal distribution. Using these seismic fragilities, MASTODON can automate step 5 of SPRA by taking the fault tree logic, event tree logic, and the seismic hazard curve as inputs.

These analyses are illustrated through a simple example in this section. Figure 15 presents a simple fault tree logic (left panel) and event tree logic (right panel) corresponding to an idealized safety system, whose function is to prevent the loss of material at risk (MAR) into the atmosphere. The event tree illustrates the two possibilities after an initiating seismic event: function or fail. The seismic risk is the probability that a seismic event results in the loss of MAR. However, the safety system is equipped with several redundancies and has multiple paths to failure, as illustrated in the fault tree logic. Here, the events at the bottom of the logic tree, marked with solid gray circles, are called basic events, which correspond to the failures of individual SSCs due to an earthquake. An occurrence of one or more basic events may lead to a top event, which is the failure of the safety system. Each of the basic events has an associated fragility, which is calculated by the Fragility object in MASTODON by processing the stochastic demands. Fault tree and event tree analyses involve the propagation of the fragilities through the fault tree and event tree logic.



a. Fault tree b. Event tree

Figure 15: Fault tree and event trees for an idealized safety system (reprinted from Yu et al., (2017)[78])

The inputs for this analysis in MASTODON are provided as CSV files. Three input files are provided: seismic hazard curve, fault tree and event tree logic, and basic events with their fragilities. Since this example involves a single system in the event tree, only a fault tree analysis is performed. The input files for seismic hazard, fault tree logic, and basic event fragilities are listed in panels, a, b, and c, respectively, of Figure 16. MASTODON can provide detailed outputs including minimal cutsets, cutset probabilities, and various importance measures for such analyses. For simplicity, a reduced version of the analysis, which calculates the top event fragility (i.e., the system fragility) and the final seismic risk, is performed for the demonstration here. For the system and the inputs of this example, MASTODON calculates median system fragility to be 1.64 g (i.e., 50% probability that the safety system fails when subjected to an earthquake with a peak ground acceleration of 1.64 g) and the lognormal standard deviation to be 0.36. The final seismic risk is calculated to be 1.35E-05.

```
0.0025, 0.3383
0.006, 0.2382
0.0098, 0.1707
0.0137, 0.1269
0.0192, 0.08854
```

```
system, OR, conf, mech, elec
conf, OR, hvac, struct
hvac, AND, airhand, duct
mech, OR, cpump, pvess, piping
elec, OR, mcc, batt
```

```
mcc,LNORM,14.5,0.46
batt,LNORM,4,0.46
cpump,LNORM,3.1,0.5
airhand,LNORM,3.4,0.5
duct,LNORM,33.8,0.61
```

```
0.0269, 0.058
0.0376, 0.03576
0.0527, 0.02062
0.0738, 0.01125
0.103, 0.005896
0.145, 0.002939
0.203, 0.00145
0.284, 0.0007026
0.397, 0.0003322
0.556, 1.50E-04
0.778, 6.33E-05
1.09, 2.43E-05
1.52, 8.30E-06
2.13, 2.36E-06
3.3, 3.11E-07
```

a. Seismic hazard input file

b. Fault tree logic input file

```
struct,LNORM,3.3,0.46
pvess,LNORM,1.9,0.46
piping,LNORM,32,0.58
```

c. Basic events input file

Figure 16: Input files for risk analysis in MASTODON

IV.E Interfacing with other applications in MOOSE framework

While capabilities demonstrated above include structural mechanics and dynamics, simulating critical infrastructure to external hazards sometimes need to be modeled using coupled multi-physics simulations. The MultiApp system in MOOSE offers a major capability to couple MASTODON with other MOOSE-based applications built for a range of physical systems. One such application is the estimation of seismic risk in concrete structures undergoing aging-related degradation. Concrete structural components in NPPs and other civil infrastructure can experience degradation over time from a number of different physical phenomena such as temperature, moisture, and expansive chemical reactions[79]. A common degradation mechanism is the alkali-silica reaction (ASR), which produces an alkali-silica gel that can absorb moisture and cause spatially nonuniform volumetric expansion, leading to potential damage. The MOOSE-based application, Blackbear is capable of simulating multiple interacting chemical reactions involved in important concrete degradation mechanisms, coupled with heat and moisture transport models, and therefore is coupled in this example with MASTODON.

