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EQUIPMENT CAPACITIES FROM EARTHQUAKE EXPERIENCE DATA FOR USE IN FRAGILITY CALCULATIONS

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ABSTRACT

Electric Power Research Institute (EPRI) has recently researched the development of refined equipment capacities from earthquake experience data for use in fragility calculations, which is a key component of nuclear seismic probabilistic risk assessments (SPRAs). Refined capacities result in more realistic fragilities, ultimately providing more accurate estimates of the risk.

EPRI develops and maintains a large database of earthquake data spanning four decades. A multi-phase project was initiated in 2014 by EPRI to review available data and apply improved statistical methods to update the seismic capacity of selected equipment classes. Phase I (EPRI 3002011627, 2017a) examines two statistical techniques (Frequentist and Bayesian) and develops updated capacities for eight classes: Control Panels, Engine Generators, Fans, Horizontal Pumps, Inverters and Battery Chargers, Motor Control Centers, Motor Operated-Valves, and Medium Voltage Switchgear. Phase II (EPRI 3002013017, 2018a) reviews the capacities of eight additional classes: Air Compressors, Air-operated Valves, Batteries on Racks, Distribution Panels, Instruments on Racks, Low Voltage Switchgear, Transformers, and Vertical Pumps. Updated best-estimate median capacities for these sixteen classes are up to 47% greater than the EPRI NP-6041-SLR1 (1991a) median of 4.8g. A series of sensitivity studies investigate the influence various inputs and demonstrate that updated best-estimate capacities are driven more by data than subjective judgment. This paper summarizes the main findings of the project and provides an example of how these capacities could be used in practice.

INTRODUCTION

Several seismic evaluation methods have used earthquake experience data to estimate capacities and demonstrate seismic adequacy for nuclear power plant (NPP) equipment. Initially, the Seismic Qualification Utility Group (SQUG) responded to Unresolved Safety Issue (USI) A-46 (USNRC, 1987) by using earthquake experience to demonstrate the seismic adequacy of several classes of equipment found in NPPs. Other EPRI guidance documents, such as NP-6041-SLR1 (1991a), TR-103959 (1994), 1002988 (2002), and 1019200 (2009)[1], provide methods for estimating seismic margins and fragilities using earthquake experience data. These documents estimate probabilistic seismic capacities for equipment commonly found in NPPs based on a simplified statistical analysis of a database of equipment that has survived actual earthquakes. The present study improves upon the approaches developed in these earlier references by:

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[1] EPRI TR-103959 (1994), 1002988 (2002), and 1019200 (2009) have been superseded by EPRI 3002012994 (2018c).

- examining and analyzing the earthquake experience database, including data collected from recent post-earthquake investigations,
- augmenting, modifying, and reformulating the statistical methodology used to develop seismic capacities from experience data.

Two statistical frameworks (Frequentist and Bayesian) and sixteen classes of equipment are examined. Results of this study are documented in two reports (EPRI 3002011627 (2017a) and 3002013017 (2018a)). This paper provides highlights from this research and discusses the results for two sample equipment classes (Horizontal Pumps (HPs) and Motor-Control-Centers (MCCs)). For brevity, only Bayesian capacities are presented in detail since they were determined to be more realistic than Frequentist capacities.

EARTHQUAKE EXPERIENCE DATA

Database

The experience data used in the seismic capacity calculations consist of seismic demands at database sites and documented equipment performance in actual earthquakes[2]. The data are primarily obtained from the EPRI eSQUG online database v2.7 (EPRI 2017b) and augmented with information from EPRI NP-7149-D and its Supplement 1 (1991b and1996).

Seismic Demands at Database Sites

Most database sites in eSQUG v2.7 have an associated 5% damped horizontal average acceleration response spectrum. The spectra characterize the free field ground motion that occurred in the vicinity of the sites and were developed according to procedures approved by the Nuclear Regulatory Commission (NRC) in TAC NO.MA9464 (2001). Only eSQUG v2.7 sites associated with a response spectrum are included in this study.

Consistent with EPRI 1002988 (2002) and EPRI 1019200 (2009), the experience-based seismic capacities are developed in terms of a broad-banded 2.5 to 7.5 Hz average 5% damped spectral acceleration (Sa_b). Figure 1 shows an example calculation of Sa_b for the Coalinga Water Treatment Plant during the 1983 Coalinga Earthquake. This quantity is computed from each eSQUG v2.7 database site response spectrum.

