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Light Water Reactor Sustainability Program

Demonstration of Coupled Multievent Scenario at a Nuclear Power Plant

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EXECUTIVE SUMMARY

Multievent hazard, time-based analysis is important to risk-informed decision making at existing and new nuclear power plants. Solving the multievent hazard analysis using a comprehensive time-based analytical process provides new insights beyond those analyses currently performed. The information presented in this report demonstrates an approach for setting up and solving time-based analysis in a comprehensive framework to gain risk-informed insights.

CONTENTS

ACRONYMS

DBE	Design Basis Earthquake
DOE	Department of Energy
INL	Idaho National Laboratory
NLSSI	NonLinear Soil Structure Interaction
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
NTTF	Near Term Task Force
PRA	probabilistic risk assessment
RIMM	risk-informed margins management
SASSI	System for Analysis of Soil Structure Interaction
SCDF	Seismic Core Damage Frequency
SPID	Seismic Evaluation Guidance Screening, Prioritization and Implementation Details
SSC	systems, structures, and components
SSI	Soil-Structure Interaction
US	United States

1. INTRODUCTION

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

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

These new methods and tools will be used in a risk-informed margins management (RIMM) approach to improve decision making in managing NPP safety. The focus on RIMM provides a technical basis to understand real-world external hazard scenarios (Figure 1), and inform the NPP for decision-making based on the hazard. At a nuclear facility, an external hazard is a condition that may cause a deviation in the normal operation. External hazards of interest have a primary impact on the nuclear facility that may also lead to secondary phenomena. Examples of external hazards that cause primary impact are seismic shaking, flooding, and high winds. Examples of secondary phenomena induced by a seismic scenario are dam and levy failure, landslide, internal flood, and internal fire. These types of hazards complicate the determination of safety in any complex facility.

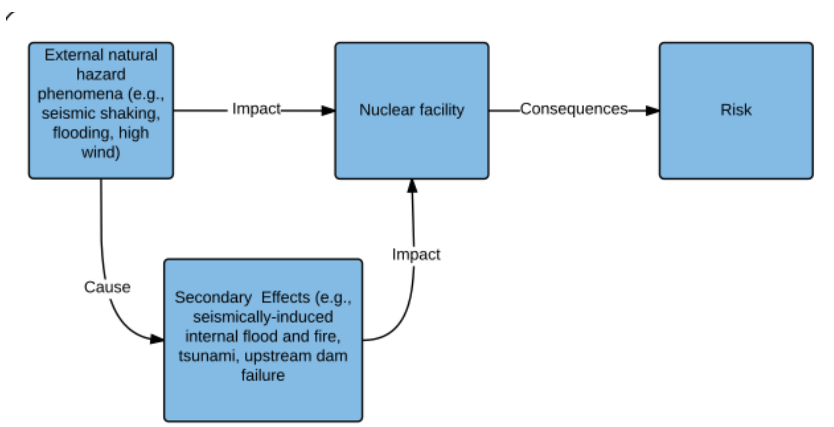

Figure 1: Real world risk propagation at NPPs

This report discusses the approach of how to perform a coupled, seismic and flooding, multievent risk-informed analysis by using technology to incorporate physics into probabilistic scenarios. Presented in the following sections are the need for multievent risk-informed analysis, the tools needed to perform the analysis, and an example of solving a demonstration problem.

2. NEED FOR MULTIEVENT SCENARIO METHODS AND TOOLS

The nuclear industry is currently addressing the Near Term Task Force (NTTF) recommendations. These recommendations focus on both seismic and flooding hazards. This indicates that these external hazards should be considered using a coupled approach in time domain to determine failure and success paths. The first NTTF recommendation dealing with seismic and flooding, recommendation 2.1, states,

> **Order licensees to reevaluate the seismic and flooding hazards at their sites against current NRC requirements and guidance, and if necessary, update the design basis and SSCs important to safety to protect against the updated hazards.”**

In response to this recommendation, EPRI has developed a document titled “Seismic Evaluation Guidance Screening, Prioritization and Implementation Details (SPID) for the Resolution of Fukushima Near-Term Task Force Recommendation 2.1: Seismic,” to provide guidance for conducting seismic evaluations.

On February 15, 2013 the NRC provided its endorsement of the EPRI-1025287 document. This document is intended to provide a process NPP owners can follow to meet the NTTF recommendation 2.1. The document includes a screening process that evaluates updated site-specific seismic hazard (based on the CEUS-SSC study). The screening process includes the following steps:

1. NPPs develop new site specific hazard curves based on CEUS-SSC;
2. Utilize screening process to eliminate certain plants from further review;
3. Perform seismic PRA (SPRA) or seismic margins assessment for NPPs;
4. Submit proposed actions to evaluate seismic risk contributions (update seismic analysis where necessary).

The updated site-specific hazard curves (item number 1) have potential for higher magnitude, higher frequency content accelerations. This would cause site-specific seismic PRA parameters such as peak ground acceleration (PGA) to increase. The increase creates a potential for the core damage frequency numbers in these SPRA’s (item number 3) to increase beyond what NRC sets as an acceptable limit. These exceedances create an opportunity to implement more advanced approaches that include consideration of multiple event scenarios to reduce uncertainties in numerical models.

Another NTTF recommendation that will have a continual impact on external hazard risk at nuclear power plants is recommendation 2.2. This recommendation requires that every 10 years NPPs address any new and significant information related to the seismic hazard:

> **Initiate rulemaking to require licensees to confirm seismic hazards and flooding hazards every 10 years and address any new and significant information. If necessary, update the design basis for SSCs important to safety to protect against the updated hazards.**

Traditional approaches for evaluating seismic and flooding are stove-piped and typically do not consider the coupling effects. The demonstration proposed in this report would couple together both seismic and flooding time-based tools to evaluated failures and successes. These methods and tools could be used by

NPP owners who are resolving NTTF recommendation 2.1 and may find that the traditional approaches have excessive uncertainty and therefore may need advanced methods and tools to reduce and effectively manage this uncertainty. The proposed advanced external hazard methodology and tools would provide the industry with the ability to identify and resolve issues.

3. MULTIEVENT SCENARIO PROBLEM DEFINITION

The early demonstration discussed herein proposes to solve two external hazards, seismic and flood. The early demonstration will demonstrate the process for solving a seismically induced flood using the RIMM process. Elements of the process include development of a generic NPP at a generic site, and generic levy and seismic hazard. The problem is initiated with multiple (potential) seismic events that produce ground motion at the generic site. These ground motions will produce probabilities of SSC failures at the NPP and levy. Based on probabilities of failure on piping systems and of the levy, flooding analysis will be run in those locations. Figure 2 visually shows the problem definition.

