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Compounding Risks from Natural Phenomena Hazards at U.S. Department of Energy Facilities

September 2022

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Prepared for the U.S. Department of Energy
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Summary

U.S. Department of Energy (DOE) facilities are exposed to adverse effects of natural phenomena hazards (NPHs). While the DOE Standard (STD) 1020-2016 provides criteria and guidance for assessing these effects, certain gaps exist, particularly related to combinations of NPHs that can compound the risk to DOE facility assets. This report describes a methodology to systematically consider compounding NPHs, identifies gaps in DOE-STD-1020-2016, and recommends ways to update the standard.

At any given DOE facility, NPH effects depend on the site-specific hydrometeorologic and geoseismic conditions. Therefore, compounding NPHs should be determined using site-specific assessments. DOE facility assets generally are assessed using site-specific NPHs with the assessment usually limited to the DOE site extents. However, an inventory analysis of a selected DOE facility also revealed that some assets may have off-site dependencies. These dependencies may be part of threat pathways that can lead to on-site asset failures because of off-site effects of the same NPHs that also affect the DOE site. These threat pathways usually are not accounted for in traditional NPH analyses.

The report also describes the effects of duration of NPH effects. Duration of disruption, particularly for off-site dependencies can lead to on-site asset failures, disruption of evacuation roadways, and consequent human health and safety effects. Finally, the report recommends some considerations for updating DOE-STD-1020-2016 to include explicit consideration of compounding NPHs.

Acronyms and Abbreviations

BBN	Bayesian Belief Network
DOE	U.S. Department of Energy
GMPE	ground motion prediction equation
IPCC	Intergovernmental Panel on Climate Change
NPH	natural phenomena hazard
O	Order (as in DOE Order)
STD	Standard (as in DOE Standard)
SSC	structures, systems, and components

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1.0 Background

U.S. Department of Energy (DOE) Standard (STD) 1020-2016 provides criteria and guidance for meeting the natural phenomena hazard (NPH) requirements of DOE Order (O) 420.1C, Chg. 1, Facility Safety. Its purpose is to make sure structures, systems, and components at DOE facilities will perform their safety functions during and after NPH events.

Per Title 10 of the Code of Federal Regulations Part 830, DOE-STD-1020-2016 defines two categories of structures, systems, and components (SSC):

- *Safety-class SSCs*. These SSCs provide preventive or mitigative functions that are necessary to limit radioactive hazardous material exposure to the public.
- *Safety-significant SSCs*. These SSCs are not designed as safety-class SSCs, but they provide preventive or mitigative functions that contribute significantly to defense-in-depth and/or worker safety.

Together, safety-class and safety-significant SSCs collectively are called safety SSCs. In this document, we use the two more specific designations—safety-class SSCs and safety-significant SSCs—where the distinction is important. Where the more specific designations are not needed, the collective designation, SSC, is used.

DOE-STD-1020-2016 lists the following six NPHs:

1. Seismic
2. Wind
3. Flood
4. Lightning
5. Precipitation
6. Volcanic.

While some combinations of NPHs are listed in DOE-STD-1020-2016, it is not clear how these combinations affect DOE facility SSCs. The motivation for this work is the Fukushima accident that was a result of compounded risks from both on-site hazards (an earthquake generating a tsunami that reached SSCs, resulting in a loss of emergency diesel generators) and off-site effects from the same NPH (extended loss of off-site power and subsequent exhaustion of backup batteries). To improve nuclear safety, we identified risks to selected SSCs via multiple pathways under a hypothetical compounding NPH scenario.

2.0 Compounding Natural Phenomena Hazards and Associated Risks

At DOE facilities, interactions between natural hazards and facility infrastructure are considered for design, operations, and emergency planning purposes. Currently, NPH analysis and design criteria are described in DOE-STD-1020-2016 and address the following NPHs: seismicity; high winds; floods, including those from seiches and tsunamis; precipitation; and volcanism. Depending on the types and the functions of SSCs at a DOE facility, they may be exposed to multiple NPH events. It is quite common to encounter infrastructure design guidance documents that strategize handling of a single hazard at a time. Hazards associated with an event as well as across multiple events could interact with engineered infrastructure. Compounding hazards often are omitted from risk assessments because they are assumed to be too complex to consider, not obvious for a given infrastructure, or the possibility of such interactions occurring. Note that the interactions referred to here emphasize those between hazards and facility infrastructure and not among the hazards themselves, although such complexity could be considered if the phenomenon is well understood, and the epistemic uncertainties could be discerned. Having a structured methodology and acknowledging the influence of compounding hazards are pivotal to infrastructure resilience and gives a path to the development of improved guidance.

We propose a methodology and an application framework to illustrate the modeling of such compounding hazards for critical infrastructure. Examples using hypothetical data also are provided in addition to the methodological formulation. Assets belonging to an infrastructure (i.e., infrastructure assets) are susceptible to risk events when they get exposed to stresses from NPHs. In some cases, there is a single natural hazard that is associated with multiple stressors. A typical example is a hurricane with its high winds, storm surges, and heavy precipitation. There might as well be disparate events of separate natural phenomena, though extremely rare, happening simultaneously. As an example, two different NPH events might be encountered in which one event is a consequence of the other (e.g., a tsunami following an earthquake). A fire following an earthquake is another example where a fire results because of infrastructure damage after an earthquake; this combination is addressed in a probabilistic risk assessment (see ASME/ANS RA-Sa-2009). Another asset of concern could be a pipeline carrying flammable gases. Although there is large epistemic uncertainty in understanding the cause-consequence logic with compounding events, carrying out a risk analysis considering such events as independent occurrences may severely underestimate the compound risk.

The ability to model such events in the risk context is not new (e.g., Sadegh et al. 2018; Leonard et al. 2014; Zscheischler et al. 2018). Regardless of this previous work, some gaps exist in the methodological treatment of models, especially when compounding events affect engineered infrastructure, such as SSCs at DOE facilities. In this work, our focus is primarily on external floods in combination with seismic events to illustrate the compounding nature of on-site hazards and off-site effects that can lead to novel, currently unaccounted for, risk pathways at DOE facilities.

One of the motivations for this work was the severe accident at the Fukushima Daiichi Nuclear Power Plant in 2011. The precursor to this accident was a severe earthquake that occurred in the Pacific Ocean offshore from the nuclear facility. Subsequently, a tsunami caused by the earthquake affected both on-site SSCs (e.g., loss of emergency diesel generators) and off-site plant-dependent services (e.g., extended loss of power from off-site sources). These on-site and off-site losses eventually resulted in failure of backup systems (e.g., complete discharge of backup battery energy supply systems). The Fukushima disaster clearly demonstrated the need to comprehensively identify and document all off-site dependencies that may constitute threat pathways for nuclear facilities. Some backup systems may not even be classified as SSCs, yet their loss contribute to a threat pathway that may be activated under rare compounding phenomena events with significant risk contribution.