Treatment of Independence

Multiple experience datasets for the same equipment class were often collected at each database site. Therefore, some degree of correlation may exist between two equipment items. The statistical analysis in this study assumes each equipment item as statistically independent and discards data that do not meet the IEEE 344 (2004) independence criteria:

> *"Independent items are components and equipment that: (a) have different physical characteristics or (b) experienced different seismic motion characteristics, e.g., different earthquakes, different sites, different buildings, or different orientations/locations in the same building. For example, two or more identical items of equipment located side by side are considered a single independent item for each earthquake experienced."*

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[2] Data were collected at power plants, substations, and large industrial facilities located in the epicentral regions of moderate-to-large earthquakes (magnitudes ranging 5.3 to 8.1). The database includes data from worldwide events spanning 1971-2010.

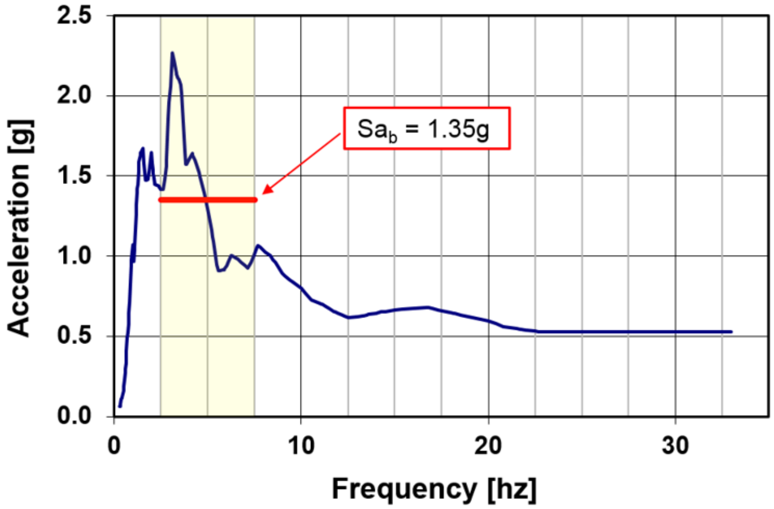

Figure 1 – Broad-banded Ground Spectral Acceleration (Sa$_b$) at Coalinga Water Treatment Plant for the 1983 Coalinga Earthquake

In-Structure Seismic Demands

EPRI 1002988 (2002) developed capacities expressed in terms of ground spectral acceleration. EPRI 1019200 (2009) improved the EPRI 1002988 approach by developing capacities in terms of in-structure spectral acceleration using an estimated median amplification factor of 1.407 for the database site structures. This is a reasonable approach, but can be improved by accounting for the distribution of equipment along the height of the structures. The present study improves upon EPRI 1019200 (2009) by adopting a "graded" approach like that in MCEER-99-0008 (1999). The equipment elevation is used to estimate a structural amplification factor (AF_{Dj}) for each location j according to the following criteria:

- For elevations < 20 ft (6.1 m), AF_{Dj} = 1.0
- For elevations of 20 ft to 40 ft (6.1 m to 12.2 m), AF_{Dj} = 1.5
- For elevations > 40 ft (12.2 m), AF_{Dj} = 2.0
- When the elevation is not discernable from the available information, AF_{Dj} is conservatively set to 1.0 (i.e., the equipment is conservatively assigned to the < 20 ft (6.1 m) elevation bin)

Table 1 shows the elevation distribution for independent equipment items included in the database for HPs and MCCs.

Table 1 – Independent Equipment Items and Locations within Database Site Structures

Equipment Class	**< 20 ft (6.1 m)**	**20 ft to 40 ft (6.1 m to 12.2 m)**	**> 40 ft (12.2 m)**	**Total**
Horizontal Pumps	228	1	1	230
Motor Control Centers	236	30	10	257

Equipment Performance

The seismic capacity characterized for this study is described in the SPRA literature as "function after" the earthquake (EPRI 3002012994 (2018c)). As such, only those failures from the earthquake experience data that are associated with the functionality of the equipment following the earthquake are treated as failures.