A preliminary effort of coupling MASTODON and BlackBear to develop a unified capability and demonstrate its application for determining the seismic response of an ASR-degraded concrete dam is presented here. For a demonstration, the Koyna dam in Maharashtra, India[80] is considered, which is a concrete dam with a cross section shown in Figure 17(a). ASR in the concrete is modeled and Mazar's damage model[81] is used to evaluate elastic stiffness degradation and softening behavior of concrete. The dam is assumed to be sited on a linear soil domain that is representative of a rock site (with a V_s of approximately 1700 m/s). In this example, the dam is first subjected to a 3-year ASR, assuming average upstream and downstream temperatures of 5°C and 15°C as well as relative humidity of 100% and 70%, respectively. A seismic wave in a form of sinusoid with amplitude of 0.01g, frequency of 5 Hz, and duration of 4 sec is then applied at a depth of 100 m below the dam foundation. Figure 17(b) shows the extent of ASR and the evolution of the isotropic damage (indicated as damage_index in panel b of the figure) after 3 years of aging. Figure 17(c) shows the acceleration response spectra at the soil base and top and base of the dam, compared to those without the 3-year ASR but keeping the same concrete constitutive model. This preliminary effort demonstrates the potential for concurrent simulations of long-term material degradation and short-term seismic behavior of an SSI model. Further efforts will be made to include multi-physics capabilities of fluid-structure interaction for hydrodynamic pressure from the adjacent reservoir, nonlinearity of soil material and soil-structure interface contact for NLSSI, and seismic wave propagation from a fault rupture scenario (Figure 9).

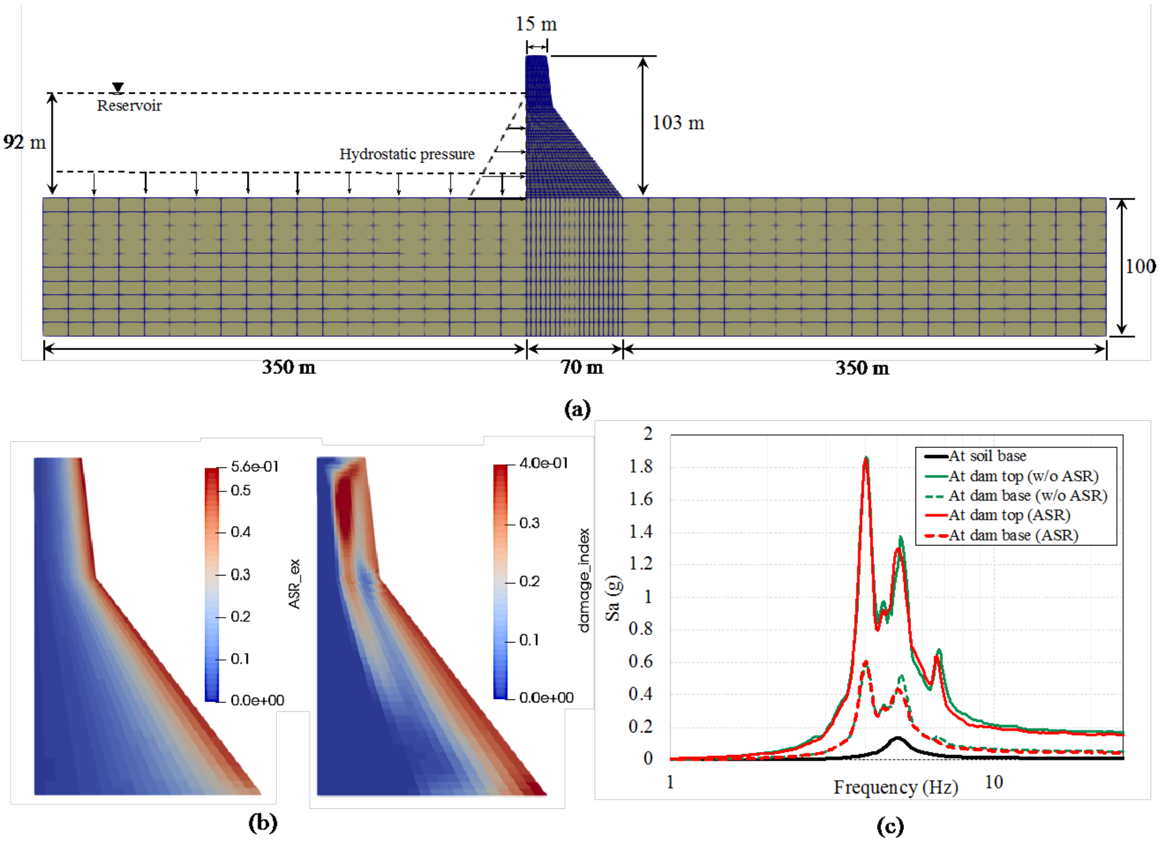


Figure 17: 2D plane strain analysis of the concrete dam including ASR and dynamic soil-structure interaction: (a) 2D plane-strain finite-element model of the Koyna dam including hydrostatic pressure from the reservoir, (b) contour of ASR extent and Mazar's damage index after 3 years, and (c) acceleration response spectra with and without ASR damage after 3 years.