2.1 Review of Relevant Literature

We first refer to published literature for a few examples where a single NPH disables critical infrastructure systems leading to societal risks where a probabilistic treatment is deemed appropriate (Nogal et al. 2017). Yang and Frangopol (2020) discussed corrosion impacts of hurricane on deteriorating coastal bridges. Zuev and Beer (2017) edited a special journal issue dedicated to the reliability, risk, and uncertainty of complex engineered networks with some of these networks being susceptible to NPH. A similar special collection was compiled by Francis and Attoh-Okine (2018) on uncertainty analysis of built infrastructure under the influence of climate change. Mortagi and Ghosh (2020) placed special emphasis on aging infrastructure vulnerable to NPH, Ayyub and Walker (2022) linked the need for resilient infrastructure design with climate change in their editorial article, and Stewart and Deng (2015) introduced the term climate adaptation engineering to address the broader scope of climate change and resilience studies. Studying the interaction between NPHs and infrastructure systems enables developing recommendations to build resilient infrastructure (e.g., metro-rail transit networks) (Saadat et al. 2020) and for sustainability quantification within a risk and valuation framework (Webb and Ayyub 2017). Some organizations consider pandemics as NPHs, and on that basis, studies such as the one by McDonald et al. (2018) developed infrastructure resilience models against pandemic outbreaks. A built-infrastructure/NPH-interaction study could be instrumental in deciding whether infrastructure upgrades offer economic and resilience incentives, given local hazard conditions (Savvidis et al. 2019).

While there are generic frameworks and methodologies discussed in the literature, some studies are focused on specific applications. Yamano et al. (2018) raised concerns about ash hazards to critical systems (such as nuclear reactors) in the aftermath of a volcanic eruption. Wang and Zhang (2020) assessed power grid seismic resilience in terms of component deterioration and dependencies. Likewise, Scherb et al. (2017) explored common-cause events and cascading failures associated with power grid networks. Guerra and Abebe (2019) developed a theoretical framework to bolster city infrastructure resilience against flooding hazards. Abdollahzadeh and Rastgoo (2015) used fault-tree and event-tree approaches to assess the risk of bridge construction activities when exposed to NPHs.

A tradeoff between ignoring compounding hazards and undertaking a complete dependency analysis is an assessment that considers complexities only to a level sufficient for risk-informed decision-making. Nevertheless, compounding events are considered high-impact, low-frequency events whose risk quantification is challenged by multiple factors including an understanding of interactions (Wuebbles et al. 2017). There is a distinction between multi-hazard and compounding hazard events. While the former area refers to disparate hazard types affecting an infrastructure potentially at different time scales, while the latter area emphasizes a possible correlation or causation between events. An example of a multi-hazard risk assessment is the resource allocation determination by Veeramany et al. (2017) in the analysis of grid assets affected by potential earthquakes and geomagnetic storms. Some examples of compounding events are listed below:

- Sea level rise combined with heavy precipitation (Hoegh-Guldberg et al. 2018)

- Heavy precipitation and storm surge (Bevacqua et al. 2019)
- Wildfire and extreme heat events (Burillo 2018)
- Earthquake and fire (Mousavi et al. 2008)
- Extreme rainfall and flooding from high tide (Lian et al. 2017)
- Flooding and wind damage (Halliday et al. 2020)
- Sea level rise and land subsidence (Esteban et al. 2020)
- Sea level rise and tropical cyclones (Woodruff et al. 2013)
- Heavy precipitation over burned areas causing flash flooding (AghaKouchak et al. 2020).

The ability to model such events, in the context of risk assessment, is not new, although some gaps exist in the methodological treatment of the models, especially when compounding events affect engineered infrastructure. Apart from a general methodology to model such phenomena, we focus on earthquake-induced dam breaches that subsequently result in inundation of infrastructure. Sadegh et al. (2018) proposed a copula and Bayesian inference-based multivariate model for multiple hazards that could potentially occur either concurrently or in succession. They chose the copula methodology for its ability to describe the dependence structure between multiple variables. Their model is applied to combined terrestrial and ocean flooding. Additionally, in the proposed methodology, the impact of compounding hazards on essential infrastructure also is considered. Leonard et al. (2014) referred to the definition of compounding events as given by the Intergovernmental Panel on Climate Change (IPCC). According to the IPCC definition, events happen simultaneously or successively and result in extreme impacts either due to a combination of 1) extreme events or 2) moderate events whose individual impacts are amplified. According to Leonard et al. (2014), a compound event would have an extreme impact and would have multiple variables with dependencies involved. Leonard et al. (2014) also provided examples of events that are not compounding events. They acknowledged modeling complexity and data availability as inherent challenges of simulating such events. They recommended the use of influence diagrams to model dependence probabilities as they are a good generalization of several types of network diagrams (e.g., graphs).

Zscheischler et al. (2018) explored the near-simultaneous occurrence of multiple dependent events and resulting conditions. The cited example was the concurrence of a severe heat event and air pollution. The impacts are amplified by the concurrence; however, the events have a dependence structure. Heatwaves cause wildfires that in turn result in pollution (which may initiate a positive feedback loop). Zscheischler et al. (2018) also note that traditional event frequency analysis should be replaced with explicit dependence modeling that considers interactions. This combination of events may not directly result in infrastructure damage in the short term; however, it may have an adverse effect on crew availability and mission continuity.

Pescaroli and Alexander (2018) developed a framework that differentiated compounding risks, interconnected risks, interacting risks, and cascading risks. Compounding and interconnected risks relate to physical and natural events while interacting and cascading risks address humans, the environment, technology, and infrastructure. The authors identified Hurricane Sandy as an example in which all four types of risks were involved. In this report, we consider compounding risks as a spectrum ranging from the concurrence of natural hazard events to the consequences of losing built infrastructure assets or assets' functionality. An application of this kind was a motivation for Petrone et al. (2020) to develop fragility functions for concrete structures under the influence of tsunamis as well as against a sequence of earthquakes and induced tsunamis.

2.2 Compounding Risk Methodology

The benefit of applying a compounding risk methodology is the ability to systematically compile a list of scenarios that challenge the mission of the facility (referred to simply as the infrastructure from this point on) Some constituent mathematical models support risk estimation corresponding to the elements of these scenarios. Risk assessment to the infrastructure of interest includes critical assets and supporting assets. There are about 16 critical asset sectors defined by the U.S. Department of Homeland Security Cybersecurity and Infrastructure Security Agency. An example of a critical asset is an upstream dam that poses a flooding risk. The risk to facility may or may not directly depend on the failure or loss of the critical asset; however, the loss of one of those critical assets could adversely affect the facility due to an accompanying or compounding event that overwhelms the infrastructure. The infrastructure, on the other hand, may depend on other supporting assets (either directly or indirectly) for continued operations. Supporting assets could be in the vicinity of the infrastructure but separated by some distance. An example is fuel delivery for on-site operations. The scenario development process is illustrated in the upper half of Figure 1.