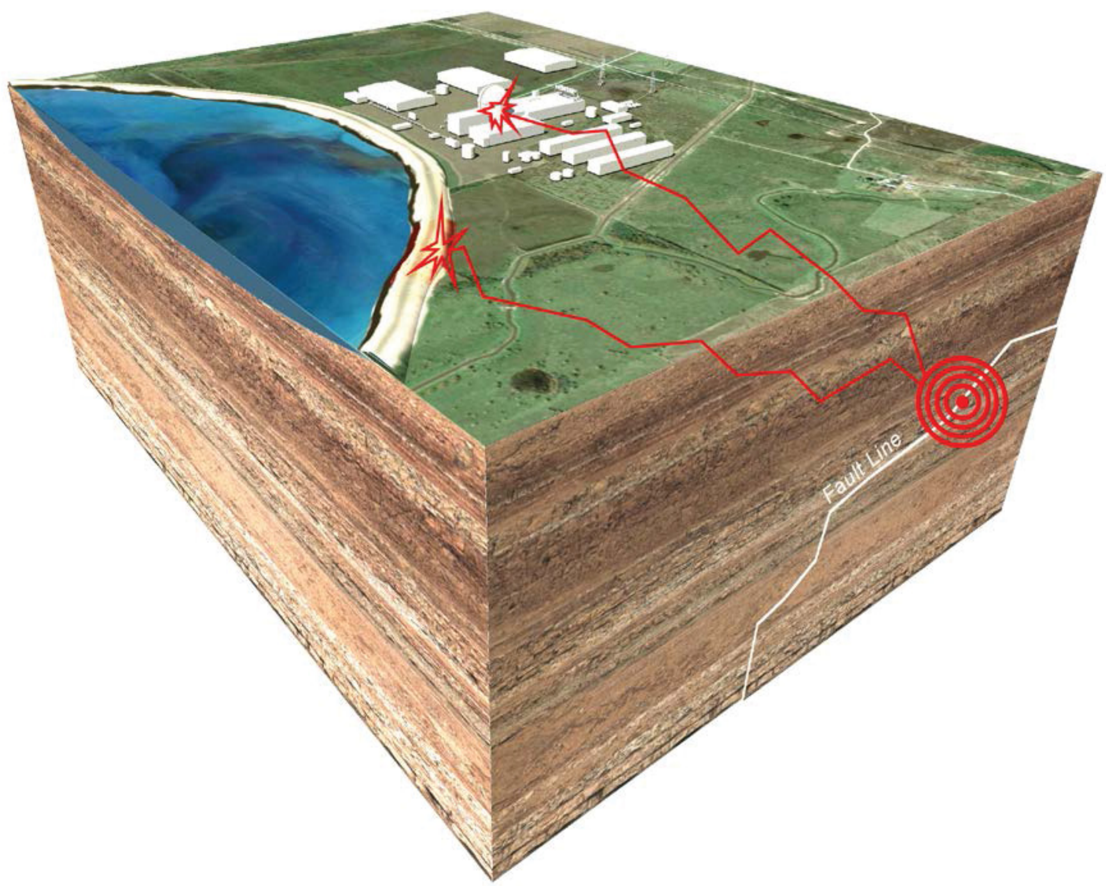

Figure 2: Problem definition of early demonstration. Initiating event is an earthquake that causes probability of failure of a levy holding back water and at NPP internal piping.

The RISMC Toolkit provides the numerical tools needed to solve the problem defined above. As shown in Figure 3 the Toolkit provides the tools needed to perform a seismic PRA using nonlinear soil-structure interaction (NLSSI) tools, secondary flooding analysis using advanced flooding tools, and to quantify all scenarios in a risk-informed decision making process.

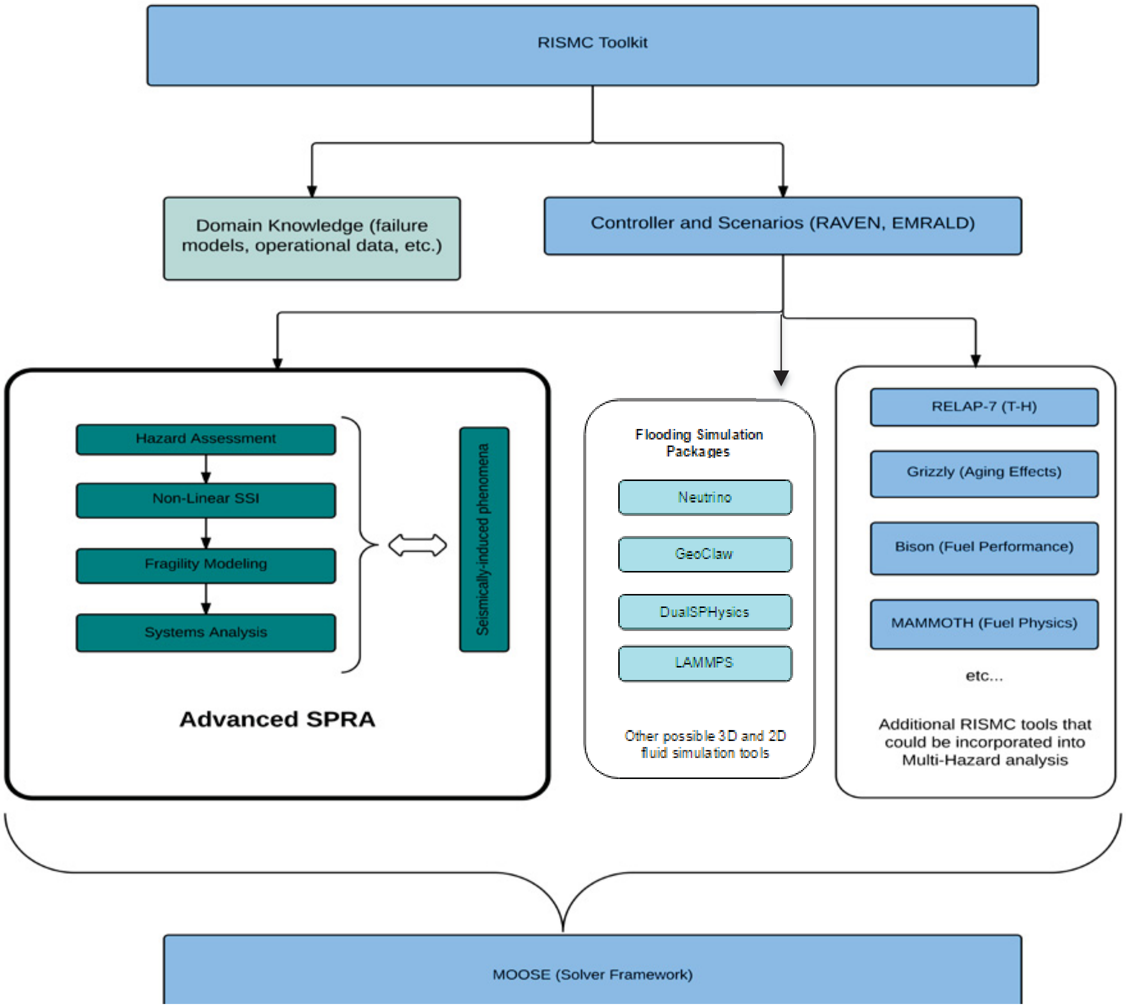

Figure 3: RISMC Tools

Each scenario-based analysis process will follow the general event tree structure shown in Figure 4. During the scenario evolution, the scenario controller applies the appropriate physics needed to solve the time-based problem. For instance, if an initiating scenario earthquake causes large enough strains in the levy (or dam) to cause probability of levy failure to be high, than the secondary flooding analysis (representing that failure and outcome) will be run. Strain levels in the levy for the given scenario will be determined using NLSSI analysis. The NLSSI analysis will also model probability of failure of the internal piping systems in the NPP since it can represent the earthquake energy transfer from the soil to the structure containing the piping system. If the probability of failure is high enough related to the piping failure(s), a secondary flooding analysis will be run specific to that failure. Based on the model runs scenario, various flooding outcomes will be determined. Figure 4 shows one such scenario path through the event tree where the outcome leads to plant damage (a possible economic impact).