V SOFTWARE QUALITY ASSURANCE AND CODE CONTRIBUTION

As an open-source code, MASTODON is open to contributions from all users in all applications. The development process for MASTODON mimics that of MOOSE. MASTODON's source code is tracked and managed using the version control and change tracking software, git, and is hosted on GitHub. Developers and users can download the source code and use it or modify it in any way that is useful. In order to contribute code to the MASTODON main repository, developers have to follow various guidelines listed in the MOOSE documentation. These guidelines include code formatting standards, documentation, issue tracking, and a review process. Development process starts with creating an "issue" on GitHub. Issues are essentially descriptions of a bug or a feature that needs to be addressed or developed. Once the developer makes necessary code changes or additions on their local git repository, they can request to merge it to the MASTODON repository by creating a "pull request" in the repository on GitHub. These code changes then go through a review process outlined in Slaughter *et al.* (forthcoming)[25] and can eventually be merged into the main version, once approved by the MASTODON team. Development of new features typically involves adding new objects such as a Kernel or a PostProcessor. For instance, adding a new soil material might involve adding objects that calculate the corresponding elasticity, strain, and stress tensors in the Materials system. Since most materials can use existing stress and strain tensors in MASTODON, developing a new material can just involve creating a new elasticity tensor object. If small changes are to be made, developers can take advantage inheritance in C++ and inherit from an existing object to avoid code duplication. For example, development of the LR isolator material involved creating the ComputeLRIsolatorElasticity, and ComputeIsolatorDeformation objects that compute the stiffness matrix and the deformation vector, respectively, of the LR isolator. During the development of the FP isolator, only the ComputeFPIsolatorElasticity object was created, since the method of computing deformations in both the isolators is identical. Such avoidance of code duplication reduces development time, maintenance time and also improves software quality.

MASTODON, along with MOOSE and other MOOSE-based applications are held to the same software quality standards as designed by the MOOSE team to achieve NQA-1 conformance. They are developed, documented, tested, and maintained with the same SQA infrastructure. This infrastructure, along with MOOSE and MOOSE-based applications are referred to as the "MOOSE platform", which includes a dynamic documentation framework called "MooseDocs", and the Continuous Integration, Verification, Enhancement, and Testing tool, CIVET. A description of CIVET, MooseDocs and their implementation is presented in Slaughter *et al.* (forthcoming) [25]. MOOSE and MOOSE-based applications are designated as quality level 2 (QL-2) non-safety software [82] (see the report NUREG/BR-0167 for safety software level descriptions) but are managed following processes that implement quality level 1 (QL-1) safety software requirements, including NQA-1 compliance. Additionally, MOOSE has recently received an NQA-1 certification allowing it to be used as a QL-1 software in the future.

Seismic analysis and risk assessment software are required to meet NQA-1 standards in order to be used for the design and risk assessment of several safety-critical facilities. Meeting NQA-1 standards is extremely challenging (and sometimes prohibitively expensive) for any software and often places a huge burden of additional documentation on the user. Although MASTODON itself does not hold an NQA-1 certification, by relying on the MOOSE platform, it ameliorates these challenges by automating the documentation and update process and creating V&V documentation and regression tests along with code development. While it may not be currently used for safety analyses, the intention is to maintain high quality standards for future use as a safety software.

VI CONCLUSIONS AND FUTURE WORK

The safety of critical infrastructure, such as nuclear power plants (NPPs) and safety-critical nuclear facilities, during earthquakes and other external hazard events is vital for the proper functioning of a society. However, building and maintaining large critical infrastructure facilities is expensive. In the case of NPPs, the capital costs of new construction have been prohibitively high, primarily due to the conservatisms and inefficiencies in the civil engineering aspects of building these plants[83]. One solution to address safety and economics at the same time is to use state-of-the-art tools in seismic design, analysis, and probabilistic risk assessment (PRA) such as nonlinear site response and soil-structure interaction analysis, seismic protective systems[84] [85], advanced seismic PRA[47], design optimization[86], etc.

MASTODON was created to bring these state-of-the-art methods and tools for design, analysis, and risk assessment under one software framework and make them more accessible to engineers and critical infrastructure stakeholders. MASTODON is under active development and it is currently capable of structural mechanics and dynamics, contact mechanics, stochastic simulations, fragility analysis, and fault-tree and event-tree analysis. This enables MASTODON to be deployed in a wide range of applications such as source-to-site wave propagation using fault-rupture simulations and domain-reduction method (DRM), nonlinear site-response and soil-structure interaction analyses, sensitivity studies, fragility analysis, and seismic probabilistic risk assessment. Being built on the MOOSE platform, MASTODON offers efficient scalability[22], streamlined integration of software quality assurance into the code, and coupled multi-physics capabilities, all of which, are important for critical infrastructure.

