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IMPROVED FRAGILITY UPDATE METHODS TO ADDRESS NEW SEISMIC HAZARD ESTIMATES

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ABSTRACT

Ongoing growth in technical knowledge about seismology leads to an evolving understanding of seismic hazards at nuclear power plant (NPP) sites. In addition to ongoing research into the basic elements of seismology, new earthquakes present opportunities to update the methods and parameters associated with seismic hazard estimates. A recent example of the nuclear industry response to a change in the seismic hazard state of knowledge occurred following the 2011 Tohoku earthquake in Japan that affected the Fukushima Daiichi nuclear plant. In the United States, all operating U.S. NPPs performed a seismic hazard re-evaluation in response to the U. S. Nuclear Regulatory Commission's (USNRC) Near Term Task Force (NTTF) request for information following the Fukushima Daiichi incident. Similar seismic hazard re-evaluations occurred in most countries that have existing nuclear power plants. The seismic hazard re-evaluations performed typically used current probabilistic seismic hazard assessment (PSHA) methods and resulted in changes to the existing characterization of the seismic hazard at many nuclear power plant sites throughout the world. This post-Fukushima seismic hazard characterization resulted in extensive and expensive assessments to verify that the new hazard did not represent unacceptable risks to each nuclear power plant. Given the wide range of ongoing seismic hazard research that currently exists and will continue to exist in the future, it is imperative that nuclear plant operators have access to a graded approach to efficiently evaluate the impacts of those seismic hazard changes on the plant seismic risk.

The Electric Power Research Institute (EPRI) is conducting research into this challenging area of responding to the ongoing changes in estimates of the seismic hazard at nuclear power plant sites. The objective of this EPRI project is to provide simplified yet effective methods to assess the impact on plant risk due to a change in the seismic hazard. This paper will summarize some of the key methods and results from this ongoing research project.

BACKGROUND

The Magnitude 9 Tohoku earthquake occurred in 2011 and represents the most powerful earthquake ever recorded in Japan. That earthquake, along with the resulting tsunami, caused the Fukushima Daiichi nuclear plant accident. As a result, most nuclear power plants throughout the world embarked upon seismic reassessments to better understand the risks related to extreme natural hazards with a particular focus on seismic events.

All operating U.S. NPPs performed a seismic hazard re-evaluation in response to the U. S. Nuclear Regulatory Commission's (USNRC) Near Term Task Force (NTTF) request for information (2012) following the Fukushima Daiichi accident. The seismic hazard re-evaluations performed for these sites included the use of state-of-the-art probabilistic seismic hazard assessment (PSHA) methods existing at that time period. The PSHAs for the central and eastern United States (CEUS) NPP sites were based on the CEUS seismic source characterization in EPRI 1021097 (2012) and the EPRI 2013 ground motion model (GMM) in EPRI 3002000717. Several NPPs with increased seismic hazards performed extensive seismic probabilistic risk assessment (SPRA) studies and used the risk results to demonstrate adequate safety.

While an SPRA is certainly an appropriate tool to quantify risk and changes in risk, it typically involves considerable effort to complete. When seismic hazards change, more simplified risk-informed evaluation methods should first be implemented to determine if a complete SPRA update may be warranted.

OBJECTIVE

To address this challenge, EPRI developed EPRI 3002020749, *Simplified Risk Impact Assessment for an Updated Seismic Hazard.* The objective of EPRI 3002020749 (2021) is to provide a graded approach incorporating simplified methods to assess the impact on plant risk due to a change in the seismic hazard.

The starting point for this graded approach consists of the risk and Δ risk estimation approaches developed by the USNRC in their GI-199 safety assessment (2010). The results from these risk and Δ risk estimates are used to guide plant specific assessments in a graded manner.

The key inputs to the risk and Δ risk evaluations are estimates of the updated seismic hazard and a simplified characterization of the plant seismic capacity. Rather than conducting a full probabilistic seismic hazard assessment (PSHA) to incorporate new seismic data, a first step should be to estimate an updated mean seismic hazard. One technique for estimated the mean hazard is described in EPRI 3002018216 (2020b). This mean hazard can then be convolved with a plant level fragility (PLF) characterizing the seismic capacity of the plant to determine an estimate of plant risk. Techniques for estimating the PLF were first suggested by Kennedy (1999), applied for U.S. plants in the NRC GI-199 safety assessment (2010), and updated for U.S. plants in EPRI 3002018215 (2020a). This use of a simplified mean seismic hazard and PLFs to perform risk and Δ risk estimates facilitates a pragmatic, graded process to assess implications of changing seismic hazards.