The experience database contains an abundance of survival data, as well as instances of damage, failures, and/or changes of state, which are denoted collectively as "anomalies" for this study. Examples of anomalies include relay chatter, unplugging of components, damage due to differential settlements, anchorage failure, excessive reaction loads, loss of power, etc. Most anomalies clearly do not represent failure for the purposes of developing seismic fragilities for NPP applications (e.g., the equipment momentarily lost power or was physically damaged but otherwise operable following the earthquake). Other anomalies require detailed reviews to classify their treatment in this seismic capacity study. The anomaly review relies on a screening process[3] (Figure 2), which involves dispositioning each anomaly per the following criteria:

- The equipment did not meet the EPRI NP-6041-SLR1 (1991b) inclusion rules[4] for the equipment class and is therefore outside the class bounds (e.g., gas turbines are specifically excluded from the Engine Generator equipment class).
- The anomaly would have been precluded or identified and evaluated separately during a review following the EPRI NP-6041-SLR1 (1991b) guidelines and caveats.
- The anomaly is determined not to be earthquake-related (e.g., a random failure).
- The anomaly would be precluded at a nuclear plant based on normally required maintenance and inspection procedures in nuclear industry (e.g., a fuse not fully engaged in its clamps).
- The anomaly is associated with a failure mode that is separately evaluated in the seismic fragility process:
    - Anchorage
    - Function during shaking (i.e., relay/contact chatter)
    - Seismic interactions (e.g., differential displacements, seismic induced fire/flooding)
- The anomaly did not preclude the specific functionality that would be modelled in a nuclear SPRA logic model (i.e., did not fail the intended safety function of the equipment).

Anomalies that do not meet any of the above screening criteria are treated as failures in this seismic capacity study.

The anomaly dispositioning process sometimes requires subjective interpretation of the equipment performance based on limited information. To gain confidence in the anomaly disposition, expert elicitation is employed for the most uncertain data. The anomalies are categorized into three groups (Figure 3):

- Group A: the anomaly is clearly not a failure for the purposes of the seismic capacity calculations in this study (e.g., anchorage clearly the basis for damage).
- Group B: the anomaly requires some limited subjective interpretation and engineering judgment in characterizing whether the anomaly should be treated as a survival. These anomalies were reviewed by an independent expert to verify the authors' opinion.
- Group C: the anomaly is ambiguous and requires review by a larger independent group of knowledgeable engineers to add confidence to the "failure" determination process. The SQUG Steering Group was invited to perform this independent review.

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[3] For a detailed description of the flowchart in Figure 2 see Appendix B of EPRI 3002011627 (2017a).

[4] EPRI NP-6041-SLR1 requires the walkdown team to be familiar with the intent and recommendations of the Senior Seismic Review and Advisory Panel (SSRAP, 1992) and SQUG Generic Implementation Procedure (GIP, 2001). As such, wherever this study refers to EPRI NP-6041-SLR1 class definitions, caveats, and restrictions, it is to be understood that this also refers to the intent and recommendations in SSRAP and GIP.