Future work will focus on (1) increasing the efficiency of existing tools including foundation-soil interface models and structural elements (beams and shells), (2) developing new tools including nonlinear material models for structural materials (e.g., reinforced concrete), acoustic elements for fluid-structure interaction in molten fuel nuclear reactor vessels and dams, etc., (3) improving the integration between finite-element analysis, PRA and design optimization, and (4) developing more documentation including examples for large nonlinear soil-structure interaction (NLSSI) models, seismic isolation including NLSSI and seismic PRA, and verification and validation (V&V) manuals through ongoing experiments as well as new experiments.

VII ACKNOWLEDGMENTS

MASTODON was developed in collaboration with Prof. Jacobo Bielak at Carnegie Mellon University, Prof. Youssef Hashash, Ozgun Numanoglu, and Omar Baltaji at University of Illinois, Urbana-Champaign, Prof. Abhinav Gupta and Saran Bodda at North Carolina State University, and Prof. Andrew Whittaker and Sai Sharath Parsi at University at Buffalo, State University of New York. The development team also received a great amount of support and advice from INL computational scientists, Benjamin Spencer, Jason Hales, Richard Martineau, Cody Permann, Derek Gaston, and Antonio Recuero. The MASTODON project was funded by the Department of Energy (DOE) Office of Nuclear Energy through the Light Water Reactor Sustainability Program, Office of Technology Transitions (OTT), National Nuclear Safety Administration, Advanced Research Projects Agency (ARPA-E), and INL's Laboratory Directed Research and Development (LDRD) program. The contributions and financial support are gratefully acknowledged. We also thank two anonymous reviewers for their valuable comments that have improved the quality of this paper.

REFERENCES

1 V. ANAND and S. S. KUMAR, "Seismic soil-structure interaction: A state-of-the-art review," Structures **16**, 317-326 (2018).

2 C. BOLISETTI, A. S. WHITTAKER, and J. L. COLEMAN, "Linear and Nonlinear Soil-Structure Interaction Analysis for Buildings and Safety-Related Nuclear Structures," Soil Dynamics & Earthquake Engineering **107C**, pp. 218-233 (2018).

3 E. KAUSEL, "Early History of Soil-Structure Interaction," Soil Dynamics and Earthquake Engineering **30** (9), 822-832 (2010).

4 H. L. WONG, "Soil-Structure Interaction: A Linear Continuum Mechanics Approach (CLASSI User's Manual)," 1979, University of Southern California, Los Angeles, California,

5 J. LYSMER, M. TABATABAIE-RAISSI, F. TAJIRIAN, S. VAHDANI, and F. OSTADAN, "SASSI: A System for Analysis of Soil-Structure Interaction," 1981, University of California Berkeley, UCB/GT/81-02.

6 J. L. COLEMAN, C. BOLISETTI, and A. S. WHITTAKER, "Time-Domain Soil-Structure Interaction Analysis of Nuclear Facilities," Nuclear Engineering and Design **298**, 264-270 (2016).

7 B. JEREMIĆ, G. JIE, M. PREISIG, and N. TAFAZZOLI, "Time Domain Simulation of Soil-Foundation-Structure Interaction in Non-Uniform Soils," Earthquake Engineering & Structural Dynamics **38** (5), 699-718 (2009).

8 O. BALTAJI, O. A. NUMANOGLU, S. VEERARAGHAVAN, Y. HASHASH, J. L. COLEMAN, and C. BOLISETTI, "Nonlinear Time-Domain Site-Response and Soil-Structure Interaction Analyses for Nuclear Facilities Using MASTODON", in *24th International Conference in Structural Mechanics in Reactor Technology (SMiRT-24)* (Busan, Korea, 2017).

9 A. G. SEXTOS, G. D. MANOLIS, A. ATHANASIOU, and N. IOANNIDIS, "Seismically induced uplift effects on nuclear power plants. Part 1: containment building rocking spectra," Nuclear Engineering and Design **318**, 276-287 (2017).

10 J. A. ABELL, N. ORBOVIC, D. B. MCCALLEN, and B. JEREMIC, "Earthquake Soil-Structure Interaction of Nuclear Power Plants, Differences in Response to 3-D, 3x1-D and 1-D Excitations," Earthquake Engineering and Structural Dynamics **47**, 1478-1495 (2018).

11 P. K. TEHRANI, I. TALEBINEJAD, B. KOSBAB, A. NYKYFORCHYN, S. STÄUBLE, and J. U. KLÜGEL, "Effects of Nonlinearities on Seismic Soil-Structure-Interaction Be-havior of a Nuclear Plant Reactor Building: A Case Study", in *TINCE 2018–Technological Innovations in Nuclear Civil Engineering* (Paris-Saclay, France, 2018).

