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ESTIMATION OF SEISMIC HAZARD SEVERITY CORRESPONDING TO THE CLIFF EDGE EFFECT

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ABSTRACT

The evaluation of seismic margin is part of the safety assessment of the design. Seismic robustness is expressed by the seismic margin capacity, which defines the capability of a nuclear installation to achieve a certain performance under a seismic loading exceeding the Design Basis Earthquake (DBE). International Atomic Energy Agency (IAEA) Safety Requirements (2016) state that the design needs to provide sufficient margin to avoid cliff edge effects. Generally, the safety margin against seismic hazard is a surrogate for the performance objective of the installation. It means that if the design demonstrates the minimum adequate margin, the performance objective of the installation is achieved. The minimum adequate margin can be established based on a risk-informed and a performance-based (RIPB) process. It is common to characterize seismic margins using the high confidence low probability of failure (HCLPF) capacity in terms of the seismic hazard ground motion parameters, e.g., peak ground acceleration (PGA). In this paper, HCLPF capacity refers to the installation-level seismic fragility.

This paper first introduces a process for characterizing the hazard severity that may trigger initiation of a class of cliff edge failures at the installation level. Second, the paper proposes criteria for checking whether there is sufficient margin capacity to achieve the installation performance goal. A seismic-induced failure at ground motions higher than the threshold identified by this process is not regarded as a cliff-edge effect if no other symptoms are detected.

SEISMC-INDUCED CLIFF EDGE EFFECTS

Classic cliff-edge failures are often triggered by seismic-induced failure modes with widespread common-cause failure (CCF) consequences of structure, system, and component (SSC) failures from which the installation cannot recover. The following are examples of classic seismic-induced failure events that can lead to cliff-edge effects:

- Structure(s) partial or total collapse can result in failure of multiple safety-related housed SSCs.
- Severe soil liquefaction can lead to ground failures or severe settlement across the installation site and the concurrent loss of one or more safety functions.
- Slope instability, ground subsidence, and surface rupture due to capable fault displacement can lead to similar outcomes to liquefaction-induced settlement.
- Seismic-induced flood (e.g., failure of upstream dams or tsunami that can flood the installation site).

A non-classic cliff-edge scenario may be possible whereby seismic-induced multiple failures of SSCs with HCLPF capacities close to the installation-level HCLPF capacity may lead to an abrupt increase in the installation-level seismic fragility without these SSC failures being triggered by a single failure event.

IDENTIFICATION OF POTENTIAL CLIFF EDGE FAILURES

As described in IAEA (2022), an installation-level fragility curve explicitly developed using probabilistic safety assessment (PSA) methods often consists of discrete conditional probability values determined at specified increments of the hazard parameter and interpolated in between. This installation-level fragility curve is typically the Boolean sum (union) of multiple fragility curves representing the minimal cutsets that can lead to unacceptable performance of the design.

For classic cliff-edge failure, identification of potential cliff-edge failure modes can be relatively straightforward from review of the cutset fragilities. The cutset fragility for a potential classic cliff-edge effect will exhibit an abrupt increase in the conditional probability of failure due to a small increase in the hazard level. Figure 1 presents an idealized example.