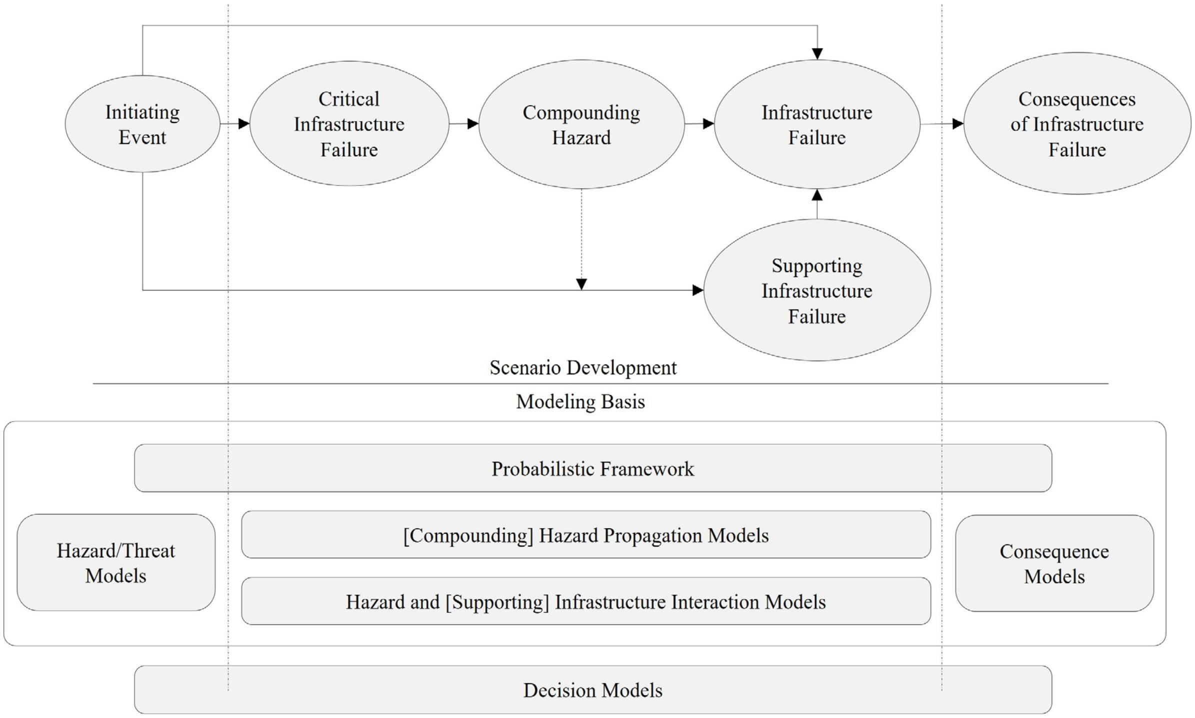

Figure 1. Scenario Development and Modeling Basis for Compounding Risks

An initiating event could potentially shut down critical and/or supporting infrastructure, thereby creating a compounding hazard to the infrastructure. In addition to infrastructure asset failures, the consequences could include the inability to carry on with the intended facility mission. An example could be the loss of production at a manufacturing site. The bottom half of Figure 1 shows modeling dependencies. The initiating event is a manifestation of a NPH, and in well-matured modeling cases, is separate from a hazard propagation model, which models the translation of effects of the hazard from its source location to a different location. The general methodology involves development of models at the intersection of hazards and infrastructure.

This would include modeling the interaction of the hazard(s) against individual assets of the infrastructure and then aggregating the effects at the infrastructure scale. The hazard-asset interaction is described next.

2.3 Hazard-Asset Interaction

A DOE facility (the infrastructure) is considered here as a set of assets and the interaction is between stress from a hazard and one of the infrastructure assets. While this subsection discusses a single hazard-asset interaction, the next subsection proposes the approach to aggregate these observations across all the assets in a DOE facility.

An asset $A = w$ (e.g., a wall) fails when the resistance, R, of an asset to the stress, S, induced by an event is inadequate (i.e., $R < S$). The associated probability for realization of the failure, (i.e., asset $A = w$ failing during an event $E = e$) is represented by $P_A = w, E = e\ (R < S)$. This probability is a scalar value and is obtained by the convolution of the hazard curve (representing the stress) and a fragility curve (representing the resistance) as described by Kennedy (1999):

The stress intensity associated with the event $E = e$ is uncertain and is represented using a hazard exceedance distribution $1 - G_e(S = s)$, where $G_e(S)$ also is a hazard distribution function in the cumulative sense. The derivative $h_e(s) = -dG_e(s)/ds$ of the exceedance distribution is its probability density function.

Given the above notations, Equation 1 and Equation 2 are mathematical expressions for estimating the probability of asset $A = w$ failure under the influence of the event $E = e$:

$$P_{A=w,E=e} = \int_0^\infty h_e(s) F_w(s)\, ds \tag{1}$$

To avoid computation of the derivative of hazard curve, an equivalent of (1) is:

$$P_{A=w,E=e} = \int_0^\infty H_e(s) f_w(s)\, ds \tag{2}$$

where fragility is represented in asset resistance cumulative distribution, $F(.)$, or its density equivalent, $f(.)$. Stress can be ground motion parameters in case of earthquakes and flow/depth parameters in case of floods, while resistance is a measure of failure (i.e., higher resistance translates to lower chances of failure) and can be expressed using strength parameters.

The above two are alternative approaches with the following interpretations: 1) for a given stress, the resistance is lesser than the induced stress, and 2) the stress exceeds the design resistance of the asset.

2.4 Risk Aggregation

While integrals in Equations 1 and 2 evaluate the interaction between the hazard and the asset, note that the event, E, itself has a frequency of occurrence. Identifying and evaluating these interactions is not trivial and may require detailed site-specific assessments. The product of the event frequency and asset failure probability, $P_{w,e}$, yields the asset failure frequency for E. The asset resistance cumulative distribution, *F*(.), or its density equivalent, *f*(.), offers a mechanism to be used as a performance function while building a performance tree to aggregate risk across the entire facility challenged by compounding events. Each branch of the performance tree is a sequence of events consisting of an initiating event, compounding events, and a consequence.

The overall risk, shown in Equation 3 due to the initiating event, e, is estimated as the summation of branch risks and then multiplied by the frequency, λ_e, of the initiator. The overall risk for the facility is the sum of risks from all possible initiators. Some of these initiators may be single events, while others may be compounding events. The tuple (a, e) includes pairs of applicable assets and events corresponding to the hypothetical asset and hazards matrix illustrated in Table 1.

Table 1. Example of a Hazard-Asset Matrix Identifying Assets and Their Susceptibility to Seismic and Flooding Compound Events. This example is hypothetical and does not reflect any real facility.