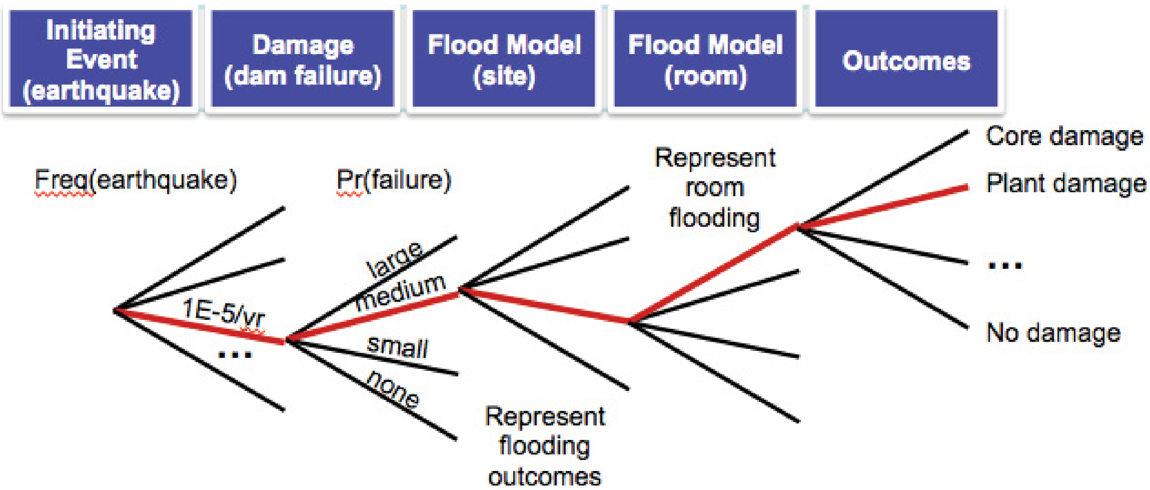

Figure 4: Event tree of scenario based seismic-flooding problem.

4. MULTIEVENT SCENARIO TIME BASED PROPAGATION

The RISMC toolkit will leverage physics based numerical tools and advanced methods to solve scenario based problems in the time-domain. Traditional approaches for determining external hazard risk at NPPs do not follow time-based approaches and therefore leave out information that could be used to inform decision-making. The time-based process followed in the seismic-flooding early demonstration problem is shown in Figure 5.

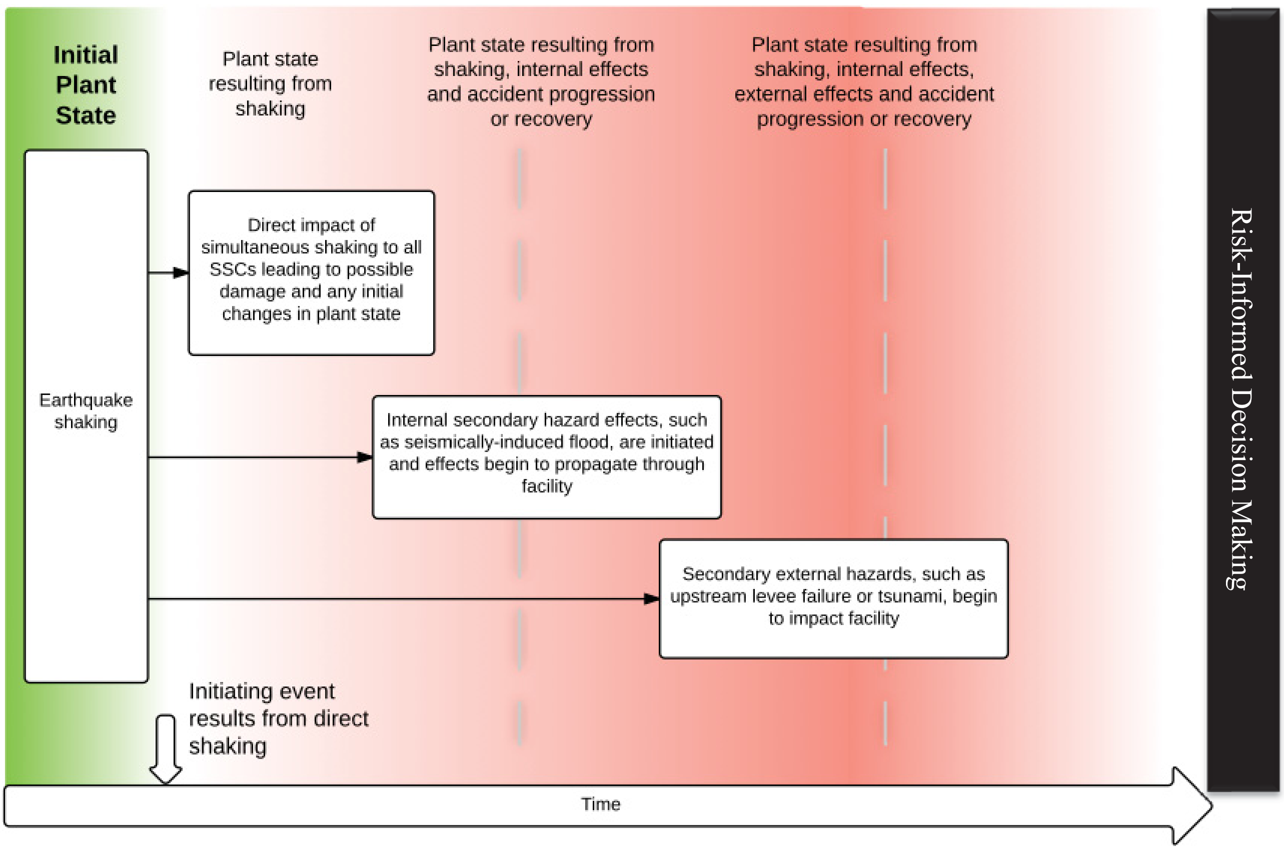

Figure 5: Time based sequence of events for the seismic-flooding scenario

4.1 Advanced Seismic Analysis

The seismic analysis portion of this demonstration is focused on understanding the effect of local nonlinearities on the probability of failure of both the levy and internal NPP piping systems. To accomplish this demonstration, it is necessary to develop seismic scenarios that include quantification of uncertainties in seismic wave propagation from source to site. This information for the simulation is contained in the seismic hazard curves developed for multiple NPP sites. To develop scenarios for the seismic NLSSI analysis, the seismic hazard curve is binned into the appropriate number of bins, 30 sets of time histories are developed for each bin, and the appropriate numbers of scenarios are analyzed. This process explicitly captures the uncertainty information used to developing the site-specific seismic hazard curve.

NLSSI numerical simulation tools are used to run site-specific earthquake scenarios at both the NPP and the levy. Figure 6 shows a model run of a generic NPP placed on the Vogtle soil site and Figure 7 shows a coupled Lagrangian-Eulerian numerical model run of the levy and water. These simulations are used to determine the probability of failure of the internal NPP piping systems and levy. Figure 8 shows stress distribution in the levy at a time step during the NLSSI model run.