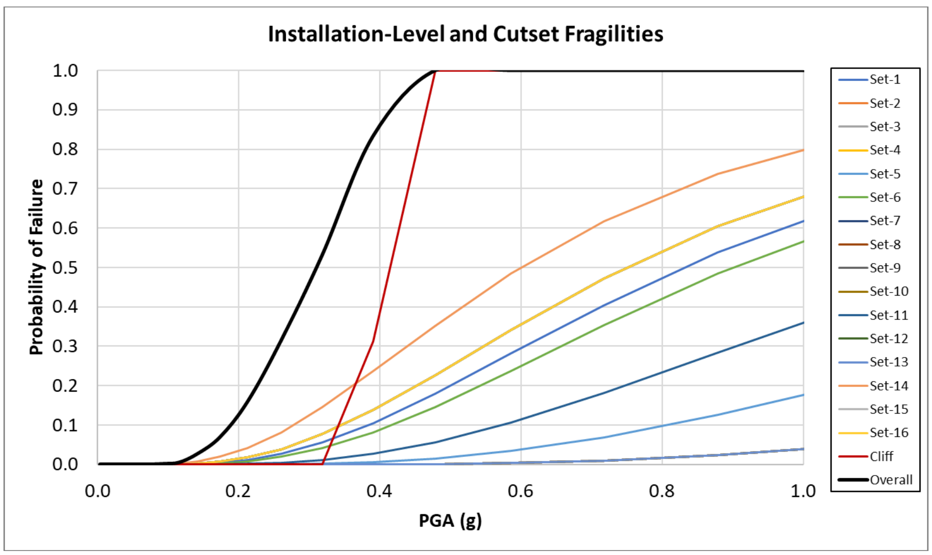

Figure 1. Example installation-level fragility with potential cliff edge failure (IAEA, 2022).

Identification of potential non-classic cliff-edge scenarios is less straightforward and is the focus of this paper. An installation design may or may not have this weakness. A practical technique to screen for potential cliff edge effects in the installation-level fragility is by using the ratio of $A_{10\%}$ to the HCLPF capacity, where $A_{10\%}$ is the seismic hazard parameter value corresponding to 10% mean conditional probability of failure. The objective is to confirm whether the conditional probabilities of failure are rising too abruptly with the increase in hazard level so as to signify that a cliff-edge behaviour may underly this behaviour and only perform a detailed review if it does. Using this ratio is robust since the relatively narrow hazard parameter range between the HCLPF capacity and $A_{10\%}$ typically contributes about 50% at least of the computed annual frequency of failure, as illustrated later in this paper.

Kennedy (1999) suggested that a $\beta_c = 0.3$ is appropriate for typical installation-level seismic fragility curves represented by lognormal fragility functions, where β_c is the composite logarithmic standard deviation controlling the slope of the mean fragility curve. Examination of installation-level seismic fragility curves compiled in EPRI (2020) from recent seismic probabilistic risk assessments (SPSAs) performed at eighteen United States nuclear power plants using modern methods confirmed that $\beta_c = 0.3$ is representative of their range. The potential occurrence of cliff edge effects at ground motion amplitudes not sufficiently higher than the HCLPF capacity will lead to considerably lower values of β_c. For β_c equal to 0.3, the ratio $A_{10\%}$ /A_{HCLPF} is equal to:

$$A_{10\%} / A_{HCLPF} = A_M \exp(-1.28\beta c) / A_M \exp(-2.33\beta c) = 1.37 \quad (1)$$

where A_M is the median seismic capacity of the lognormal fragility function.

Accordingly, a ratio of $A_{10\%}$ /A_{HCLPF} less than 1.37 on the mean installation-level fragility may indicate the presence of a non-classic cliff-edge scenario with insufficient margin to meet the performance goal.

In such case, further review of the cutsets, individual SSC fragilities, and accident sequences should be performed to understand the reason for the steep fragility curve and make decisions accordingly. Whether this finding corresponds to initiation of a cliff edge effect requires considering the seismic design basis, the existing margin in A_{HCLPF} relative to the DBE, hazard frequencies associated with the DBE, annual frequency performance goal, and proper consideration of uncertainties. While this technique offers a powerful and simple screening tool for cliff edge effects, using this technique requires the availability of the installation-level mean fragility curve from the explicit solution of a PSA logic model, that is, it cannot be fully implemented with the seismic margin analysis (SMA) methodology output but could be partially implemented using conservative assumptions, as discussed below.