For those sites with higher Δ risk estimates, simplified options are presented to develop more realistic risk estimates through improved fragilities/screening which serve to more accurately assess the effects of seismic hazard increases. A flowchart of the EPRI graded approach to assess the impact due to a change in seismic hazard is outlined in Figure 1. The three paths (in order of increasing complexity) available to assess the risk impacts of a seismic hazard change include:

- Path 1 – use seismic risk and Δ risk estimates to assess whether the seismic risk changes significantly
- Path 2 – use simplified risk updating methods described in the report to assess whether the seismic risk changes significantly, and if applicable, determine a refined Δ risk
- Path 3 – use the state-of-the-art methods in EPRI 3002012994 (2018) to update the SPRA fragilities reflecting the new seismic hazard and quantify risk using the SPRA plant logic models to assess whether the seismic risk changes significantly.

The elements that make up Paths 1 and 2 are simplified methods developed as part of this EPRI project, which provide utilities with a cost-effective alternative to the existing more detailed methods identified in Path 3.

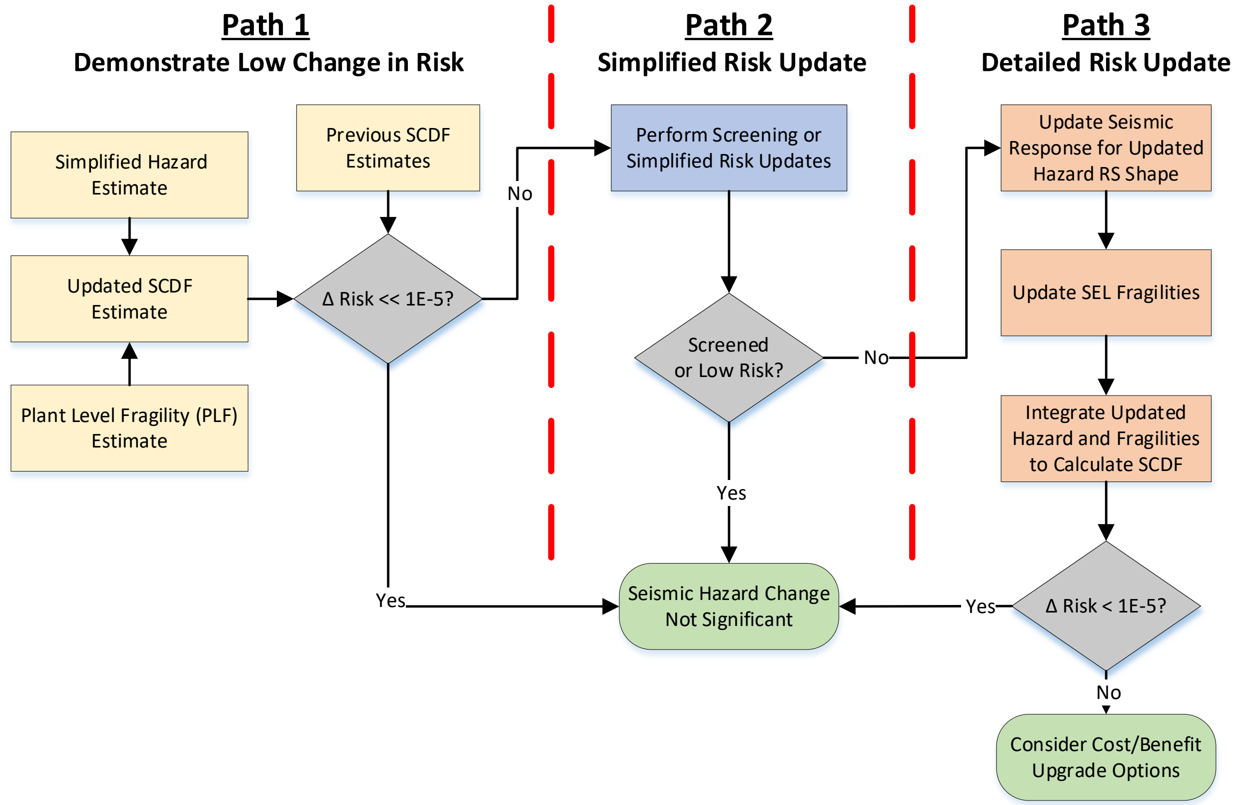

Figure 1. Risk Assessment Paths in Response to Seismic Hazard Changes

SIMPLIFIED SEISMIC HAZARD IMPACT ASSESSMENTS

Figure 1 outlines an overall graded process to assess the implications of seismic hazard changes, with each path providing more detailed and complex site-specific assessments. The elements of paths 1 and 2 of this simplified seismic hazard impact assessment process are outlined in Figure 2. A brief description of each step of the flow chart is described here, with additional details provided below.

Step 1. **SSE ≥ GMRS?** – Compare the design basis safe shutdown earthquake (SSE) to the updated ground motion response spectrum (GMRS).

Step 2. **Risk and Δ Risk Assessment** – Compute the estimated baseline seismic core damage frequency (SCDF) and Δ SCDF considering the updated hazard and compare to the established Δ risk thresholds established by the USNRC.

Step 3. **Low Seismic Hazard Assessment including Cliff Edge** – For low hazards sites, compare the updated GMRS to the Low Hazard Threshold (LHT). Special consideration must be given to risk significant low frequency sensitive structures, systems, and components (SSCs) and cliff edge effects.

Step 4a. **Qualitative Assessment** – For medium estimated Δ risk sites, perform a review of dominant risk contributors (DRCs) and consider any potential impacts from cliff edge effects.

Step 4b. **Quantitative Assessment** – For high estimated Δ risk sites and for medium estimated Δ risk sites for which a qualitative assessment was insufficient, perform a simplified quantitative assessment where the DRC SSC fragilities identified in an SPRA are scaled based on the new reference earthquake. These updated fragilities should then be reincorporated into the SPRA with the updated hazard to calculate an updated SCDF.