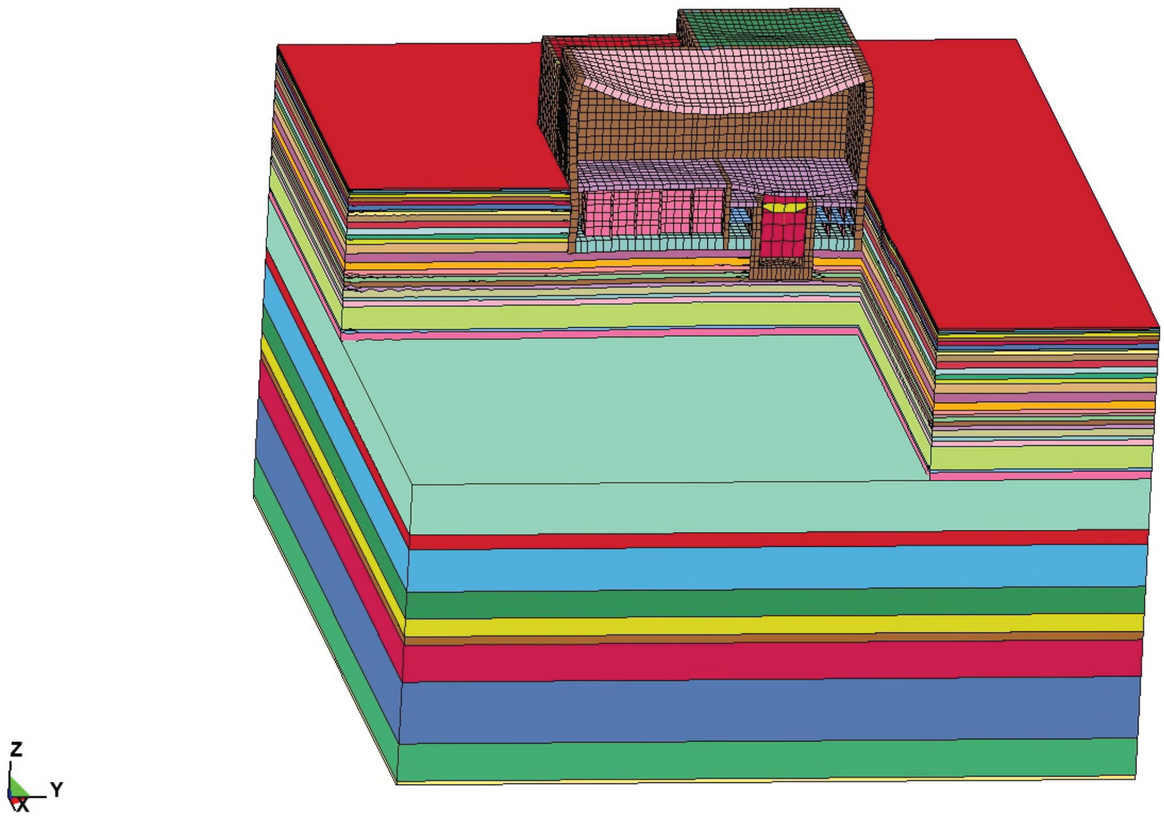

Figure 6: NLSSI analysis of generic NPP placed on the Vogtle soil site. Model run used to determine P(f) of internal piping systems.

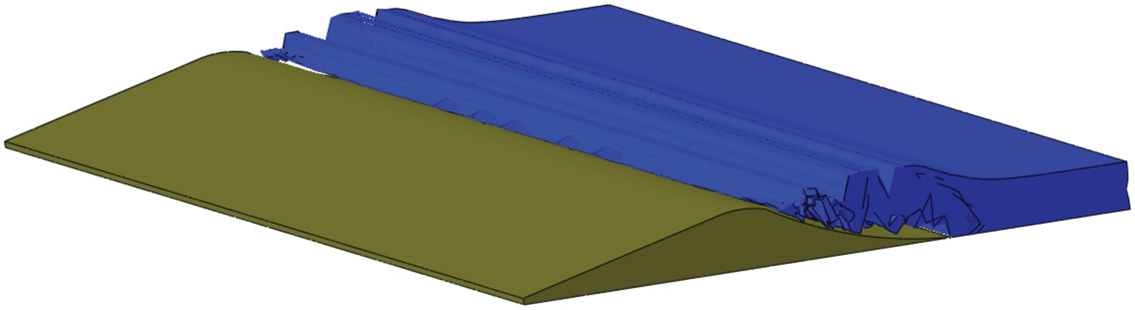

Figure 7: Coupled Lagrangian-Eulerian NLSSI analysis of levy. Used to determine strains in the levy due to earthquake loads and dynamic fluid pressure

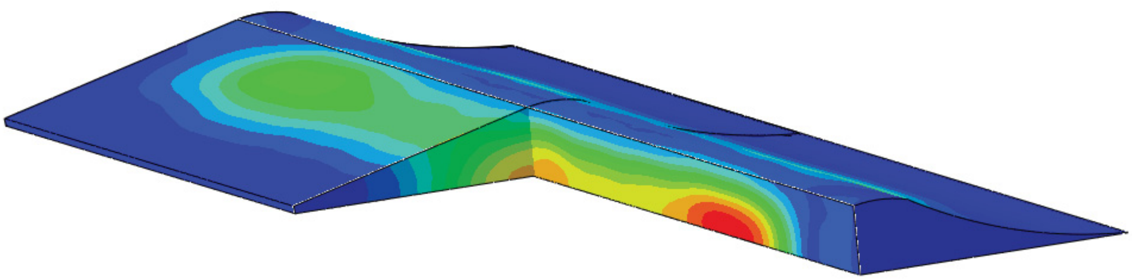

Figure 8: Stress distribution in the levy due to dynamic earthquake and fluid loads.

4.2 Advanced Flooding Analysis

In order to perform advanced flooding analysis, several preparatory steps need to be performed. These steps include developing a general site model for the large scale events, facility critical area models, and identifying components susceptible to 3D simulation interaction failures.

All simulations are done on hypothetical facilities and for example purposes only. For this problem, we are using existing terrain with a levy holding back water to represent an above grade cooling pond for a NPP.

4.2.1 Site Modeling

The terrain for the site was generated using an INL-developed tool that queries altitude data based on existing topography to generate a polygon model. The web based terrain mapping tool can be used to generate a low detail map of most land areas on the earth (see Figure 9).