MARGIN ADEQUACY ASSESSMENT FOR CLIFF EDGE FAILURES

The criteria for assessment of design margin adequacy against potential cliff edge failures depend on whether this failure is a result of a single CCF event that results in widespread SSC failures in the classic sense of the term or a result of a non-classic cliff edge failure scenario due to abrupt accumulation of failure probabilities of many individual SSC failures with commensurate HCLPF capacities. An adequate margin against cliff edge failures should satisfy the following conditions:

- The annual frequency performance metric of the facility, computed using the installation-level fragility, is below the established performance goal, or the contribution of the cliff-edge cutset fragility (for classic cliff-edge failures) is below a specific percentage of annual frequency;[1]
- The installation-level HCLPF is greater than the established minimum HCLPF; and
- The $A_{10\%}$ capacity is higher than 1.4 times the established minimum HCLPF unless justified by further cutset review.

If only the HCLPF capacities are available (e.g., from a PSA-based SMA), explicit evaluation of these criteria is not possible. As an alternative, a semi-qualitative review may be possible to justify concluding with confidence the adequacy of seismic margin. One approach to conducting this review can be implemented as follows:

- Assign conservatively biased (i.e., low) generic β_c values to SSCs and develop a conservative estimate of the mean installation-level fragility using the PSA model.
- Check the conditions listed above using the estimated installation-level fragility.

[1] Using the lesser margin from these two criteria recognizes that if only the first criterion is not achieved then the potential cliff-edge failure has a small contribution to risk, and the performance goal can be more effectively achieved by other means, e.g., hardening risk-significant SSCs. Meanwhile, for significantly flat hazard curves, the seismic margin required to achieve the second criterion may be impractically large while not significantly improving the annual performance frequency.

This alternative evaluation in the absence of an explicitly determined fragility function is clearly one which relies on judgment. Appropriate conservatism needs to be considered in exercising this judgment.

ILLUSTRATION OF SIGNIFICANCE OF $A_{10\%}$

The following illustrative example shows relations between the DBE, HCLPF capacity, and $A_{10\%}$; the corresponding mean hazard frequencies; and the cumulative contributions to the conditional core damage probability (CCDP). The hazard curve is assumed to follow a sufficiently linear slope in log-log space for the range of ground motions of interest to the installation performance. This curve is described by the following equation:

$$H(a) = Ki\ a^{-K_H} \tag{2}$$

where K_H is the slope of the hazard curve in log-log space and K_i is a constant. Note that:

$$K_h = LOG\ (1/A_R) \tag{3}$$

where A_R is the ratio by which the ground motion parameter value, a, increases over a one decade change in H(a). For the following example, the following hazard curve and fragility parameters are used.

Mean Hazard Curve Parameters:

$$A_R = 1.85 \quad K_H = 3.74 \quad K_i = 2.35E\text{-}07 \tag{4}$$

Mean Plant State Fragility Parameters:

$$A_m = 0.60g \quad \beta_r = 0.18 \quad \beta_u = 0.24 \quad \beta_c = 0.30 \tag{5}$$

where

DBE = 0.2g
HCLPF = 0.3g (1.5xDBE)
$A_{10\%}$ = $A_m \exp(\beta_c\ \Phi^{-1}(\ 0.10\ ))$ $A_{10\%} =\ 0.41g$

Figure 2 shows these characteristic points (DBE, HCLPF, and $A_{10\%}$) on the plant state mean fragility and on the mean seismic hazard curve.