Assets↓ Hazards→	Seismic	External Flood Induced by Seismic Event
Buildings	X	X
Basements		X
Landing Pads and Yards	X	X
Pumps, Pressure Vessels, and Pressure Tubes	X	X
Main Electrical Control Centers		X
Internal and External Steam/Water Valves	X	
HVAC Systems		X
Fire Protection Water Supply Systems	X	
Decontamination Units		X

The quantification for risk aggregation draws from Equation 2.

$$R_{E=e} = \lambda_e \sum_b \left(\prod_{\{(a,e)\}} P_{a',e|a,\ldots} \right) C_b = \lambda_e \sum_b \left(\prod_{\{(a,e)\}} \int_0^{\infty} H_e(s) f_{a'}(s) ds \right) C_b \tag{3}$$

In Equation 3, a’ is the revised condition of the asset a due to the event e. For each branch b of the performance tree, the risk associated with the loss of that branch is estimated. The risk in this context is the product of the likelihood of occurrence of the branch (shown by the integral in Equation 3) and the consequence, C_b, associated with loss of the branch (multiplied across each a and e pairs). The likelihood determination uses performance functions along the branch. The availability of risk measure for each asset against compounding events of interest informs planning for the design, emergencies, and resource allocation. A site-wide risk estimate is a relative measure for prioritizing resources across a portfolio of infrastructure. Equation 3 is illustrated graphically in an application in the Section 3.0.

The quantification of risk for each asset of a facility against relevant compounding events can inform design of SSCs for risk tolerance, plans for emergency actions, and allocation of resources (e.g., protective or mitigation measures).

3.0 Compounding Seismic and Flooding Risk Methodology

Based on the general compounding risk methodology described in Section 2.0, we specifically evaluated the combination of seismic and flooding risk. Seismic events at remote fault sources are known to potentially cause dam breaches by causing sliding and joint lifting (Ghanaat et al. 2012). In this compounding hazards scenario, the seismic event is the initiating event. The ensuing breach can result in a compounding flood event that could inundate a facility with a time delay; that is, the time it takes the flood to reach the facility from the breached dam. In this section, a technical methodology to systematically identify, model, and quantify the end-to-end effects is discussed. A schematic of the methodology is shown in Figure 2.

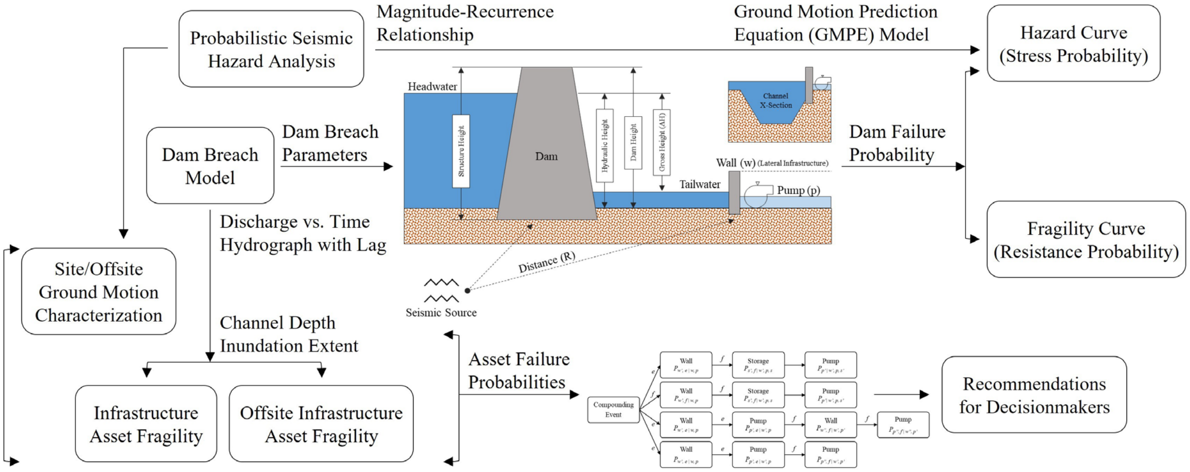

Figure 2. Methodology to Model Effects of a Compounding Seismic and Flooding Event at a Facility Located Downstream of a Dam with a Lateral Infrastructure Protecting an Asset (e.g., a pump)

3.1 Asset Inventory

To develop the methodology outlined below, an inventory of assets of interest at a DOE facility was undertaken. This inventory was not comprehensive but was meant to be illustrative of the kinds of assets at DOE facilities that may be exposed to compounding hazards. The following types of assets were generally found: 1) nuclear material processing facilities, 2) equipment that directly handle radioactive material, 3) storage areas for low-level waste, 4) building doors and walls, 5) pumps, 6) switchgear and electrical controls, and 7) liquid storage tanks.

Nuclear material processing facilities can include storage facilities, spent nuclear fuel processing facilities, surplus nuclear material storage and processing facilities, and research and test nuclear reactors. Equipment that directly handles radioactive material can include hot cells and gloveboxes. These assets usually are located inside buildings in secured areas that may have several layers of protection from NPHs. Storage facilities for low-level waste could be enclosed, semi-enclosed, or in open areas. Building doors and walls provide protection to sensitive equipment from NPHs. Pumps, switchgear, and electrical controls provide continued operational needs. Each of these assets may be exposed to NPHs. The exposure may result from a single NPH event, from concurrent NPH events (independent but occurring together), and from compounding NPH events.

3.2 Preparatory Phase

In this step, an inventory of assets of interest at the facility is established. Further, the hazards and the sources to which this facility is susceptible are identified. The outcome of this phase is a matrix identifying hazards and asset combinations. A hypothetical example is provided in Table 1. Specific steps based on this tabulation are carried in the subsequent steps.

3.3 Seismic Initiating Event Analysis

In this compounding event scenario, dam breaches are driven by seismic events at remote fault sources. These fault sources can be of different types—crustal, slab, and interface. In this step, a database of fault sources within an influential range is collected. The sources considered are typically within a 200–1000 km range depending on the source type after which the wave energy gradually decreases (Romero 2001). The anticipated range of event magnitudes and their corresponding event frequencies (i.e., magnitude-recurrence relationship or recurrence curve) are important attributes to be gathered in this step. These are a result of a source characterization study done by seismic experts. An example of a recurrence curve is provided in Figure 3(a). The impacts of this event at a site of interest are characterized in Section 3.4.