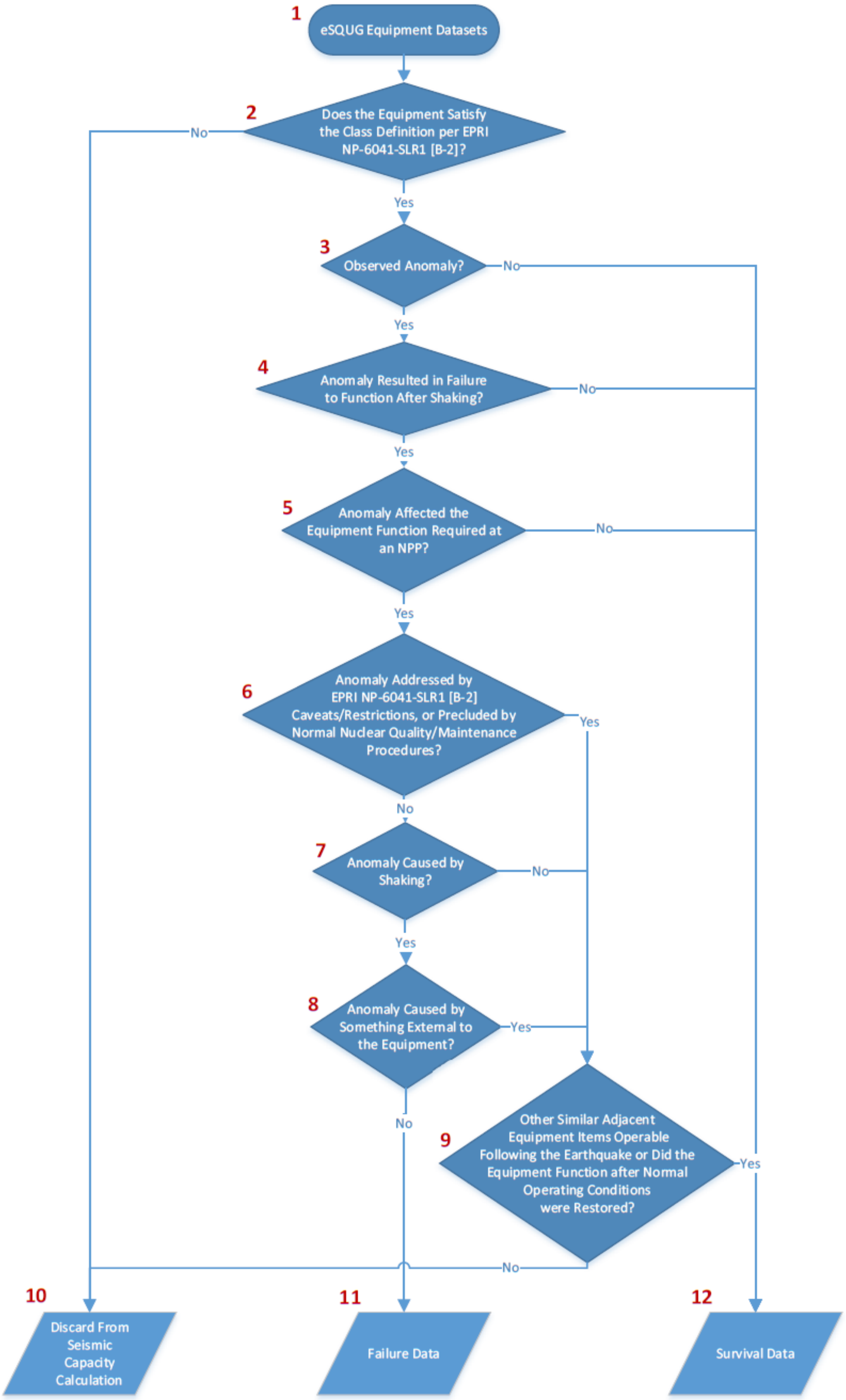

Figure 2 – Flowchart for Experience Data Screening Process

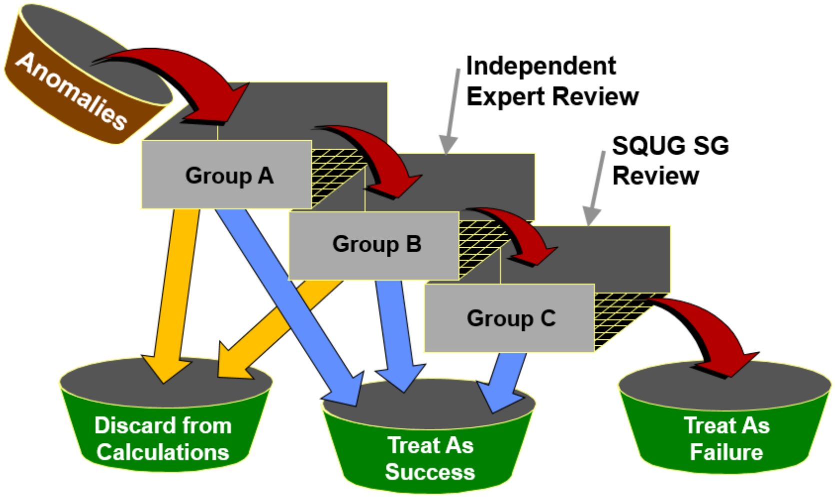

Figure 3 – Process for Reviewing Anomalies

Table 2 summarizes the anomaly review results for HPs and MCCs classes. Fewer than 10% of the HPs and MCCs datasets[5] are categorized as anomalies. All anomalies for these two classes were dispositioned as survivals in either Group A or B.

Table 2 – Database Groups for Horizontal Pumps and MCCs Datasets

Equipment Class	**Total No. Datasets**	**Group A Datasets**	**Group B Datasets**	**Group C Datasets**
Horizontal Pumps	214	16	3	0
Motor Control Centers	235	32	1	0

Special Considerations for Equipment Data from Kashiwazaki-Kariwa Nuclear Power Plant

Some of the more recent earthquake experience data considered in this study was collected from the Kashiwazaki-Kariwa (KK) NPP in Japan following the 2007 Niigataken Chuetsu Oki (NCO) earthquake. KK is the first NPP subject to a SQUG post-earthquake investigation. To ensure the capacities developed in this study are representative of the generic SQUG equipment classes, the KK data should only be included if it is similar to the balance of the database equipment.