12 LSTC, Software: LS-DYNA (Livermore Software Technology Corporation, Livermore, CA, 2010), https://www.ansys.com/products/structures/ansys-ls-dyna.

13 DASSAULT SYSTÈMES, Software: ABAQUS - Finite Element Analysis Software (Dassault Systèmes, Providence, Rhode Island, 2018), https://www.3ds.com/products-services/simulia/products/abaqus/.

14 S. MAZZONI, F. MCKENNA, M. H. SCOTT, and G. L. FENVES, Software: Open System for Earthquake Engineering Simulation (OpenSees) (Pacific Earthquake Engineering Research Center (PEER), University of California, Berkeley, California, 2009), https://opensees.berkeley.edu/.

15 B. JEREMIC, A. KAMMERER, N. TAFAZZOLI, and B. KAMRANI, "The NRC ESSI Simulator", in *21st International Conference in Structural Mechanics and Reactor Technology: SMiRT 21* (New Delhi, India, 2011).

16 S. L. N. DHULIPALA, A. RODRIGUEZ-MAREK, and M. M. FLINT, "Computation

of vector hazard using salient features of seismic hazard deaggregation," Earthquake Spectra **34** (4), 1893-1912 (2018).

17 Y. N. HUANG, A. S. WHITTAKER, and N. LUCO, "A Probabilistic Seismic Risk Assessment Procedure for Nuclear Power Plants: (I) Methodology," Nuclear Engineering and Design **241**, pp.3996-4003 (2011).

18 ASME, "Quality Assurance Requirements for Nuclear Facility Applications", in *ASME NQA-1* (American Society of Mechanical Engineers, New York, NY, 2015).

19 C. L. SMITH and T. L. WOOD, "Systems Analysis Programs for Hands-on Integrated Reliability Evaluations (SAPHIRE) Version 8," 2011, U.S. Nuclear Regulatory Commission, NUREG/CR-7039, Idaho Falls, ID, USA,

20 D. WAKEFIELD, S. EPSTEIN, Y. XIONG, and K. NOURI, "RISKMAN®, celebrating 20+ years of excellence!", in *10th International Conference on Probabilistic Safety Assessment and Management* (Settle, WA, 2010), pp. 3488-3497.

21 EPRI, Software: Computer Aided Fault Tree Analysis System (CAFTA) (Electric Power Research Institute, 2013), https://www.epri.com/research/products/000000003002000020.

22 C. J. PERMANN, D. R. GASTON, D. ANDRŠ, R. W. CARLSEN, F. KONG, A. D. LINDSAY, J. M. MILLER, J. W. PETERSON, A. E. SLAUGHTER, R. H. STOGNER, and R. C. MARTINEAU, "MOOSE: Enabling massively parallel multiphysics simulation," SoftwareX **11**, 100430 (2020).

23 J. D. HALES, S. R. NOVASCONE, B. W. SPENCER, R. L. WILLIAMSON, G. PASTORE, and D. M. PEREZ, "Verification of the BISON fuel performance code," Annals of Nuclear Energy **71**, 81--90 (2014).

24 B. W. SPENCER, M. BACKMAN, P. CHAKRABORTY, D. SCHWEN, Y. ZHANG, H. HUANG, X. BAI, and W. JIANG, "Grizzly Usage and Theory Manual," 2016, Idaho National Laboratory, INL/EXT-16-38310, Idaho Falls, Idaho,

25 A. E. SLAUGHTER, C. J. PERMANN, J. M. MILLER, B. K. ALGER, and S. R. NOVASCONE, "Continuous Integration, In-code Documentation, and Automation for Nuclear Quality Assurance Conformance," Nuclear Technology, American Nuclear Society (Forthcoming).

26 O. A. NUMANOGLU, "Numerical modeling and simulation of seismic settlements on dense sands," PhD thesis, University of Illinois Urbana Champaign, 2019.

27 W. D. IWAN, "On a Class of Models for the Yielding Behavior of Continuous and Composite Systems," Journal of Applied Mechanics **34**, 612-617 (1967).

28 D. Y. CHIANG and J. L. BECK, "A New Class of Distributed-Element Models for Cyclic Plasticity -I. Theory and Application," International Journal of Solids and Structures **31** (4), 469-484 (1994).

29 M. B. DARENDELI, "Development of a new family of normalized modulus reduction and material damping curves," PhD thesis, University of Texas at Austin, 2001.

30 D. R. GROHOLSKI, Y. M. HASHASH, B. KIM, M. MUSGROVE, J. HARMON, and J. P. STEWART, " Simplified Model for Small-Strain Nonlinearity and Strength in 1D Seismic Site Response Analysis," Journal of Geotechnical and Geoenvironmental Engineering **142** (9), 04016042 (2016).