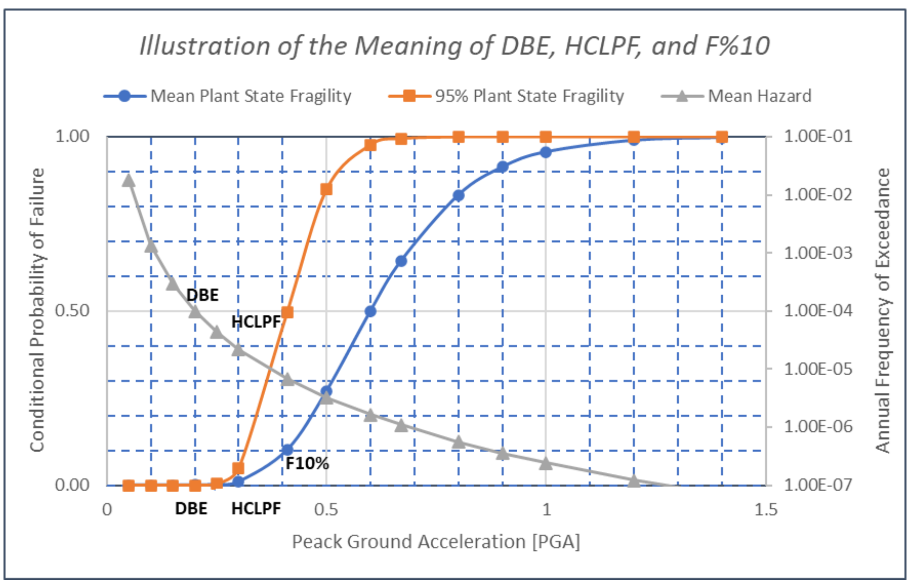

Figure 2. Illustration of DBE, HCLPF, and $A_{10\%}$.

Figure 3 shows contribution of the acceleration bins to the mean core damage frequency (CDF). Acceleration bins are defined in Table 1. Table 2 shows the contribution of each acceleration bin to CDF and cumulative CDF. It also shows the corresponding 95% confidence CCDP and ratio to Safe Shutdown Earthquake ground motion. The 95% confidence CCDP is calculated using a lognormal distribution with a standard deviation equal to β_r and a median capacity equal to the following:

$$A_{m,95\%} = A_m \exp(\beta_R \, \Phi^{-1}(0.5) - \beta_U \, (\Phi^{-1}(0.95)) \qquad (6)$$

Review of Table 2 and Figure 3 indicates the following:

- The acceleration bin with the highest CDF contribution includes or is close to the $A_{10\%}$ point. In this example, Bin #4 (0.4g to 0.5g) includes the $A_{10\%}$ point of 0.41g.
- The acceleration bins that contains the $A_{10\%}$ point and lower contribute about 50% of the mean CDF (cumulative).
- The 95% confidence CCDP at $A_{10\%}$ is typically greater than 0.5, i.e., the installation is more likely to fail than to recover from ground motions stronger than $A_{10\%}$ at the 95% confidence level.

Review of other examples with hazard and fragility curve parameter ranges representative of typical installations indicated qualitatively similar observations.

Table 1: Acceleration Bins

Bin	a1	a2	a (average of a1 and a2)	H(a1)	H(a2)	dH
1	0.1	0.20	0.15	1.30E-03	9.71E-05	1.20E-03
2	0.2	0.30	0.25	9.71E-05	2.13E-05	7.58E-05
3	0.3	0.40	0.35	2.13E-05	7.25E-06	1.40E-05
4	0.4	0.50	0.45	7.25E-06	3.15E-06	4.11E-06
5	0.5	0.60	0.55	3.15E-06	1.59E-06	1.56E-06
6	0.6	0.70	0.65	1.59E-06	8.93E-07	6.97E-07
7	0.7	0.80	0.75	8.93E-07	5.42E-07	3.51E-07
8	0.8	0.90	0.85	5.42E-07	3.49E-07	1.93E-07
9	0.9	1.00	0.95	3.49E-07	2.35E-07	1.14E-07
10	1	1.10	1.05	2.35E-07	1.64E-07	7.05E-08

Table 2: CDF Contributions by Individual Acceleration Bins

Bin	dH	$F_{(a,mean)}$	$dH*F_{(a,mean)}$	CDF%	Cumulative CDF %	$F_{(a,95\%CCDP)}$	xDBE
1	1.20E-03	1.91E-06	2.30E-09	7.49E-02	7.49E-02	1.82E-08	0.75
2	7.58E-05	1.76E-03	1.33E-07	4.35E+00	4.42E+00	3.80E-03	1.25
3	1.40E-05	3.62E-02	5.08E-07	1.66E+01	2.10E+01	2.12E-01	1.75
4	4.11E-06	1.69E-01	6.93E-07	2.26E+01	4.36E+01	7.24E-01	2.25
5	1.56E-06	3.86E-01	6.01E-07	1.96E+01	6.31E+01	9.56E-01	2.75
6	6.97E-07	6.05E-01	4.22E-07	1.37E+01	7.69E+01	9.96E-01	3.25
7	3.51E-07	7.72E-01	2.71E-07	8.83E+00	8.57E+01	1.00E+00	3.75
8	1.93E-07	8.77E-01	1.69E-07	5.52E+00	9.12E+01	1.00E+00	4.25
9	1.14E-07	9.37E-01	1.06E-07	3.47E+00	9.47E+01	1.00E+00	4.75
10	1.65E-07	9.89E-01	1.63E-07	5.30E+00	1.00E+02	1.00E+00	5.25