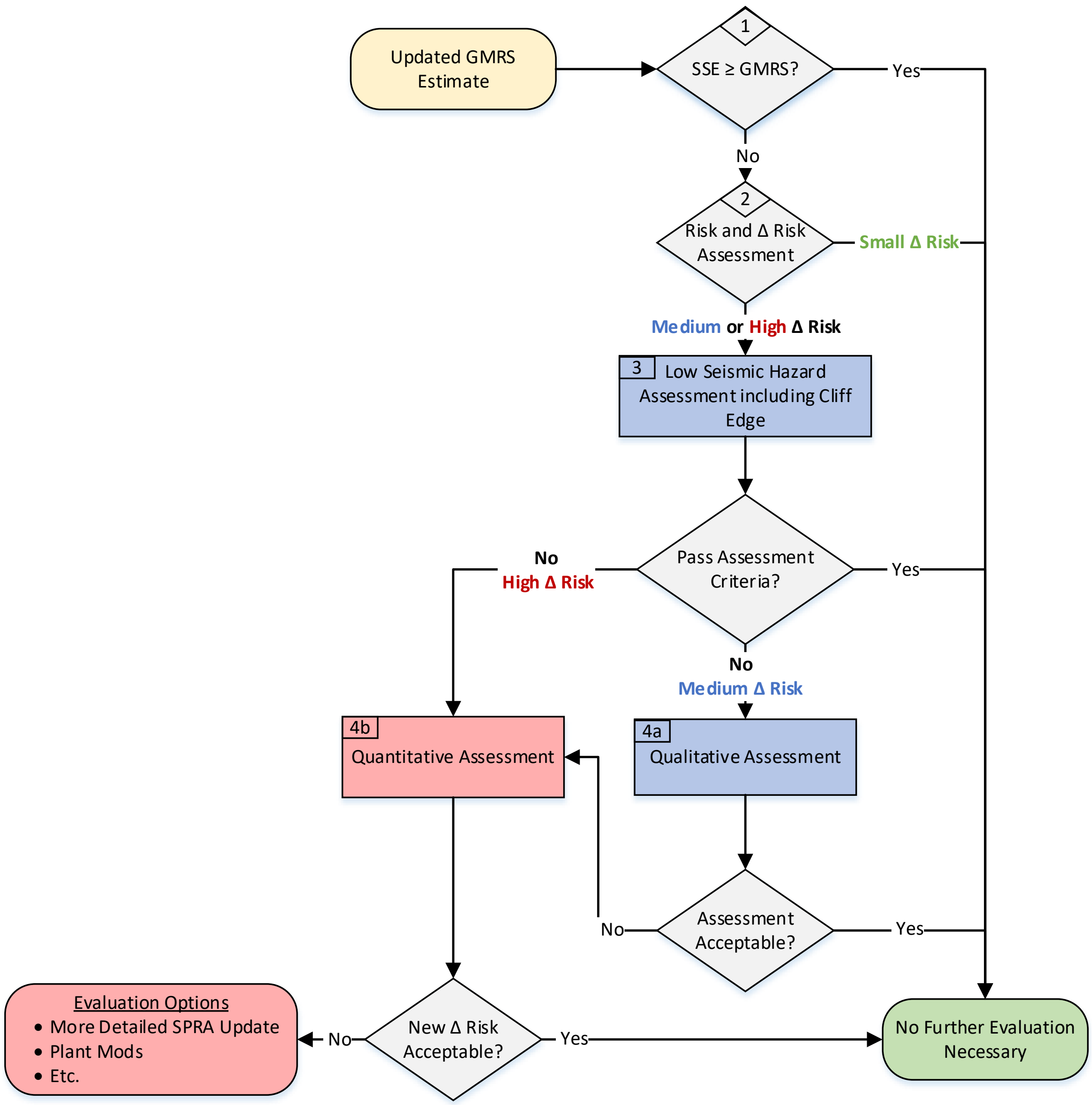

Figure 2. Simplified Seismic Hazard Assessment Process

Step 1 – SSE Screening (SSE-to-GMRS Comparison)

This initial screen is based on the GMRS comparisons and screening in EPRI 1025287, *Seismic Evaluation Guidance - Screening, Prioritization and Implementation Details (SPID) for the Resolution of Fukushima Near-Term Task Force Recommendation 2.1: Seismic*, (2013) commonly referred to as the SPID. The SPID provides guidance for a graded seismic evaluations pf plant performance. The recommendations developed within the SPID for comparison of the SSE to the GMRS in Section 3.2, *SSE Screening Task (SSE-to-GMRS Comparison)*, are judged to be appropriate to use for a similar review of updated seismic hazards.

This Step 1 screen compares the plant licensing basis earthquake (design SSE) and the updated site GMRS.

- If the SSE envelops the GMRS across all frequencies, then no further action is required.
- If the GMRS exceeds the SSE between 1 Hz and 10 Hz, then the Step 2 screening in Figure 2, Risk and Δ Risk Assessment, should be performed.
- If the GMRS exceeds the SSE above 10 Hz, then a high-frequency confirmation should be performed in accordance with EPRI 3002004396, *High Frequency Program: Application Guidance for Functional Confirmation and Fragility Evaluation*.
- If the PGA is exceeded, then a liquefaction review, discussed later, should be performed.

Step 2 – Risk and Δ Risk Screening

The Δ risk threshold used by USNRC in their GI-199 safety/risk assessment (2010) is in the range of 1E-5, provided the baseline SCDF is less than 1E-4. The approaches used to assess the change in risk impact depend on the magnitude of estimated Δ risk in comparison to the 1E-5 threshold and can be binned, as shown in Figure 3, roughly according to their relation to the 1E-5 threshold:

- Small estimated Δ risk – A change in risk well below the 1E-5 Δ risk threshold. These sites do not require any further evaluation.
- Medium estimated Δ risk – A change in risk near, above or below, the 1E 5 Δ risk threshold
- High estimated Δ risk – A more substantial risk change above the 1E-5 Δ risk threshold

For those sites that do not pass the design basis SSE screening and have medium or high estimated Δ risk assessments, further steps are recommended to determine if, and to what extent, additional evaluations are warranted to demonstrate the potential impact due to the hazard change.