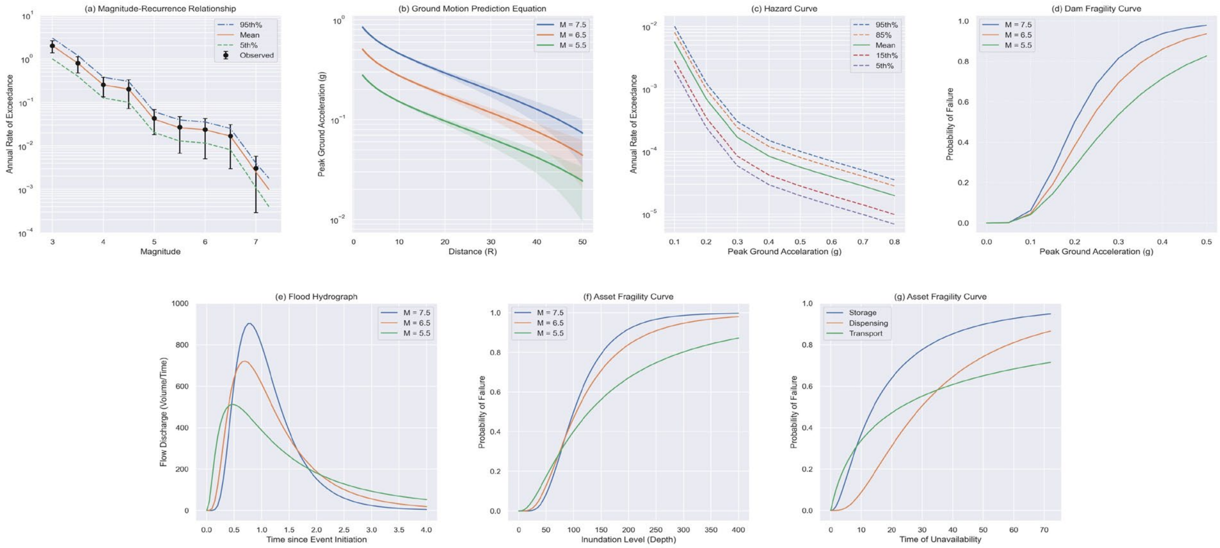

Figure 3. Hypothetical Examples of Seismic Consequences. (a) Magnitude-recurrence relationship of a seismic source, (b) ground motion prediction equation of a seismic source, (c) hazard curve of a dam due to earthquakes, (d) fragility curve of a dam due to earthquakes, (e) flood hydrograph after dam breach due to earthquakes, (f) fragility curve of an asset due to flood inundation, and (g) fragility curve of an asset due to supporting asset unavailability.

3.4 Dam Site Ground Motion Characterization

A seismic event at a remote source creates a disturbance at the dam site owing to a fluctuating ground motion. The intensity of generated stress at the site depends on the magnitude of the source event, the distance of the site from the source, and the geological conditions in between. This relationship between the source intensity and the site intensity is described by a ground motion prediction equation (GMPE) or ground motion attenuation models. The choice of the model itself is dependent on the fault type. A hazard curve (illustrating the exceedance probability of ground motions) is constructed based on the recurrence curves and GMPEs. Examples of GMPE and hazard curves are provided in Figure 3b) and Figure 3(c). The impacts of the ground motion on the dam are determined in Section 3.5.

3.5 Dam Fragility

The response of the dam to the accelerated ground motion depends on its strength to resist the motion. This vulnerability characteristic of the dam is described through a fragility curve that expresses the probability of failure of the dam in response to the ground motion. The fragility curve is dependent on the type of material used in the dam construction and the age of the dam. If the stress from the motion exceeds the dam's ability to resist it, the dam is likely to be breached with finite probability either through sliding at the base or lifting of joints. An example of a fragility curve is provided in Figure 3(d). The consequence of a dam breach is captured in the next Section 3.6.

3.6 Dam Breach Flood Model

The failure probability of the dam is determined from the event characterization (i.e., hazard curve) and the dam's fragility from Sections 3.4 and 3.5. This probability can then be translated into a set of parameters in a dam breach model to estimate the dam breach flood hydrograph. This flood hydrograph could be translated (i.e., routed) from the dam to the infrastructure site and would then result in stresses on the infrastructure assets. It is expected that parameters of the models (i.e., dam breach and flood routing models) would be uncertain (e.g., dam failure timing, breach shape, shape development, and river channel properties) requiring some random sampling. A more comprehensive probabilistic approach to flood modeling may be warranted. The model yields a hydrograph that represents the river water discharge and/or elevations at the infrastructure site. In the uncertain case, the result would be a family of hydrographs (Figure 3(e)). The flood impacts on the infrastructure are discussed in Section 3.7.

3.7 Asset Fragility

An application of the dam-breach-flood-routing-model from Section 3.6 would be to create an infrastructure inundation map accounting for the river channel bathymetry and infrastructure site topography. This application also would result in a time history of hydraulic stresses at asset locations on the infrastructure site. A fragility curve for each asset determines the probability of its failure given the inundation level and the duration of inundation at the asset location (Figure 3(f)). The asset could fail because of exceedances of its design limits (e.g., water level over-topping a threshold could lead to compromised electrical equipment). It is also possible that an asset does not directly fail because of inundation but becomes dysfunctional due to the unavailability of one or more of its off-site dependencies (i.e., supporting assets). These include failure of storage and transportation of necessary services (Figure 3(g)). On the other hand, the assets may also be directly susceptible to seismic damage as well. Assuming that the infrastructure site is located some distance downstream from the dam, seismic waves could reach the site well before floodwaters. In this case, a significant ground motion could cause partial to total damage to the asset before being further exacerbated by flooding.

3.8 Infrastructure Fragility

The infrastructure fragility following the net effect of on-site and off-site effects is its ability to withstand the flooding event under a range of inundation levels. These effects are consolidated using a performance tree with inputs obtained from the rest of the steps described above. The tree identifies a comprehensive list of compounding failure pathways impacting the site. The infrastructure failure likelihood and the pathways together are anticipated to provide insights into the improvement of the site's resilience from compounding seismic and flooding hazards. The performance tree consolidation approach is described in Section 3.9.

Seismic and flooding events are assumed to be compounded with a delay owing to the lag between the seismic event and time to flooding with a remote dam breach as the compounding source. The possibility of a compounding event with negligible delay is ignored. The condition of the asset after the first event is considered as the input for the compounding event. This staggered approach is achieved through either a shifted fragility function or a revised performance function for the asset, both of which are assumed to be probabilistic distributions or equivalent alternatives thereof. At the same time, the possibility of repairing or replacing a damaged asset within this lag is assumed to be ignored. This assumption, however, does not limit an analyst from including the effects of asset repair in the model.

In this case, the resistance is against the ground motion (stress) $S = m$ (magnitude) stemming from the earthquake event, $E = e$, affecting the asset, $A = w$. In the case of flooding, the resistance would be against the flood level stress, $S = l,$ (level) for a flooding event, $E = f$. In the former case, the cumulative distribution function for asset resistance is $Fw(S = m)$, and in the latter case, it is $Fw(S = l)$. The corresponding probability distribution function is denoted by $fw(S = m)$ and $fw(S = l)$, respectively. These notations fit into the expression for asset failure determination in Equation 2.

