Mitman, Jeffrey

From: Ferrante, Fernando MLR
Sent: Tuesday, August 17, 2010 7:00 PM
To: James, Lois
Subject: IN on NSAC/60
Attachments: NSAC60 Discussion.docx

Lois,

Can we meet tomorrow at some point if possible to discuss the IN on NSAC/60? I completed a draft analysis I performed in support of this effort (see attached) and I have some questions about what are we trying to really say with this or which information to use as support for our statements. I would like to have Jeff Mitman attend if possible, given his involvement on this issue, as I think it would be helpful to have his perspective on it.

Thank you,

Fernando Ferrante, Ph.D.
Office of Nuclear Reactor Regulation (NRR)
Division of Risk Assessment (DRA)
Operational Support and Maintenance Branch (APOB)
Mail Stop: 0-10C15
Phone: 301-415-8385
Fax: 301-415-3577

B-117

DISCUSSION ON THE HISTORICAL USE OF DAM FAILURE RATES IN PROBABILISTIC RISK ASSESSMENT OF OPERATING NUCLEAR POWER PLANTS IN THE US

Background

In April 2006, NRC staff identified a performance deficiency involving the Oconee Nuclear Station (ONS) maintenance activities associated with the Standby Shutdown Facility (SSF). The SSF contains the only means to shut down all three existing units following a station blackout induced by a potential catastrophic flood, since the site does not have emergency diesel generators (on-site emergency ac power is provided by two hydro-electric generators at the Keowee Dam). The importance of this finding is that ONS is located immediately downstream from two large dams in Seneca, South Carolina: Keowee Dam and Jocassee Dam.

The licensee was eventually issued a White Finding under the Significance Determination Process within the Reactor Oversight Process. Subsequent activities related to this finding led to interactions with the licensee on external flooding analysis. As part of the discussions, the issue of dam failure rate estimates and their use in probabilistic risk assessments (PRAs) was raised.

The historical record of dam failures in the US provides a basis for understanding the various causes and mechanisms by which dams can fail. It should be noted that dam failures ultimately involve complex interdependent physical phenomena involving meteorological, geological, structural, and hydrological processes. However, generally speaking, dam failures can be binned in three broad categories: (i) hydrologic, (ii) non-hydrologic, and (iii) combinations events. Hydrologic-related causes include, for example, severe precipitation and/or snowmelt flooding resulting in a flood loading that exceeds the dam capacity (e.g., resulting in dam overtopping). Non-hydrologic hazards of concern include seismic events that may cause soil liquefaction, embankment sliding, cracking in concrete structural members, and other phenomena leading to the loss of load bearing capacity to impound the reservoir. Another subset of non-hydrologic events that are particularly relevant to embankment dams (i.e., earthfill, rockfill, earth-rockfill dams) are internal erosion mechanisms where seepage through portions of the dam (i.e., embankment, foundation) progresses sufficiently enough to eventually erode a volume of material that leads to breaching and reservoir release. This subset is commonly referred to in the literature as "piping", among other definitions. Finally, dams can also fail due to a combination of various hydrologic and non-hydrologic events that may or may not be dependent on each other, such as snowmelt and internal erosion.

ONS was licensed prior to the publication of the Generic Design Criteria 2 (GDC2) in 10 CFR Part 50 Appendix A, that describes the design requirements and bases for the capability of important to safety structures, systems, and components (SSC) to withstand the effects of natural phenomena. However, the Updated Final Safety Analysis Report (UFSAR) for ONS contains a pre-GDC2 commitment that reflects similar requirements, in their scope, to those in 10 CFR Appendix A. Therefore, the analysis contained in the UFSAR for ONS includes considerations of a postulated failure of upstream dams due to seismic events.