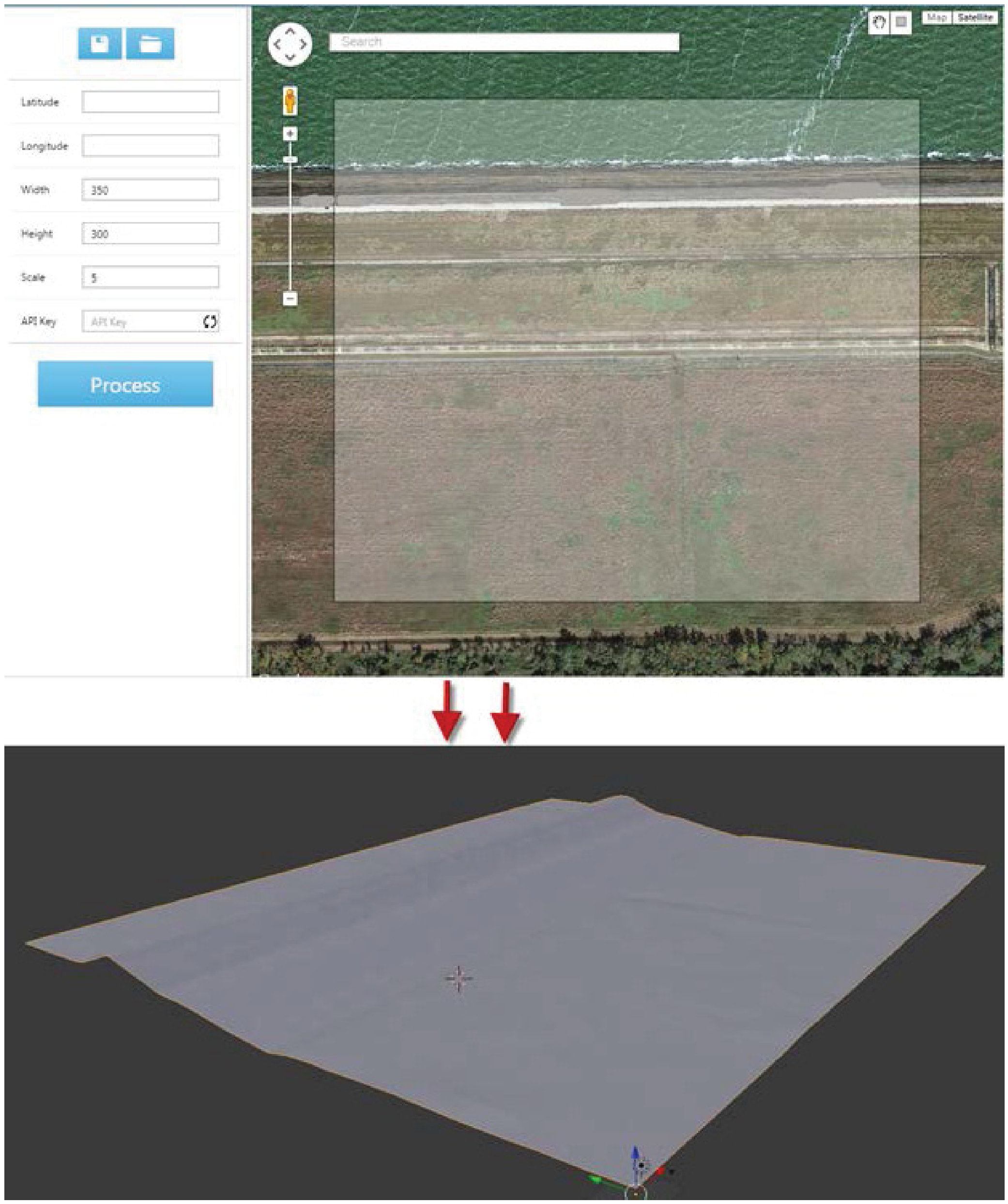

Figure 9: Terrain Map Construction Using Web-Based Mapping Tool.

Buildings and other features, based upon common NPP designs, were modeled and added to the terrain for a complete site to be used in the main simulations (see Figure 10). These methods can also be used to construct a model with specifications matching an actual facility.

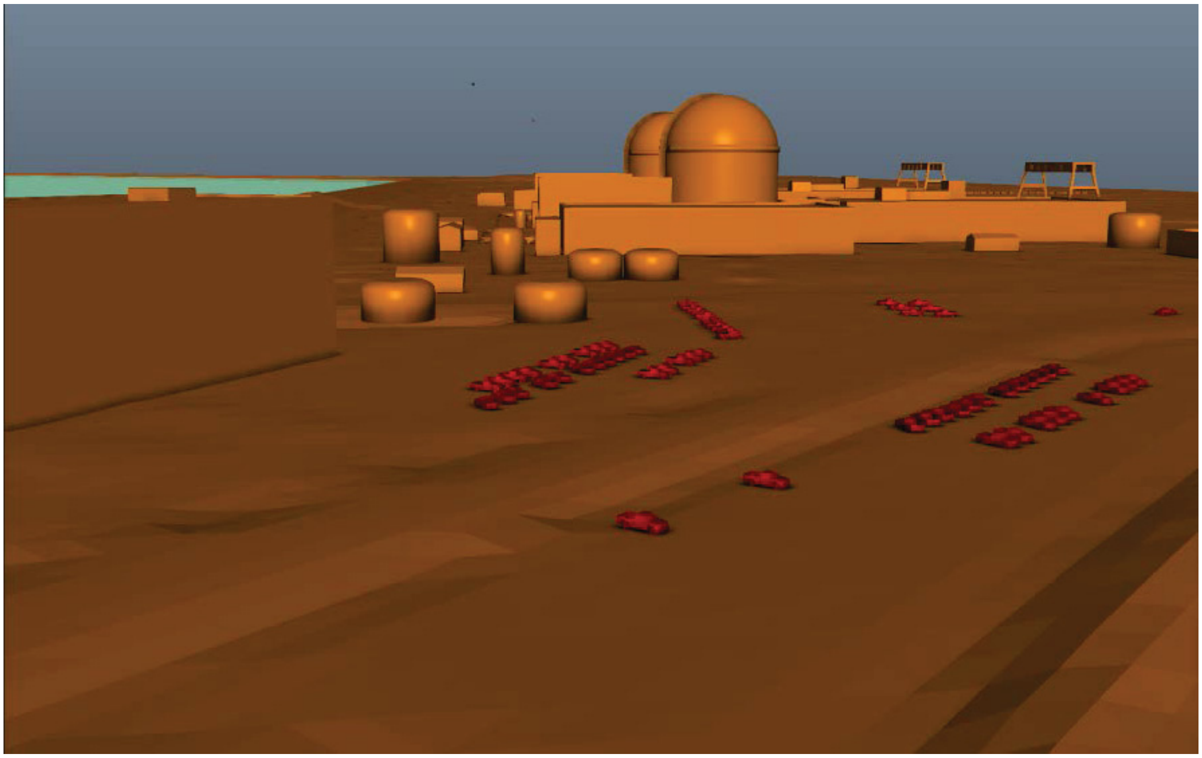

Figure 10: 3D model of NPP facility on a terrain map (the levy is shown in the upper left corner).

4.2.2 Dam Break Fluid Simulation Method

After developing a site model, external events can be simulated at the virtual facility. The 3D simulations for flooding are done using the Neutrino tool, a physics engine with advanced particle-based methods based upon Smoothed Particle Hydrodynamics.

For the event tree sequence shown previously, a levy failure with the failure parameters calculated from the previous section needs to be simulated. To accomplish this simulation, a variable particle emitter that can match the size and flow parameters of the erosion model was developed (see Figure 11). Using this new emitter tool allows us to run multiple simulations with varying failure scenarios (different levy failure magnitudes) guiding the results.

The input to this variable emission system is data from an erosion model as an file containing the time and discharge flow rate information along with the width and height of the breach. The variable flow rate emitter takes the input at the particular time and computes the emission velocity of the particles in the direction of the flow (normal of the flow plane emitter). However in order to make the fluid conserve mass as well as to prevent excessive splashes, queries are made to the sorted hashing collider for room to insert the particles at the current time step. New particles are inserted into the system by the emitter only if there are no overlaps between neighboring particles. This method guarantees stability and therefore prevents excessive splashes and small time steps. Adaptive time stepping in the solver prevents excessive gaps between particles in the flow so as to conserve volume thereby creating a steady flow. Due to the limitations in the adaptive time stepping algorithm used, there could be cases where the flow velocity is excessive enough to create gaps. An algorithm to tackle such particle deficiencies is currently being investigated.