31 S. S. PARSI, M. KUMAR, C. BOLISETTI, J. COLEMAN, and A. S. WHITTAKER, "Implementation and benchmarking of seismic protective devices in MASTODON", in *Structural mechanics in reactor technology - SMiRT 25* (2019).

32 M. KUMAR, A. S. WHITTAKER, and M. C. CONSTANTINOU, "Seismic isolation of nuclear power plants using elastomeric bearings," 2015, MCEER: Earthquake Engineering to Extreme Events, MCEER-15-0008, University at Buffalo, State University of New York,

33 M. KUMAR, A. S. WHITTAKER, and M. C. CONSTANTINOU, "Seismic isolation of nuclear power plants using sliding bearings," 2015, MCEER: Earthquake Engineering to Extreme Events, MCEER-15-0006, University at Buffalo, State University of New York,

34 A. M. REINHORN, C. LI, and M. C. CONSTANTINOU, "Experimental and analytical investigation of seismic retrofit of structures with supplemental damping, part 1: fluid viscous damping devices," 1995, National Center for Earthquake Engineering Research, NCEER-95-0001, University at Buffalo, State University of New York,

35 S. AKCELYAN, D. G. LIGNOS, and T. HIKINO, "Adaptive Numerical Method Algorithms for Nonlinear Viscous and Bilinear Oil Damper Models Subjected to Dynamic Loading," Soil Dynamics & Earthquake Engineering **113**, 488-502 (2018).

36 S. L. KRAMER, *Geotechnical Earthquake Engineering*. (Upper Saddle River, New Jersey, 1996), Prentice Hall.

37 C. BOLISETTI, A. S. WHITTAKER, B. H. MASON, I. ALMUFTI, and M. WILLFORD, "Equivalent linear and nonlinear site response analysis for design and risk assessment of safety-related nuclear structures," Nuclear Engineering and Design **275**, 107-121 (2014).

38 R. SPEARS, S. VEERARAGHAVAN, and J. COLEMAN, "Nonlinear modeling of ground motions at Lotung LSST site with nested surface soil constitutive model," Nuclear Technology **205** (9), 1205-1218 (2019).

39 A. O. L. KWOK, J. P. STEWART, and Y. M. A. HASHASH, "Nonlinear ground-response analysis of Turkey flat shallow stiff-soil site to strong ground motion," Bulletin of the Seismological Society of America **98** (1), 331-343 (2008).

40 J. LYSMER and R. L. KUHLEMEYER, "Finite dynamic model for infinite media," Journal of Engineering Mechanics Division, ASCE **95, EM4**, 859-877 (1969).

41 K. AKI and P. G. RICHARDS, *Quantitative seismology*. (2002), University Science Books.

42 J. BIELAK, K. LOUKAKIS, Y. HISADA, and C. YOSHIMURA, "Domain Reduction Method for Three-Dimensional Earthquake Modeling in Localized Regions, Part-I: Theory," Bulletin of the Seismological Society of America **93** (2), 817-824 (2003).

43 S. BALAY, S. ABHYANKAR, M. ADAMS, J. BROWN, P. BRUNE, K. BUSCHELMAN, L. DALCIN, A. DENER, V. EIJKHOUT, W. GROPP, and D. KARPEYEV, "PETSc users manual," 2019 https://www.mcs.anl.gov/petsc/petsc-current/docs/manual.pdf.

44 Y.-N. HUANG, A. S. WHITTAKER, and N. LUCO, "Performance Assessment of Conventional and Base-Isolated Nuclear Power Plants for Earthquake and Blast Loadings," 2008, Multidisciplinary Center for Earthquake Engineering Research, MCEER-08-0019, University at Buffalo, The State University of New York, Buffalo, NY,

45 F. JALAYER and A. C. CORNELL, "Alternative non-linear demand estimation methods for probability-based seismic assessments," Earthquake Engineering & Structural Dynamics **38** (8), 951-972 (2009).

46 J. W. BAKER, "Efficient Analytical Fragility Function Fitting Using Dynamic Structural Analysis " Earthquake Spectra **3** (1), pp. 579-599 (2015).

47 C. BOLISETTI, M. M. TALAAT, J. L. COLEMAN, and P. S. HASHIMOTO, "Advancing Seismic Probabilistic Risk Assessment to Include Nonlinear Soil-Structure Interaction", in *24th International Conference in Structural Mechanics and Reactor Technology, SMiRT24* (Busan, Korea, 2017).

48 S. L. N. DHULIPALA, A. RODRIGUEZ-MAREK, S. RANGANATHAN, and M. M. FLINT, "A site-consistent method to quantify sufficiency of alternative IMs in relation to PSDA," Earthquake Engineering and Structural Dynamics **47** (2), 377-396 (2018).