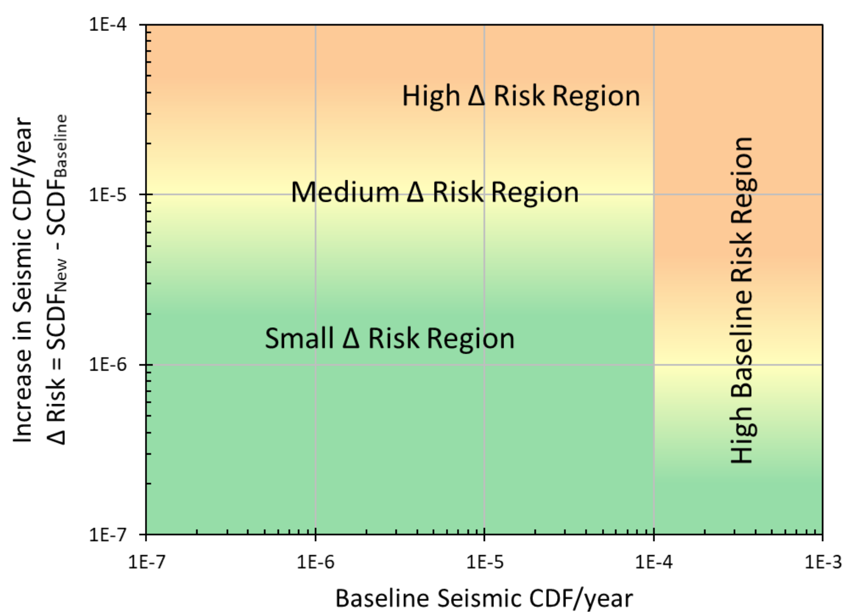

Figure 3. Plant Bins for Change in Risk Associated with a Seismic Hazard Change

Step 3 – Low Seismic Hazard Assessment

The LHT screening methodology is based on Section 3.2.1.1 of the SPID (2013). Low hazard sites that have a GMRS below the LHT and do not identify any risk significant low frequency sensitive SSCs or cliff edge effects do not require any further evaluation. The Low Hazard Assessment from the SPID reviews two main aspects:

- Seismic demand comparison – A "low seismic hazard" site is defined in the SPID (2013) as a site where the GMRS peak 5% damped spectral acceleration at frequencies between 1 Hz and 10 Hz does not exceed 0.4g. The low likelihood of any seismically designed SSC being damaged by ground motion with an acceleration less than this LHT makes further evaluations unwarranted for plants at sites where the GMRS is less than this LHT in the 1 to 10 Hz range.

- Low frequency sensitive SSCs – Low-frequency exceedances at low seismic hazard sites do not require the performance of detailed analyses. Instead, it is sufficient to first identify all safety-significant SSCs that are potentially susceptible to damage from spectral accelerations at frequencies below the highest frequency at which the GMRS exceeds the SSE.

  Examples of common SSCs and failure modes potentially susceptible to damage from spectral accelerations at low frequencies are provided in the SPID (2013):
    - Liquid sloshing in atmospheric pressure storage tanks
    - Very flexible distribution systems
    - Sliding and rocking of unanchored components
    - Fuel assemblies inside the reactor vessel
    - Soil liquefaction

After identifying all safety-significant SSCs that are potentially susceptible to lower frequency accelerations, these SSCs, and any previous evaluations, should be reviewed to assess the impact of increased low-frequency accelerations.

Step 3 – Cliff Edge Assessment

For some failure modes, even a modest increase in seismic hazard can lead to significant nonlinear characteristics warranting additional screening reviews to assess their plant specific potential impacts. SPRAs have traditionally used the lognormal probability distribution to develop fragility curves and this closely approximates the actual fragility distribution for most SSCs. However, components with highly nonlinear behavior failure modes are not approximated well by the smooth lognormal distribution. These failure modes have associated fragilities that can exhibit "cliff edge effects" and need to be evaluated in more detail.

From a seismic perspective, the two most important groups of cliff edge effects are geotechnical failures and SSC-to-SSC interactions. Geotechnical failures such as liquefaction, lateral spreading, and slope failure are very sensitive to the seismic input due to the nonlinear behavior of the soil at varying ground motion levels. There is a threshold demand past which the soil loses its strength dramatically and fails, potentially resulting in large displacements and settlements, which can directly lead to failure for many SSCs. Similarly, seismic impact between closely spaced buildings or equipment are inconsequential until contact occurs. A small increase in seismic input could cause contact and result in shock waves, local crushing, and even collapse if the impact is sufficiently strong. These impact loads can result in a dramatically different system seismic response.