Based on a review of the descriptive information in the database and interviews with the SQUG engineers who performed the KK investigation, it is judged that the mechanical equipment classes (e.g., HPs) at KK are generally similar to their respective generic SQUG classes; therefore, KK data may be included in the capacity calculations for mechanical classes. Conversely, the electrical equipment in Japanese NPPs (e.g., MCCs) are often designed significantly stiffer than the common configurations in the experience database. Overall, it is not yet well known whether the Japanese electrical equipment is representative of the generic equipment classes, and further study is needed in this area. As such, the best-estimate capacity calculations for the electrical equipment classes have been performed excluding the KK datasets.

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[5] A "dataset" is a collection of information describing a component including dimensions, location, photos, etc., and a summary of its performance during and after the earthquake. Each dataset has a unique identification number (ID), and may describe an individual component or multiple similar components.

The KK site acceleration recordings are unique because they were collected in the free field, as well as at various elevations within the various structures. Similar to the other sites, the broad-banded horizontal average Sa_b demands are computed for each KK recording, but structure amplification factors are not estimated for the KK equipment since the recordings are generally in-structure and representative of the equipment mounting locations.

BAYESIAN SEISMIC CAPACITY CALCULATIONS

The Bayesian updating approach begins with the selection of a subjective prior, which captures the analyst's expert judgment or current state of belief concerning the equipment seismic capacity. The prior is then updated according to Bayes' Theorem, which quantitatively adjusts the seismic capacity parameters to account for the observed equipment performance data using a likelihood function. The result is a posterior estimate of the seismic capacity parameters, which accounts for both the prior state of belief as well as the observed experience data.

Prior

The seismic capacity model in Eq. 1 depends on two statistical parameters: median capacity C_m and related logarithmic standard deviation $\beta_{\hat{C}}$. Their values are uncertain, and their estimates can be improved by considering experience data. The local, in-structure spectral acceleration demand at the equipment mounting point, Sa_{bl}, is calculated by multiplying the broad-band demand (Sa_b) by the structural amplification factors (AF_{Dj}) presented above. The probability of failure is therefore defined as:

$$P_F = \Phi\left(\ln\left(Sa_{bl}/C_m\right)/\beta_{\hat{C}}\right) \tag{1}$$

where $\Phi(\cdot)$ is the cumulative standard normal distribution function.

The Bayesian Updating process begins by quantifying the current state of belief about C_m and $\beta_{\hat{C}}$. Each parameter is modeled with a lognormal distribution representing the best estimate value and uncertainty. As described in EPRI 3002011627 (2017a):

- The best estimate value of C_m, denoted C_{mbe}, is judged to be 4.8g for all equipment classes.
- The logarithmic standard deviation representing qualitative uncertainty in C_m is $\beta_{\hat{C}m} = 0.42$.
- The best estimate value of $\beta_{\hat{C}}$, denoted $\beta_{\hat{C}be}$, is also judged to be 0.42.
- The logarithmic standard deviation representing qualitative uncertainty $\beta_{\hat{C}}$ is $\beta_{\beta\hat{C}} = 0.20$.

The above lognormal distributions on C_m and $\beta_{\hat{C}}$ characterize the current state of belief about the seismic capacity parameters for equipment in the generic SQUG equipment classes. They both depend on analyst judgment and could vary within a reasonable range depending on the opinion and experience of the analyst. To examine whether the Bayesian approach produces stable results across different analysts, multiple sensitivity studies are discussed below in which the prior parameters are adjusted within a reasonable range to determine the effect on the results.

As described in EPRI 3002011627 (2017a), the prior is defined by the joint probability distribution obtained by multiplying together the two lognormal probability density functions for C_m and $\beta_{\hat{C}}$:

$$p\left(C_m, \beta_{\hat{C}}\right) = \varphi\left(\ln\left(\frac{C_m}{C_{mbe}}\right)\Big/\beta_{\hat{C}_m}\right)\cdot\varphi\left(\ln\left(\frac{\beta_{\hat{C}}}{\beta_{\hat{C}be}}\right)\Big/\beta_{\beta_{\hat{C}}}\right) \tag{2}$$

where $\varphi(\cdot)$ is the standard normal probability density function.