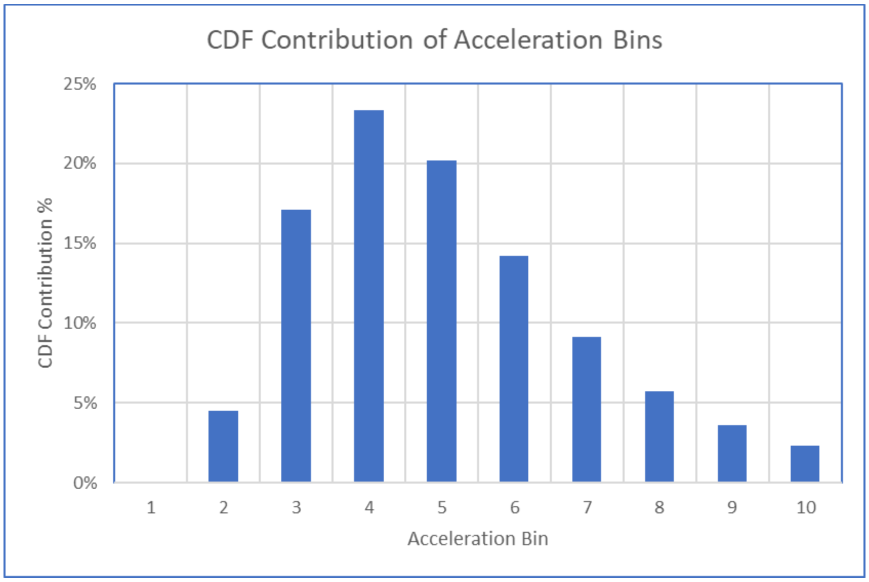

Figure 3. Percentage Contributions of Ground Acceleration Bins to Annual Performance Frequency

CONCLUSION

This paper summarizes an approach for characterizing the adequacy of seismic margins against cliff edge effect. This approach was developed in an IAEA project and documented in IAEA (2022). It is expected to be published in an IAEA Technical Document (TECDOC) in 2023. Seismic margin is characterized as the HCLPF capacity compared to the DBE ground motion. The paper introduced the definition and examples of classic CCF cliff edge effects that lead to abrupt increase in conditional probabilities of installation-level failure with small increases in the hazard parameter.

In addition, the paper identified a potential non-classic edge failure scenario whereby independent failures of several SSCs with HCLPF capacities close to the installation-level HCLPF capacity may lead to an abrupt decrease in the likelihood of the installation ability to recover safety or mitigation functions. The paper introduced proposed criteria for identifying and assessing the adequacy of seismic margin against potential classic and non-classic cliff edge failures. These criteria use the HCLPF capacity as a measure of seismic margin, the $A_{10\%}$ acceleration corresponding to 10% conditional mean failure probability as a measure of potential abruptness in the installation-level fragility curve, and the mean annual frequency of installation failure as a measure of overall seismic safety performance.

The proposed criteria offer a powerful and efficient screening tool for the presence of potential non-classic cliff edge effects that utilizes the ratio of $A_{10\%}$ / A_{HCLPF}, which can be readily computed from probabilistic safety assessment output. While some of these metrics require the presence of safety analysis results from SPSAs or PSA-based SMAs, the use of this criteria could be partially implemented using results from SMAs.

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