49 FEMA, "Seismic performance assessment of buildings," 2012, Federal Emergency

Management Agency, Washington, District of Columbia, https://www.fema.gov/media-library/assets/documents/90380.

50 CUBIT, Software: CUBIT 15.3 User Documentation (Sandia National Laboratories, 2017), https://cubit.sandia.gov/public/15.3/help_manual/WebHelp/cubithelp.htm.

51 COREFORM, Software: Trelis: Advanced meshing for challenging simulation (2020), https://coreform.com/products/trelis/.

52 C. GEUZAINE and J.-F. REMACLE, "Gmsh Reference Manual," 2020https://gmsh.info/doc/texinfo/gmsh.html.

53 K. WATANABE, F. PISANÒ, and B. JEREMIĆ, "Discretization effects in the finite element simulation of seismic waves in elastic and elastic-plastic media," Engineering with Computers **33**, 519-545 (2017).

54 U. AYACHIT, Software: The ParaView Guide: A Parallel Visualization Application (Kitware, 2015), https://dl.acm.org/doi/abs/10.5555/2789330.

55 J. C. ANDERSON, "Seismic response effects on embedded structures," Bulletin of the Seismological Society of America **62** (1), 177-194 (1972).

56 J. BIELAK, "Dynamic behaviour of structures with embedded foundations," Earthquake Engineering & Structural Dynamics **3**, 259-274 (1975).

57 T. MASAO, Y. TAKASAKI, M. HIRASAWA, and M. OKAJIMA, "Earthquake response of nuclear reactor building deeply embedded in soil," Nuclear Engineering and Design **58** (3), 393-403 (1980).

58 M. HASEGAWA, T. ICHIKAWA, S. NAKAI, and T. WATANABE, "Nonlinear seismic response analysis of an embedded reactor building based on the substructure approach," Nuclear Engineering and Design **104** (2), 175-186 (1987).

59 I. TAKEWAKI, N. TAKEDA, and K. UETANI, "Fast practical evaluation of soil-structure interaction of embedded structures," Soil Dynamics and Earthquake Engineering **23** (3), 13-20 (2003).

60 M. MAHSULI and M. A. GHANNAD, "The effect of foundation embedment on inelastic response of structures," Earthquake Engineering and Structural Dynamics **38**, 423-437 (2009).

61 W. IMPERATORI and P. MAI, "The role of topography and lateral velocity heterogeneities on near-source scattering and ground-motion variability," Geophysical Journal International **202**, 2163-2181 (2015).

62 D. RESTREPO, J. BIELAK, J. GOMEZ, J. JARAMILLO, and R. SERRANO, "Effects of realistic topography on the ground motion of the Colombian Andes: A case study of the Aburr valley, Antioquia," Geophysics Journal International **204**, 1801-1816 (2016).

63 S. VEERARAGHAVAN, J. L. COLEMAN, and J. BIELAK, "Simulation of site and topographic effects on ground motion in Los Alamos, NM mesas," Geophysical Journal International **220** (3), 1504-1520 (2020).

64 S. VEERARAGHAVAN, J. BIELAK, and J. COLEMAN, "Effect of inclined seismic waves on deeply embedded nuclear facilities", in *24th International Conference on Structural Mechanics in Reactor Technology (SMiRT)* (Busan, South Korea, 2017).

65 T. GANEV, F. YAMAZAKI, T. KATAYAMA, and T. UESHIMA, "Soil- structure interaction analysis of the Hualien containment model," Soil Dyn. Earthquake Eng. **16** (7), 459-470 (1997).

66 J. XU, C. MILLER, C. COSTANTINO, and C. HOFMAYER, "Assessment of Seismic Analysis Methodologies for Deeply Embedded Nuclear Power Plant Structures," 2006, U.S. Nuclear Regulatory Commission, Washington, District of Columbia NUREG/CR-6896.

67 K. KUROKAWA, "Fukushima nuclear accident independent investigation commission by the National Diet of Japan," Nippon Genshiryoku Gakkai-Shi **55** (3), 146-151

(2013).

68 J. LI, K. KIM, and A. ELGAMAL, "Three-dimensional seismic response of a large embedded structure and induced earth pressure," Journal of Geotechnical and Geoenvironmental Engineering **146** (5), 04020025 (2020).

69 C. BOLISETTI and A. S. WHITTAKER, "Site Response, Soil-Structure Interaction and Structure-Soil-Structure Interaction for Performance Assessment of Buildings and Nuclear Structures," 2015, Multidisciplinary Center for Earthquake Engineering Research, MCEER-15-0002, University at Buffalo, The State University of New York, Buffalo, NY,

70 T. HAGIWARA and Y. KITADA, "A test to evaluate non-linear soil structure interaction", in *18th International Conference on Structural Mechanics in Reactor Technology (SMiRT 18)* (Beijing, China, 2005).