Likelihood Function

The Bayesian updating procedure involves defining the likelihood of observing the experience data across the domain of possible values for C_m and $\beta_{\hat{C}}$. The experience data is expressed in terms of survivals and failures, and the seismic capacity gives the probability of failure P_F. The likelihood function[6] is defined in EPRI 3002011627 (2017a):

$$L'\left(\{n, Sa_{bl}\} \mid C_m, \beta_{\hat{c}}\right) = \prod_{i=1}^{m} \left(1 - \left(P_F\right)_i\right)^{n_i} \tag{3}$$

Here $\{n, Sa_{bl}\}$ is used to denote a set of observations $(n_1, Sa_{bl,1})$, $(n_2, Sa_{bl,2})$…$(n_m, Sa_{bl,m})$, where:

- n_i is the number of components observed to survive local spectral acceleration $Sa_{bl,i}$
- $(P_F)_i$ is the probability of a single component failing at acceleration level $Sa_{bl,i}$, given capacity parameters C_m and $\beta_{\hat{C}}$
- $(1\text{-}P_F)^n$ is the probability of observing n survivals and zero failures in n observations
- m is the total number of different local spectral accelerations included in the experience data for the equipment class

Bayesian Update

The "posterior" joint distribution on C_m and $\beta_{\hat{C}}$, which quantifies the state of belief about these parameters after considering the observed equipment performance, is given by Bayes' Theorem:

$$f\left(C_m, \beta_{\hat{c}} \mid \{n, Sa_{bl}\}\right) = L'\left(\{n, Sa_{bl}\} \mid C_m, \beta_{\hat{c}}\right) \cdot p\left(C_m, \beta_{\hat{c}}\right) \tag{4}$$

In this case, $f\,(C_m, \beta_{\hat{C}} \mid \{n, Sa_{bl}\})$ is the posterior distribution of C_m and $\beta_{\hat{C}}$, conditional on the observed experience data. The normalization factor (denominator of Bayes' Theorem) is omitted from this equation, as is common in computational Bayesian analyses.

The posterior statistical parameters are estimated by approximating the posterior $f\,(\cdot)$ as a joint distribution on independent variables C_m and $\beta_{\hat{C}}$. Updated best estimates C'_{mbe} and $\beta'_{\hat{C}be}$ are then taken as the medians of the respective constituent distributions. Similarly, $\beta'_{\hat{C}m}$ and $\beta'_{\beta\hat{C}}$ are the updated logarithmic standard deviations for the posterior distributions on C_m and $\beta_{\hat{C}}$.

BEST-ESTIMATE RESULTS

Table 3 shows the updated median and 1% probability of failure capacities and logarithmic standard deviations including KK data for HPs and excluding KK data for MCCs. For both classes, the median capacities increased by more than 30% over the 4.8g prior, and the capacity uncertainty was slightly reduced. The capacities in Table 3 represent best-estimate values.

Table 3 – Updated Best-Estimate Probabilistic Bayesian Capacities for HPs and MCCs

Equipment Class	**Number of Survivals**	**C'_{mbe} (g)**	**$\beta'_{\hat{C}be}$**	**$C_{1\%}$ (g)**
Horizontal Pumps	203	6.59	0.39	2.65
Motor Control Centers	200	6.28	0.40	2.48

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[6] The likelihood function presented herein is appropriate for updating with data that includes only survivals, which is the case for HPs and MCCs classes. An alternative likelihood function capable of including failure data is developed in EPRI 3002011627 (2017a).

SENSITIVITY STUDIES

EPRI 3002011627 (2017a) included nine sensitivity studies to investigate how various elements of the Bayesian approaches influence the calculated capacities. Three key sensitivity studies are summarized below, with results for HPs provided in Table 4.

Sensitivity Case 1 – Equipment Independence

The Bayesian calculations consider only independent equipment survivals. This study examines the extreme hypothetical situation in which all items are considered independent. This sensitivity study does not imply that including the full population is a reasonable alternative to only including independent items; indeed, it is inappropriate to include the full population. The purpose is merely to investigate the consequence of substantially increasing the number of items included in the calculations, where the additional data have elevation and spectral demand distributions similar to data already included in the database.