3.9 Risk Aggregation

In this section, seismic event frequencies and individual asset failure probabilities estimated in previous sections are used to aggregate compounding event risk across a set of scenarios (performance tree branches). A scenario is a combination of initiating event and a set of ensuing events. An example of a scenario is the partial damage of a pump due to a seismic event followed by a total failure due to compounded flooding event with no opportunity to repair or detect the initial damage within the time lag. A comprehensive set of independent, mutually exclusive scenarios is represented using a performance tree with each branch representing a scenario. The aggregation operation is the addition of scenario occurrence risks. Note that the set of scenarios is comprehensive, not necessarily collectively exhaustive. This is attributable to completeness uncertainty.

Consider an earthquake, $E = e$, compounded by a flooding event, $E = f$. Assume there are two assets protecting the pump: 1) a pump, p, and 2) a wall, w. Four possible damage pathways (scenarios, performance tree branches) that could affect the pump are listed below and are illustrated in Figure 4.

7. The seismic event compromises the wall letting the subsequent flood to degrade the pump's functionality
8. The flood compromises the wall letting the flood degrade the pump's functionality
9. The seismic event compromises the wall and partially degrades the pump
10. The subsequent flood further degrades the wall and pump's functionality.

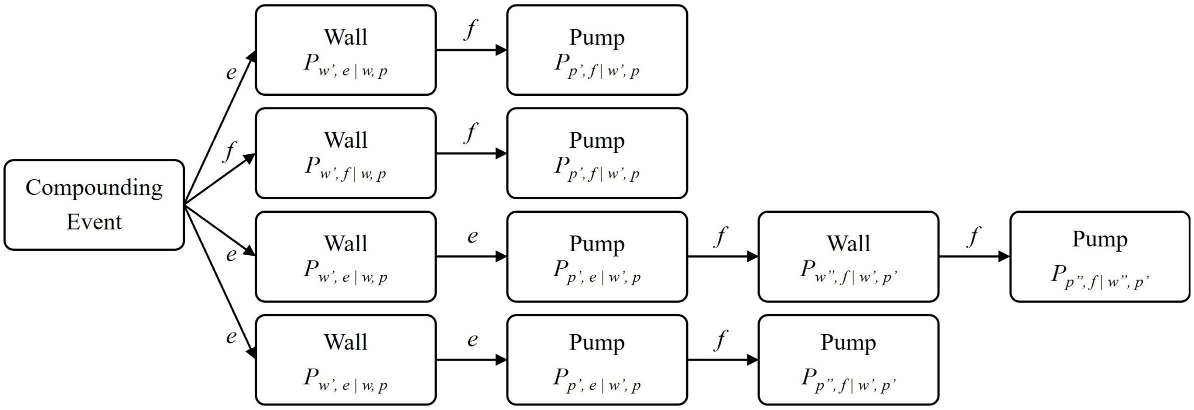

Figure 4. Snippet of the Performance Tree with Compounding Hazardous Event Possibilities for an On-Site Pump

The seismic event compromises both the wall and the pump. The subsequent flood degrades the pump's functionality. These enumerated branches are not necessarily a comprehensive list of possibilities.

Each asset is assumed to have a fragility curve or an equivalent simplified performance function represented by $Pa',E=e|a,...$ where a is an asset whose performance is revised to a due to the event e, and "..." represents other assets that may influence the performance of the asset a during event e. The performance function is an indicator of the functional state of the asset given the event. The indicator can be as simple as a time-dependent percentage or a more involved multi-variate function of the hazard's intensity (e.g., the resistance distribution referred to in hazard-asset section). The indicator also can be subject to elicitation by a group of experts. If a wall w degrades from normal state w to state w' due to the first event, it then moves onto state w'' due to the compounding event. Notations for some of the performance functions for the example described above are described below.

- $Pw',e|w,p$. Performance function of the wall with revised state w' after the earthquake e. The prior performance of the wall was w and that of the pump was p. The pump's performance may not affect the revised state of the wall, yet it is included in the expression for completeness.
- $Pp'', f|w',p'$. Performance function of the pump with revised state p'' after the flooding event f.

The performance functions before the event were w' and p' for the wall and the pump, respectively (as a consequence of the earthquake or other preceding event). The performance tree shown in Figure 4 can be implemented as a Bayesian Belief Network (BBN) as illustrated in Figure 5, given its conduciveness to uncertainty and quantitative treatment with conditional probabilities. For example, Sen and Dutta (2020) and Sen et al. (2021) integrated geospatial information with BBNs to quantify resilience of roadway networks and housing infrastructure against flooding hazards. It is highly likely that intricate fragility curves are not available for all assets subject to varying hazard types. Fragility curves can be discretized down to three simple segments—minor damage, median damage, and major/total failure.

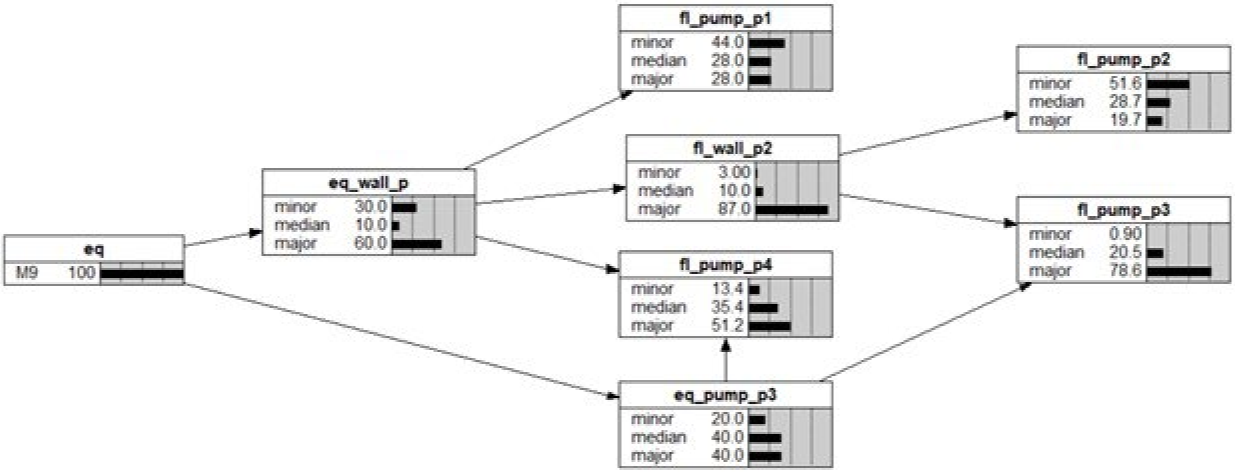

Figure 5. Sample BBN Representation of the Performance Tree in Figure 4 with Fragility Curves Discretized Down to Minor, Median, and Major Thresholds

Equation 4 illustrates the determination of the probability of a median damage to the pump due to flooding. The different “$\_p$” terms represent pathways of damage. The term “eq_wall_p” is the probability of damage of the wall due to the initiating earthquake. The probability of a minor damage due to the earthquake under consideration is 30%. For the next node, “fl_pump_p1” representing median damage to pump due to consequential flooding (conditional on the wall condition), is estimated at 28%. This illustration is conceptual and does not exactly translate the fragility curves provided in Figure 3 but provides the implementation logic for solving a real problem based on this proposed framework.

$$
\begin{aligned}
&P(fl\_pump\_p1 = median) = \\
&P(fl\_pump\_p1 = median \mid eq\_wall\_p = minor)P(eq\_wall\_p = minor) + \\
&P(fl\_pump\_p1 = median \mid eq\_wall\_p = median)P(eq\_wall\_p = median) + \\
&P(fl\_pump\_p1 = median \mid eq\_wall = major)P(eq\_wall = major) \qquad (4)
\end{aligned}
$$

The probability of a median damage to the pump, for example, can be evaluated with BBN as follows for a given earthquake scenario of magnitude 9.0.