71 K. P. SUBRAMANIAN, "Soil structure interaction model and variability of parameters in seismic analysis of nuclear island connected building", in *18th International Conference on Structural Mechanics in Reactor Technology* (International Association for Structural Mechanics in Reactor Technology, Beijing, 2005).

72 T. KOYANAGI, R. KIKUCHI, M. KANECHIKA, and A. SUZUKI, "Simulation analysis of reactor buildings on Niigataken Chuetsu-oki earthquake at Kashiwazaki-Kariwa nuclear power plant", in *Transactions of the 20th Int. Conf. on Structural Mechanics in Reactor Technology* (International Association for Structural Mechanics in Reactor Technology, Finland, 2009).

73 T. SUZUKI, K. MATSUMOTO, N. NAKAMURA, K. KOSAKA, and T. KINOSHITA, "A study on influence of ground condition and surrounding building for seismic response of nuclear power plant building", in *22nd Int. Conf. on Structural Mechanics in Reactor Technology* (International Association for Structural Mechanics in Reactor Technology, San Francisco, 2013).

74 D. DATTA, J. COLEMAN, and A. H. VARMA, "Comparative analyses of contact algorithms for interface modelling in non-linear soil structure interaction", in *Proceedings of the 11th National Conference in Earthquake Engineering* (Earthquake Engineering Research Institute, Los Angeles, 2018).

75 J. COLEMAN, "Evaluation of site response, with application to nuclear structures," PhD thesis, State University of New York at Buffalo, 2019.

76 K. KIM and A. ELGAMAL, "Cut-and-cover tunnel shake table test program," 2017, University of California San Diego, La Jolla, CA, https://rosap.ntl.bts.gov/view/dot/43657/dot_43657_DS1.pdf?

77 S. L. N. DHULIPALA, A. RODRIGUEZ-MAREK, and M. BAHRAMPOURI, "Intensity measure adequacy assessment for nonlinear site response using Information Theory," Soil Dyn. Earthquake Eng. **134**, 106144 (2020).

78 C.-C. YU, C. BOLISETTI, J. L. COLEMAN, B. KOSBAB, and A. S. WHITTAKER, "Using Seismic Isolation to Reduce Risk and Capital Costs of Safety-Related Nuclear Facilities," Nuclear Engineering and Design **326**, pp. 268-284 (2018).

79 R. BALLARINI, B. GENCTURK, A. JAIN, H. ARYAN, Y. XI, M. ABDELRAHMAN, and B. W. SPENCER, "Multiple degradation mechanisms in reinforced concrete structures, modeling and risk Analysis," 2020, Idaho National Laboratory, DE-NE0008438, Idaho Falls,

80 M. S. POURBEHI, G. P. VAN ZIJL, and J. A. V. STRASHEIM, "Analysis of combined action of seismic loads and alkali-silica reaction in concrete dams considering the key chemical-physical-mechanical factors and fluid-structure interaction," Engineering Structures **195**, 263-273 (2019).

81 G. PIJAUDIER-CABOT and J. MAZARS, *Damage models for concrete*. (2001), Handbook of Materials Behavior Models, 500-512, Elsevier.

82 NRC, "Software quality assurance program and guidelines," 1993, Nuclear Regulatory Commission, NUREG/BR-0167

83 J. BUONGIORNO, J. PARSONS, M. CORRADINI, and D. PETTI, "The future of nuclear energy in a carbon constrained world - An interdisciplinary MIT study," 2018, MIT Energy Initiative, Massachusetts Institute of Technology, Cambridge, MA, USA,

84 C. C. YU, C. BOLISETTI, J. L. COLEMAN, B. KOSBAB, and A. S. WHITTAKER, "Using seismic isolation to reduce risk and capital cost of safety-related nuclear structures," Nuclear Engineering and Design **326**, 268-284 (2018).

85 C. BOLISETTI, C. C. YU, J. L. COLEMAN, B. KOSBAB, and A. S. WHITTAKER, "Characterizing the Benefits of Seismic Isolation for Nuclear Structures: A Framework for Risk-Based Decision Making," 2018, Idaho National Laboratory, INL/EXT-16-40122, Idaho Falls, Idaho,

86 C. BOLISETTI, W. HOFFMAN, S. S. PARSI, K. J. KRAMER, P. KIRCHMAN, J. REDD, J. COLEMAN, and A. S. WHITTAKER, "Risk- and cost-based seismic design optimization of advanced nuclear reactor systems", in *25th International Conference on Structural Mechanics in Reactor Technology (SMiRT25)* (Charlotte, NC, 2019).