The variable flow rate emitter also has an option to read the height of the fluid exerting the pressure on to the emitter thereby creating a value for depth averaged hydrostatic pressure and therefore a flow velocity. This method would average the pressure over the height of the emitter itself. Additional information on the physics behind the flooding methods and coupling are described in “3D Simulation of External Flooding Events for the RISMC Pathway.” [INL/EXT-15-36773]

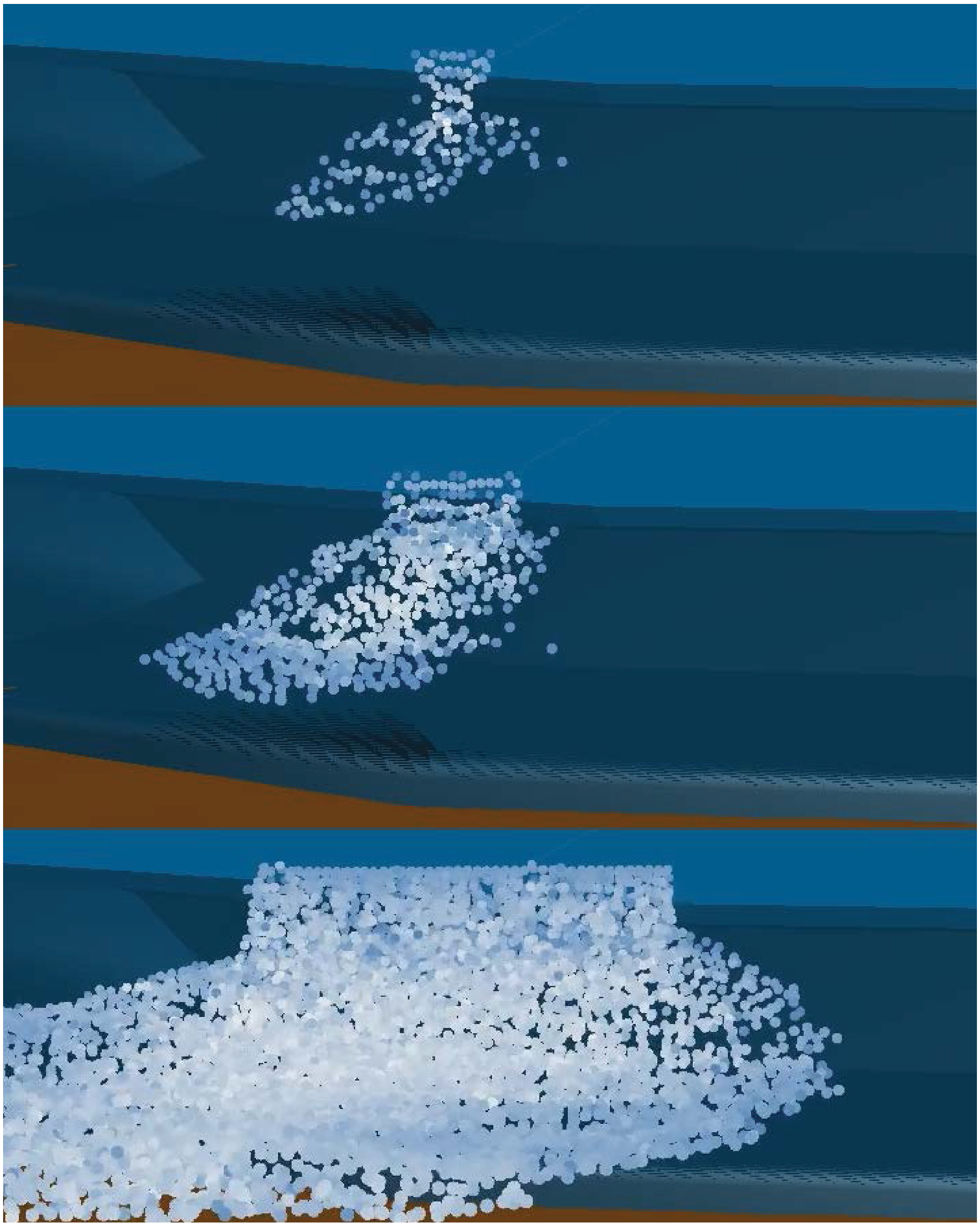

Figure 11: Variable particle emitter progress matching an erosion model.

After adding the variable particle emitter to the levy failure location in the model, the site facility can be simulated for this failure external event (see Figure 12). Critical site attributes and components that need to be tracked must be previously identified and included in the 3D model. Note that not every component in the NPP needs to be represented, just the ones that may play a role in the seismic or flooding scenarios. These items would include outside components such as electrical panels, venting, orifices and doors. Measurement tools in the simulation can measure water contact, water pressure, debris impact force, and flow rate through openings, all over time, and for any location in the model.

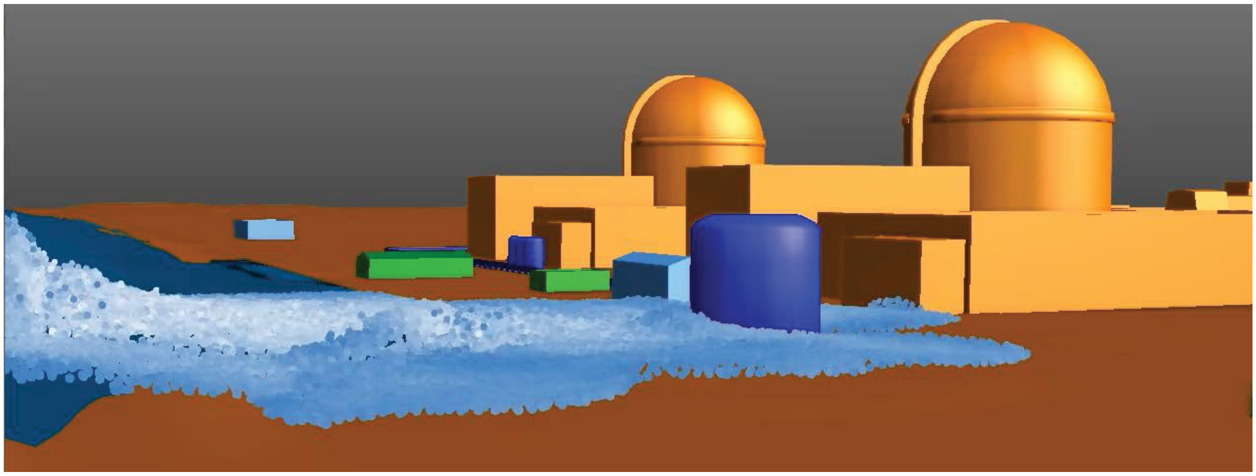

Figure 12: Flooding simulation from a dam failure on a NPP.

4.2.3 Room Flooding Model

For this Event Tree Sequence (room flooding), we get interior flooding from two possible sources, seismic-induced pipe rupture and room orifice/penetration inflow. Many other sequences or seismic scenarios such as door failures could be set up to contribute to flooding and be analyzed, but we will just demonstrate this sequence.

4.2.3.1 Room Modeling Method

To demonstrate internal modeling methods of existing facilities, we used an actual room with similar components and features of what could be in a NPP (but is not from a NPP). To construct this model, a 3D scanner (Faro Laser Scanner) was used to generate a point cloud representation of the room (see Figure 13).