The input probabilities to the BBN are provided in the form of Conditional Probability Tables as illustrated hypothetically in Table 2 and Table 3. For example, Table 2 entries are read the probability of a minor wall damage given an earthquake of magnitude M9.

Table 2. Conditional Probability Table for Wall Damage Due to a Seismic Event (eq_wall_p)

Minor Damage	Median Damage	Major Damage
0.30	0.10	0.60

The entries in Table 3 are read as the probability of a minor damage to the pump due to flooding given that the wall has already undergone a major damage due to the seismic event and exposed the pump to flooding.

Table 3. Conditional Probability Table for Pump Damage due to Flooding Following a Seismic Event that Damages a Wall (*fl_pump_p1*)

eq_wall_p	Minor Damage	Median Damage	Major Damage
Minor Damage	0.70	0.20	0.10
Median Damage	0.50	0.40	0.10
Major Damage	0.30	0.30	0.40

The BBN branches in general yield probabilities of pump failure but do not yet consider frequency of the earthquake event and the consequences of failure of the pump. The risk associated with the loss of the pump for the branch is estimated as the product of earthquake frequency (e.g., once in 350 years), the probability of median damage to the pump given wall damage (e.g., 28%) from the BBN (given the inundation), and the consequences associated with the loss of the branch (e.g., an economic loss of $50,000). The overall risk due to this manifested risk from all branches of the BBN is additive. Similarly, considering earthquake events varying in frequencies and epicenters, Equation 3 is invoked to obtain the overall risk to the pump from all seismic sources compounded with flooding conditions. In summary, Table 4 describes the series of events, models, curves, and possible sources where such models and curves may be found.

Table 4. Series of Events, Relevant Models and Curves and Sources to Obtain Them

Event	Models and Curves	Source
Earthquake	Earthquake frequency-magnitude curve	U.S. Geological Survey
Site asset failure	From earthquake fragility curve for site assets (asset failure probability vs. seismic peak ground acceleration)	Site asset design datasheets
Dam failure	Fragility curve for a dam (dam failure probability vs. seismic peak ground acceleration)	Curves for dam material (e.g., concrete wall) from literature
Flooding	Flooding model simulation resulting in asset failure probability vs. inundation depth)	g., HEC-HMS, HEC-RAS, FLO-2D modeling
Site asset failure from flooding	Fragility curve for site assets (asset failure probability vs. inundation depth)	Site asset design datasheets or literature

3.10 Supporting Infrastructure

The compounding events also can cause damage to the external infrastructure upon which the assets depend. For example, consider a situation in which the pump relies on fuel for reliable operations. Fuel availability can be hindered if either storage, transportation, or dispensing is affected in the supply chain. Note that the location at which storage or transportation is impacted is likely to be different with distinct ground motion or flooding effects compared to the assets on the site. Coincidentally, there could be an event unrelated to the compounding events that affect the ability to serve the pump with the needed dependencies. An example of this is a random operational event at the storage location. While Figure 4 does not capture these effects, performance trees can also be built with dependency effects as additional events. Figure 6 illustrates an example wherein the pump is affected due to the loss of off-site resources. Note that loss of the pump follows the loss of off-site resources and is not necessarily due to a natural hazard. One example of this is the inability to operate the pump because of exhaustion of backup fuel supply and lack of replenishment. This scenario could result if the seismic event and/or the subsequent flood cause a damage to roadways from the fuel storage location to the site or make the roadways impassable. The duration of such offsite disruption is then the main cause of onsite asset failure. This threat pathway needs to be included in the risk estimation. More importantly, it points to facets of NPH analysis that must include both onsite and offsite effects, potentially expanding the spatial and temporal scope of NPH analyses.

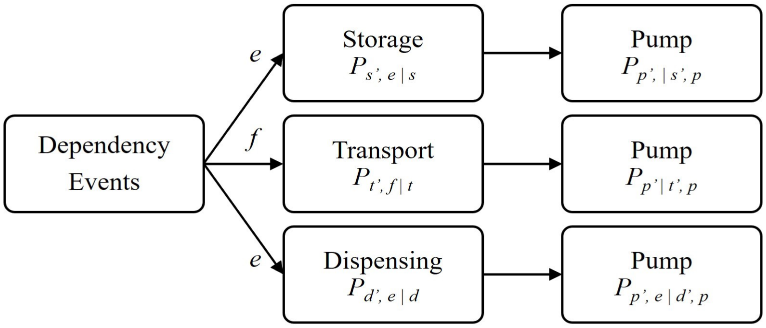

Figure 6. Snippet of the Performance Tree with Off-Site Dependencies

The following are examples of a general approach to interpreting the off-site effects performance tree:

1. $Ps', e|s$. The performance function of the off-site storage system with the revised state, s', following an earthquake. The prior state of the storage system was s.
2. $Pp'|s',p$. The performance function of the pump with the revised state, p', given the new state of the storage system s' and the prior state of the pump, p.

As a final step of the assessment, Equation 3 is used to estimate risk for each scenario (branch of the tree) as well as for the infrastructure. An off-site only tree alone does not provide a holistic view of the dynamics between hazards, off-site assets, and on-site assets. Figure 7 illustrates a sample wherein the interaction with fuel storage is included. Note that a natural hazardous event is not associated with the pump in the top two branches (e.g., no 'f' above the arrow) (same as Figure 6). This is because the pump is in good condition, but its fuel supply has been cut off due to the failure of the storage tank because to flooding.