Sensitivity Case 2 – Structural Amplification

The current study uses a “graded” approach to estimate structural amplification for each equipment item in the experience database. In contrast, EPRI 1019200 (2009) estimates a median structural amplification factor of 1.407 regardless of the distribution of equipment along the height of the database structures. To examine the effects of the structural amplification method, calculations are performed using the methods developed herein with all free field motions scaled by the median amplification factor of 1.407 without regard for location in the structure. KK spectra are not scaled because they are reasonably representative of the seismic demand at the equipment mounting point.

Sensitivity Case 3 – Bayesian Prior

The Bayesian approach uses prior distributions on C_m and $\beta_{\hat{C}}$ that are heavily dependent on expert judgment of the analyst. While the values presented above are judged to represent best estimates, different knowledgeable analysts could propose different priors within a reasonable range. To investigate whether differences in the subjective priors could significantly affect the Bayesian results, four alternate cases are evaluated:

a) C_{mbe} is a factor of 1.5 lower than the best estimate case. All other parameters are held the same. This is considered to be a conservative estimate, but still within a reasonable range that could be judged by a knowledgeable analyst.
b) C_{mbe} is a factor of 1.5 lower than the best estimate case and $\beta_{\hat{C}m}$ is increased to an upper bound estimate of 0.55. The increased $\beta_{\hat{C}m}$ accounts for the fact that decreasing C_{mbe} by a factor of 1.5 reflects additional uncertainty in C_{mbe} compared to the base case, which should be quantified in $\beta_{\hat{C}m}$. This case effectively accomplishes the same objective as Case (a) by considering the possibility that an analyst could judge a lower value of C_{mbe}, and also accounts for the additional uncertainty in C_m that would be implied by variant judgments among knowledgeable analysts.
c) $\beta_{\hat{C}m}$ is reduced to 0.25 and other parameters are held the same. This case represents a lower-bound on the reasonable range of $\beta_{\hat{C}m}$, corresponding to a situation wherein the analyst is highly confident in judging a value for C_{mbe}.
d) $\beta_{\beta\hat{C}}$ is reduced to 0.11 and other parameters are held the same. This case represents a lower-bound on the reasonable range of $\beta_{\beta\hat{C}}$, corresponding to a situation wherein the analyst is highly confident in judging a value for $\beta_{\hat{C}}$.

Sensitivity Study Results

Table 4 shows that the HP capacity is fairly stable across a reasonable range of alternative subjective input parameters and data interpretations, suggesting that the results are primarily governed by objective experience data rather than analyst judgment. Similar trends were observed for other classes with varying numbers of datasets and elevation distributions.

Table 4 – Horizontal Pumps Capacities Calculated for Different Sensitivity Case

Case		**Number of Survivals**	**C'_{mbe} (g)**	**$\beta'_{\hat{C}be}$**	**$C_{1\%}$ (g)**	**% Diff. in C'_{mbe} from Base Case**
Base Case	Best-estimate	203	6.59	0.39	2.65	-
Sensitivity Case 1	Equipment Independence	462	6.97	0.38	2.84	5.7%
Sensitivity Case 2	Structural Amplification	203	6.84	0.39	2.77	3.8%
Sensitivity Case 3a	Bayesian Prior Case (a) (C_{mbe} = 3.2g)	203	5.58	0.38	2.32	-15.3%
Sensitivity Case 3b	Bayesian Prior Case (b) (C_{mbe} = 3.2g and $\beta_{\hat{C}m}$ = 0.55)	203	6.29	0.39	2.55	-4.6%
Sensitivity Case 3c	Bayesian Prior Case (c) ($\beta_{\hat{C}m}$ = 0.25)	203	5.68	0.38	2.34	-13.8%
Sensitivity Case 3d	Bayesian Prior Case (d) ($\beta_{\beta\hat{C}}$ = 0.11)	203	6.67	0.41	2.56	1.2%

EXAMPLE FRAGILITY CALCULATION

To illustrate an application of the updated equipment capacities, an example seismic fragility is developed below. This sample calculation follows the same procedures and uses the same hypothetical seismic demands as the example fragility presented in EPRI 1019200 (2009). The calculation is performed for the MCCs equipment class using the best estimate seismic capacity excluding KK data from Table 3. This example uses the same hypothetical in-structure seismic demand from EPRI 1019200 (2009). Table 5 itemizes the demand variables obtained from EPRI 1019200.