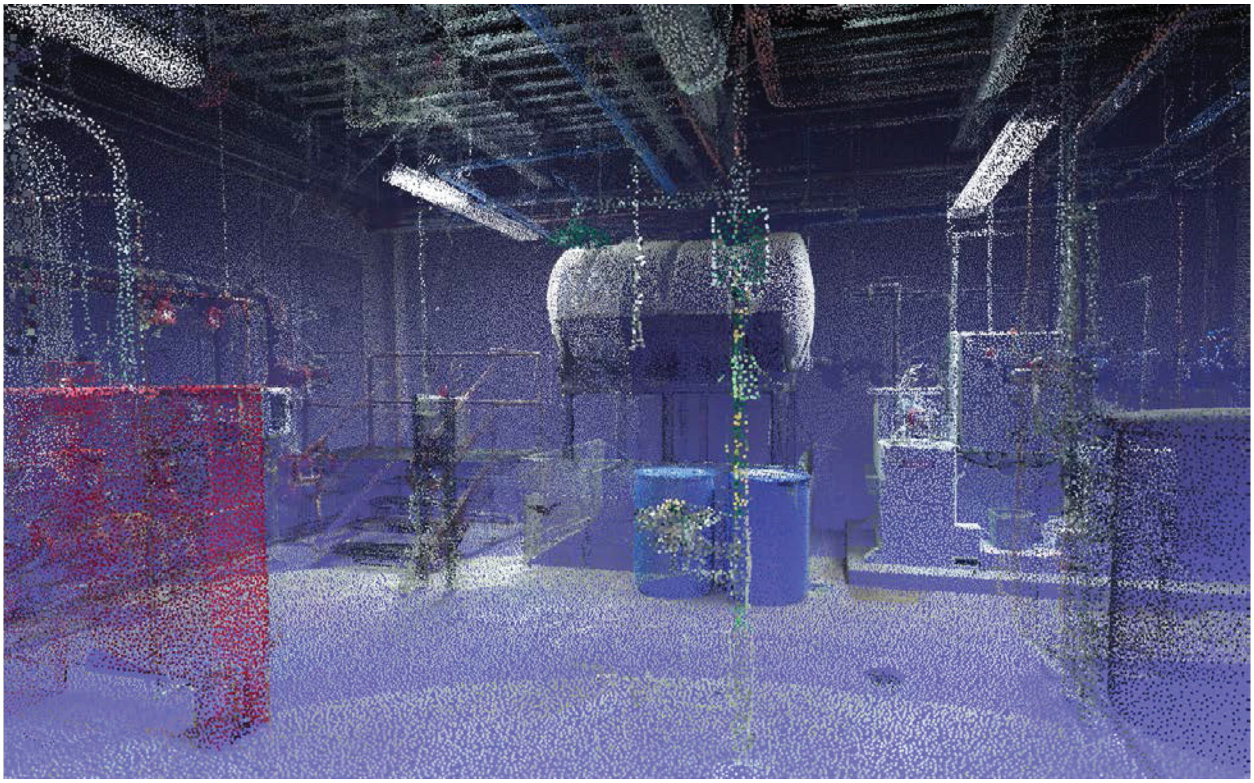
Figure 13: Point cloud of a chemical room taken using the Faro laser scanner.

Point cloud data cannot be used directly in simulations, polygon mesh models are needed. Several automated steps were developed and combined to convert the point cloud into a usable mesh model.

- Clean the point cloud data
- Compute the object "normals" (the direction of the points face)
- Surface identification and construction
- Component point segmentation
- Component polygon construction

After running these steps, a basic but spatially accurate polygon mesh model with the room structure and individual components is produced (see Figure 14). Even with only this initial development, much of the time consuming aspects of modeling has been eliminated. Further work will improve component identification shape construction.

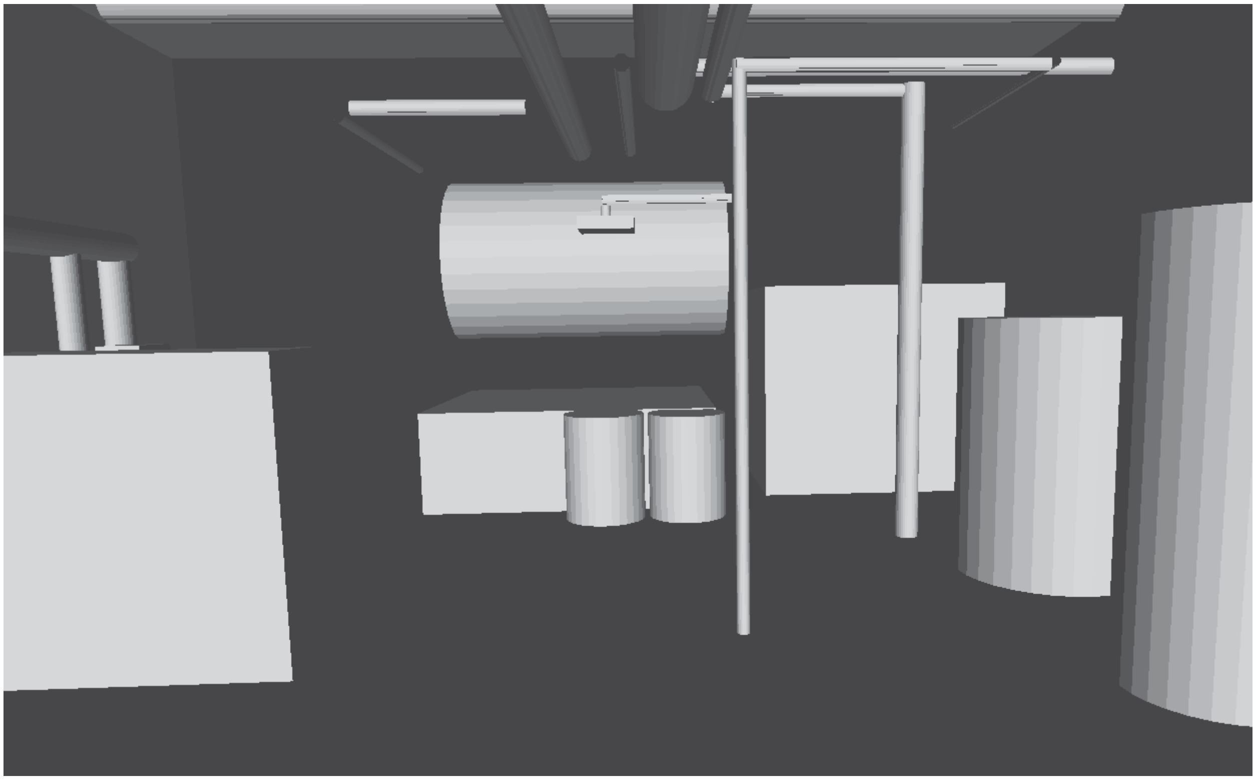

Figure 14: The polygon mesh model auto created from the point cloud in Figure 13.

4.2.3.2 Flooding Methods

Inundation measurements from the site simulation, such as the flow rate through orifices, are used to determine the flow rate into the internal simulations. A particle emitter is attached to each opening and data from the site simulation determines the flow rate to these emitters. For this room and event, flooding enters the room from the gap under the entry door.

Data from the sampled seismic event can cause other flooding events. Pipe stress analysis can indicate the likelihood and location of pipe fracturing. If a failed pipe is a water supply line, the secondary effect would be localized flooding in the 3D simulation. A fluid particle emitter can be attached to the facture location on the pipe. The flow rate can then be dynamically adjusted over time according to fracture size, pressure, and available volume.