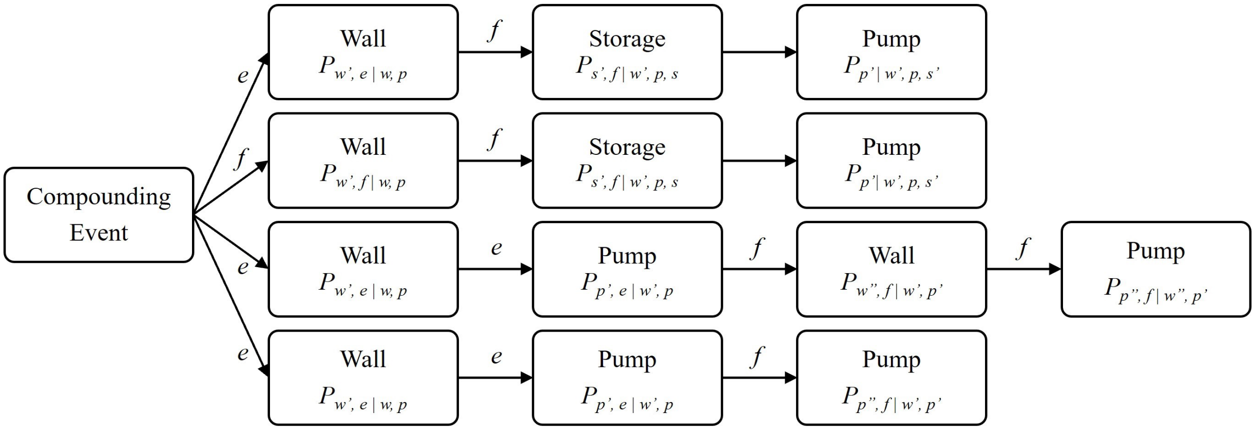

Figure 7. Snippet of the Performance Tree with Combined On-Site and Off-Site Dependencies

4.0 Discussion and Conclusion

The performance tree approach offers a way of systematically, if not comprehensively, identifying compounding pathways to infrastructure failure that would have been otherwise not evident from the combinatorics of events and assets. It is quite common to encounter failures driven by single events. While situations when more than two events occur are extremely rare, it is not uncommon to experience circumstances in which the effects of the two events are compounded. Such limited compounding makes the performance tree practical and amenable for design by an analyst or a team of risk analysts. Three event combinations are a combinatorial stretch, but it is still possible to construct performance trees for them to help understand the failure pathways.

When challenges become intractable with continuous fragility curves, the use of Monte Carlo sampling techniques is recommended to sample from the curves or to use BBNs with discretized fragility curves. The choice of performance functions affects the quality of analysis. If the number of observations is adequate, one could resort to a comprehensive probabilistic analysis. If data are not available, these functions can be reflective of the post-event asset performance in terms of percentage loss of functionality or remaining useful functionality. In the interim case in which data collection is not adequate, yet not too scarce, a combination of quantitative estimates and subjective knowledge could be applied to construct performance functions. An example is a case in which an appropriate statistical distribution cannot be discerned. Expert elicitation could help arrive at the choice of performance distribution with data-driven parameters that are themselves uncertain. The identified hazard sources, failure mechanisms, and failure pathways are anticipated to provide insights into design and resilience improvement at critical facilities. The proposed framework is complementary to and incremental over existing standards and guidance for infrastructure resilience management, namely extending single natural hazard event analysis to compounding events with compounded hazards.

Guidance documents on infrastructure resilience should consider compounding events. A structured methodology supports the modeling of such events. In this report, we discuss a generic framework and illustrate its use in a compounding seismic and flooding event that adversely affects an infrastructure. We used performance trees to capture infrastructure-wide effects while the stress resistance (i.e., hazard-fragility) relationship was used at the asset level. The benefits of undergoing such an exercise for risk management also are described. Limitations are acknowledged in terms of scaling up the method to a complex system with a large number of possibilities. Probabilistic hazard analysts of critical infrastructures may benefit from the proposed framework.

Finally, this work points to future work that can address compounding hazards and potentially unidentified risk to DOE facilities. These include:

- Performing a study following the methodology outlined in this report. This study will also fill identified technical needs: identification of site-specific compounding hazards, identification of unidentified threat pathways for SSCs, development of fragility curves for SSCs, and development of progressive degradation of fragility curves under sequential but disparate NPH loadings.

- Convening an expert panel to investigate each of the technical needs mentioned above (e.g., guidance development to elicit input from expert panels in developing performance functions and fragility curves including assessment of uncertainties).

5.0 Observations on Current DOE Guidance

The current DOE guidance (primarily DOE-STD-1020-2016) addresses NPHs individually and in selected combinations. However, there is limited consideration of compounding NPHs that may result in rare, high-consequence threat pathways to SSCs, non-safety systems, backup systems, and off-site dependencies. Each of these considerations is likely to point to avenues for improving DOE-STD-1020-2016.

5.1 Inclusion of Compounding NPHs

Because compounding NPH events can lead to high consequences, DOE-STD-1020-2016 should include a section that outlines systematic considerations of these events. Most compounding NPH events would be highly dependent on the hydrometeorological and geoseismic characteristics of a given DOE site and its vicinity. While consideration of a limited number of combinations of NPH scenarios is included in DOE-STD-1020-2016 (e.g., river flooding including upstream dam releases or flooding from failure of a dam combined with wind waves), there is no mention that exposure to SSCs could be subject to different failure mechanisms from compounding NPHs. As described in Section 3.0, the compounding effects can lead to multiple, potentially unidentified pathways and increase the overall risk to facility assets and to the mission of the facility.

5.2 Treatment of Compounding NPHs

Inclusion of compounding NPHs in guidance documents also should include a description of the treatment of these scenarios. Section 3.0 provides an example (i.e., a seismic event followed by flooding). However, compounding NPHs would be highly dependent on the hydrometeorological and geoseismic characteristics of the site and its vicinity. Furthermore, the location of the site and its off-site dependencies also can be complicating factors. Some sites may be more self-reliant than others. Therefore, an asset inventory and careful consideration of on-site and off-site dependencies should be carried out. Usually, NPH assessments for DOE sites focus on the site itself. However, off-site dependencies can not only increase threat pathways, but they also can expand the scope of the NPH assessment to include off-site areas and facilities that typically are not considered. Treatment of these dependencies and supporting structures should be carried out before detailed NPH event analyses are formulated. DOE-STD-1020-2016 does not include duration of disruption as a hazard parameter that should be evaluated for seismic and flooding events. As described earlier in Section 3, this gap can lead to unidentified threat pathways with potentially severe yet unanalyzed consequences.

5.3 Evacuation Pathways and Facility Recovery

While not explicitly addressed in this report, NPH events have the potential to block access routes to a DOE facility. This could be either a short duration disruption or could last for a longer period in the case of a particularly rare event. In these scenarios, not only would the DOE facility become isolated but evacuating personnel from the site or rotating and supplementing site crews for recovery efforts could also be a major issue. For NPH events that can cause widespread disruption to transportation infrastructure (e.g., a major earthquake that damages roadways and subsequent flooding that renders roadways unusable), both the temporal and spatial scopes may be expanded from normal practices. Again, the duration of disruption, both onsite and offsite (e.g., unusable roadways that connect the DOE facility to surrounding population centers) can be a major contributor to human health and safety.

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