EPRI 3002020749 (2021) provides more in-depth discussion on the proposed simplified assessments of liquefaction, slope stability, and SSC-to-SSC interactions. Graded evaluation guidance is provided for each failure mode including:

- Screening criteria considering the failure's contribution to plant risk,
- Qualitative evaluation guidance using simplified, conservative criteria, and
- Quantitative evaluation guidance using more detailed evaluation methods, although still less detailed that a completely new fragility assessment.

Step 4a – Qualitative Assessment

For plants where the seismic hazard change could not be accepted using the criteria in Steps 1 through 3 above, a qualitative assessment can be used to evaluate the updated hazard. The qualitative assessment is composed of four main aspects:

1. Establishing a seismic assessment baseline demand (previous seismic assessments) for comparison to the updated GMRS.
2. Review of SSCs that are DRCs.
3. Review of potentially risk significant SSCs with natural frequencies in the range where the updated GMRS has significant exceedance over previous seismic assessment baseline.
4. Review of cliff edge failure modes, which may not have been identified as DRCs previously.

The goal of the qualitative assessment is to evaluate the risk changes of any SSCs that may be impacted by the change in hazard. If it can be qualitatively judged that the hazard change does not significantly affect any of the SSCs identified in the steps above, no further evaluation is needed. If the SSCs cannot be qualitatively screened out, HCLPF capacities for these components can be developed to determine if further quantitative assessment is needed.

EPRI 3002020749 (2021) provides more in-depth discussion on each of the main aspects of the qualitative assessment.

Step 4b – Quantitative Assessment

The quantitative approach is intended to be used at NPPs that have performed a previous SPRA and that have an existing plant logic model to estimate the change in risk. If this is not available, further detailed seismic assessments of the identified susceptible DRC SSCs is recommended, or plant modifications can be considered to address any identified issues.

The quantitative approach limits the scope of component evaluation to DRC SSCs. For medium estimated Δ risk plants not passing the qualitative review, this is limited to those DRC SSCs whose frequency range of interest (FROI) falls in the frequency range where the GMRS exceeds the previous seismic assessment baseline. For high estimated Δ risk plants, the scope should be expanded to include all DRCs identified in the SPRA quantification, independent of the FROI. For both medium and high estimated Δ risk plants, the component evaluation should also include a review of the potentially risk significant low frequency sensitive SSCs and cliff edge failure modes that may not have been identified as DRCs previously.

Once the applicable SSCs have been identified, their fragilities can be scaled to account for the impact of the updated hazard. After the fragilities have been scaled, they should be reincorporated into the logic model and the quantification rerun to assess the impact on SCDF and determine a refined Δ risk.

EPRI 3002020749 (2021) provides more in-depth discussion on the scaling of fragilities and suggestions for modifications or sensitivities in the logic model to determine the Δ risk. A fragility scaling approach is proposed to update the seismic fragility for a given structure, system, and component (SSC) due to the seismic hazard change. The proposed approach assumes, as is typical for most scaling approaches, that the governing failure mode for the SSC of interest does not change due to the hazard change. The approach focuses on the SSC frequency governing the response and includes features to account for potential structural frequency shifts affecting the in-structure response spectra. Two examples are provided within the EPRI report which demonstrate the application of the methodology for component fragility scaling and structure fragility scaling.

CONCLUSION

EPRI has conducted a research program to develop a graded approach for evaluating the risk implications/insights when changes to the seismic hazard occurs at nuclear power plant sites. As part of this graded approach, simplified methods are proposed to assess the impact on plant risk due to a change in the seismic hazard. The full description of this research project along with its results and recommendations are documented in EPRI 3002020749 (2021). The key elements of this process include:

- Screening criteria based on a comparison of the updated seismic demand spectra to the SSE.
- Screening criteria based on the estimated Δ risk.
- Qualitative evaluation methods to assess the impact of the hazard change on dominant risk contributors.
- Simplified quantitative evaluation methods to scale existing fragilities to determine a refined Δ risk.
- Simplified evaluation methods to assess potential impacts on the non-linear cliff edge fragilities of liquefaction, slope stability, and SSC-to-SSC interaction, where the probability of seismic-induced failure can change abruptly with modest changes in seismic hazard.

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