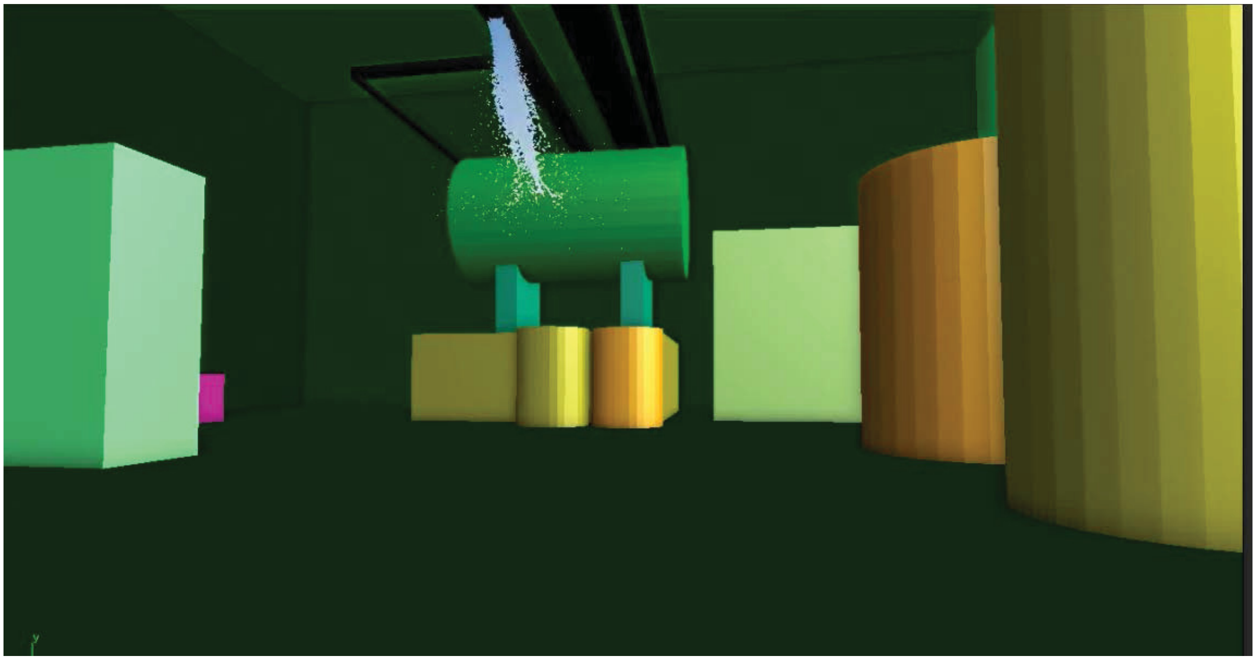
Figure 15: Simulated pipe rupture from a seismic event.

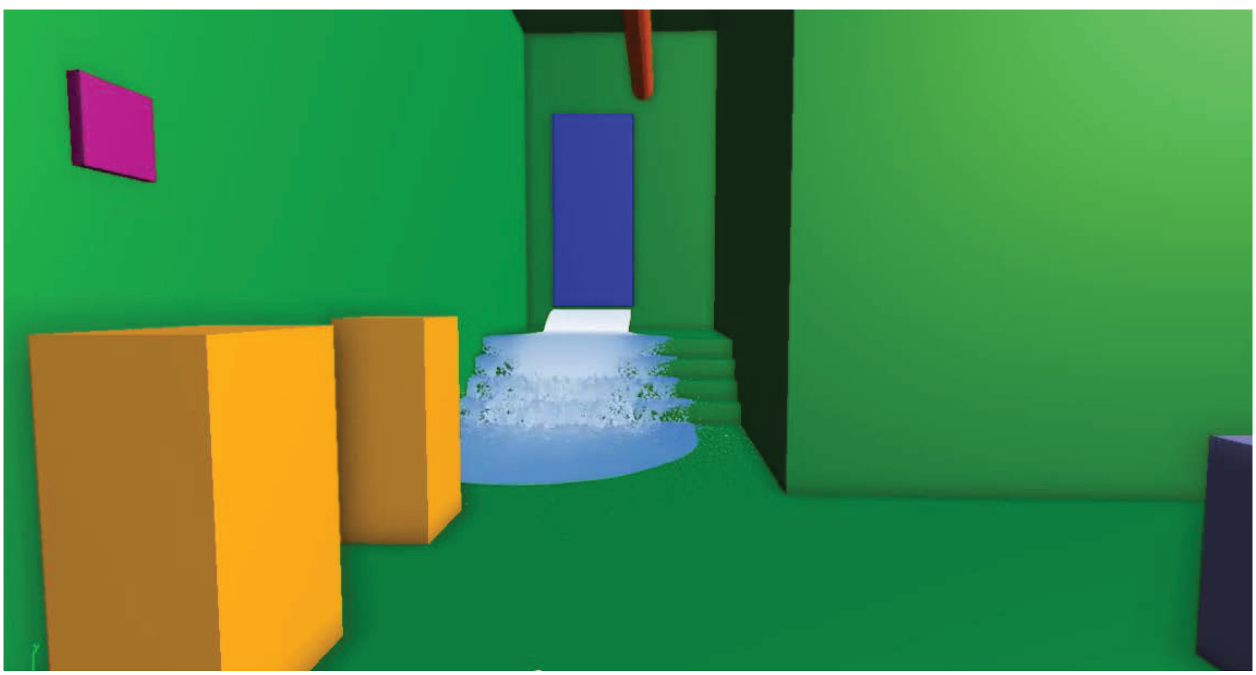
Figure 16: Simulation of secondary internal flooding from external dam break through door penetration.

In addition to the existing simulation, other substances besides water could also be simulated and tracked. Dissimilar fluid interactions such as oil and water are also representable during 3D simulation. Also, the transport and tracking of debris due to water flow is possible.

4.2.3.3 Component Failure

Items in the model are identified for various methods of failure. A pump may fail from water spray or contact. However, a water resistant electrical panel may be able to withstand spray, but inundation may cause failure due to water pressure. Since we currently do not have fragility models for flooding component failures, the failure criterion is a conservative assumption that has been made. With further research and component testing, an improved fragility model could be developed.

Failures are determined during the simulation by keeping track of the local environment around each component. For each time step, if the simulated water physics indicates a property change of a component, the component's failure state is analyzed for failure. All failures and their times are logged and/or sent back to the controller program to be incorporated with other analysis processes, contributing to the final analysis outcome.

5. Conclusions

Discussion in this report has been on development and demonstration of advanced methods and tools for solving time-based, multiple-hazard scenarios. Information gathered from the scenarios will be used to provide risk-information that can inform decision makers on where to allocate resources. Based on the risk-informed information provided by the time-based analysis runs, NPP owners can make appropriate decisions on what risk mitigation approaches are necessary, if any. Some of these potential modifications may be related to emergency response facilities such as FLEX, operating procedures in NPPs, modifications to systems and components inside NPPs, which could include:

- Modifying existing connection hardware
- Reducing inspections for components that are not important to margin
- Stiffening systems and components (more pipe hangers, ….)
- Seismic isolation of systems and components
- Providing additional levels of redundancy and/or diversity for vulnerable systems/components

6. References

EPRI-1025287, "Seismic Evaluation Guidance, Screening, Prioritization and Implementation Details (SPID) for the Resolution of Fukushima Near-Term Task Force Recommendation 2.1: Seismic," November 2012.

INL/EXT-15-36773, Steven Prescott, Diego Mandelli, Ramprasad Sampath, Curtis Smith, Linyu Lin, “3D Simulation of External Flooding Events for the RISMC Pathway,” September 2015.

INL/EXT-1536101, Ronaldo, Coleman, Smith, Prescott, Kammerer, Youngblood, Pope, “Industry Application External Hazard Analyses Problem Statement” July 2015