Table 5 – Seismic Demand Variables

Variable	**Symbol**	**Value**
Clipped Peak In-Structure Spectral Acceleration Demand	Sa_c	0.63g
Clipping Factor Uncertainty	$\beta_{Cc,U}$	0.30
Structural Response Factor	F_{RS}	1.22
Structural Response Randomness	$\beta_{RS,R}$	0.15
Structural Response Uncertainty	$\beta_{RS,U}$	0.30
Reference Earthquake Peak Ground Acceleration	PGA	0.102g

Using the MCCs best-estimate capacity of C'_{mbe} = 6.28g and $\beta'_{\hat{C}be}$ = 0.40, the capacity factor is:

$$F_C = C'_{mbe} / Sa_C = 6.28g / 0.63g = 9.97 \tag{5}$$

The median capacity, expressed in terms of the reference earthquake peak ground acceleration (PGA), is:

$$A_m = F_C \cdot F_{RS} \cdot PGA = 9.97 \cdot 1.22 \cdot 0.102g = 1.24g \tag{6}$$

The variability $\beta'_{\hat{C}be} = 0.40$ is judged to be primarily uncertainty with only a small contribution from randomness[7], such that $\beta_{\hat{C},U} = 0.39$ and $\beta_{\hat{C},R} = 0.09$. This uncertainty is combined with clipping factor uncertainty to obtain the total capacity factor uncertainty:

$$\beta_{F_C,U} = \sqrt{\beta_{\hat{C},U}{}^2 + \beta_{Cc,U}{}^2} = \sqrt{0.39^2 + 0.30^2} = 0.49 \tag{7}$$

The randomness in C_m is the only contribution to randomness in the capacity factor: $\beta_{Fc,R} = \beta_{C,R} = 0.09$. Randomness and uncertainty in capacity factor are then combined with structure response factor variability:

$$\beta_U = \sqrt{\beta_{F_C,U}{}^2 + \beta_{RS,U}{}^2} = \sqrt{0.49^2 + 0.30^2} = 0.57 \tag{8}$$

$$\beta_R = \sqrt{\beta_{F_C,R}{}^2 + \beta_{RS,R}{}^2} = \sqrt{0.09^2 + 0.15^2} = 0.17 \tag{9}$$

Finally, the high confidence low probability of failure (HCLPF) capacity may be calculated as follows:

$$A_{HCLPF} = A_m e^{-1.65(\beta_U + \beta_R)} = 1.24g \cdot e^{-1.65(0.57+0.17)} = 0.366g \tag{10}$$

CONCLUSIONS AND RECOMMENDATIONS

This study refines experience-based seismic capacities by considering the full extent of the EPRI experience database and updating methodologies used to develop seismic capacities from earthquake experience data. Two statistical approaches are considered: a frequentist approach that adopts the statistical framework from EPRI 1019200 (2009) and a Bayesian updating approach. The best-estimate seismic median capacities developed using the Bayesian approach for the sixteen equipment classes evaluated in this study exceed the generic median capacity of 4.8g developed in EPRI NP-6041-SLR1 (1991a) by up to 47%. The extent to which the capacities can be increased depends on several factors including the number of independent samples documented in the earthquake experience database, the ground motion response at the sites, the location of the equipment within the database structures, and the successes and failures documented in the database.

Bayesian inference techniques provide a powerful tool to effectively integrate existing information or “prior” knowledge on the seismic capacity with newly collected information from earthquake experience to obtain the updated or “posterior” capacity estimate. For the sixteen classes investigated, the experience data dominate the results such that the results are relatively insensitive to variations in the subjective judgments defining the Bayesian prior distribution.

The seismic capacities and experience-based methodology evaluated in this study can be used to support the development of refined seismic fragilities in current and future SPRAs. The increased seismic capacities will assist in screening high capacity equipment from further review, which will improve the realism of SPRA results and focus efforts on the most risk significant systems and components. Furthermore, the Bayesian framework presented in this paper and EPRI 3002011627 (2017) is suggested as a valuable statistical tool to develop more realistic capacities based on available experience or test data for other applications.

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[7] Experience with past equipment fragility analyses has shown that randomness (β_R) variability is typically dominated by ground motion variability rather than equipment capacity, such that randomness associated with equipment capacity ($\beta_{\hat{C},R}$) is typically small compared to uncertainty ($\beta_{\hat{C},U}$).

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