NSAC/60 External Flooding Analyses

In the early 1980s, a case study applied to ONS Unit 3 was developed by the Nuclear Safety Analysis Center (NSAC) with the intention of advancing the use of PRA by the electric utility industry. This effort culminated in a report published in 1984, titled "NSAC/60: A Probabilistic Risk Assessment of Oconee Unit 3," which included internal and external events, accident progression analysis, and public risk estimates. For external flooding contributors, the two potential sources identified were events exceeding the maximum precipitation considered physically possible within the watershed where ONS is located, and a "random" failure of Jocassee Dam. With respect to the latter, the "random" definition is associated with specific non-hydrologic failure mechanisms considered credible for Jocassee Dam: (1) piping, (2) seepage, (3) embankment slides, and (4) structural failures of the foundation or abutments. In order to estimate the initiating event frequency for these two external flooding contributors, a Bayesian framework was developed in NSAC/60 to:

- Extrapolate the annual frequency associated with the Probable Maximum Precipitation (PMP), i.e., the maximum precipitation considered physically possible, using 50-year rainfall-intensity-duration-frequency regional curves and,

- Estimate the annual rate applicable to a "random" failure of Jocassee Dam using operating experience as input (i.e., historic dam failures, and dam-years of operation).

For the severe precipitation analysis, the result was an annual PMP median failure rate value of 2.9E-7/year, with a 90% confidence interval of [4.9E-8/year, 8.9E-7/year], while the annual dam failure was estimated as having a mean of 2.5E-5/year, with a 90% confidence interval of [7.9E-6/year, 5.5E-5/year]. In both cases, a grid of values for the parameters that characterize the equations assumed for PMP and dam failure rate needs to be established in order to converge to the region of relevance for the probability distribution estimate (i.e., the non-zero values). A more detailed summary of the input data and methodology applied is discussed next.

<u>PMP Calculation</u>

The source of data used for rainfall duration, precipitation depth and storm frequency for ONS in NSAC/60 were two reports by the US Weather Bureau published in the 1960s, which provide curves derived from 50 years of rainfall data. The data provides a distribution of rainfall intensity for the continental United States, from which actual values for the ONS site were interpolated (see Table 1). Figure 1 shows the corresponding cumulative precipitation depth versus annualized storm frequency (i.e., hazard curve) for various rainfall duration times, fitted with a polynomial (similar to the figure presented in NSAC/60).

The characteristics of the PMP used in NSAC/60 are obtained from a 1966 flood study performed by the licensee, which correspond to a 48-hour flood duration producing 26.6 inches of precipitation depth. In order to extrapolate the frequency of the PMP, it is assumed that the rainfall frequency-depth data can be modeled by an exponential function defined as:

$$c = a \cdot \exp[-(b \cdot h/\tau^{n})]$$

Where *a*, *b*, and *n* are the exponential function coefficients, τ is the rainfall duration, h is the precipitation depth, and c is the storm frequency. A Bayesian updating approach is derived where a uniform prior for the probability distribution of values of *a*, *b*, and *n*, i.e., *P*(*a*,*b*,*n*), is updated to obtain the posterior distribution *P*(*a*,*b*,*n* | *data*), i.e., the probability of the coefficient values given the observed data, assuming a Poisson distributed likelihood function *P*(*data* | *a*,*b*,*n*). Once the Bayesian updating is performed, the probability distribution of the extrapolated PMP frequency corresponding to τ = 48 hours and h = 26.6 inches is derived.

The methodology with the input data in Table 1 was replicated using MATLAB, using both the original grid for *a*, *b*, and *n* in NSAC/60 and a more refined grid:

Grid 1

a = [10, 15, 20,..., 55, 60] (increments of 5)

b = [1, 1.1, 1.2,..., 2.5, 2.6] (increments of 0.1)

n = [0.1, 0.12, 0.14,..., 0.38, 0.4] (increments of 0.02)

Grid 2

a = [10, 11, 12,..., 59, 60] (increments of 1)

b = [1, 1.05, 1.1,..., 2.55, 2.6] (increments of 0.05)

n = [0.1, 0.11, 0.12,..., 0.39, 0.4] (increments of 0.01)

A comparison of the results is shown in Figure 2. The results from NSAC/60 (Page 9-117) appear to under predict the replicated values where, for example, the 95th percentile is obtained as 1.6E-6/year versus the NSAC/60 result of 8.9E-7/year. Since the original analysis is not available, it is difficult to assess whether this difference is due to numerical calculations, data input, or another cause. Ultimately, the real challenge in the analysis presented is the justification for extrapolating limited data to such extreme low values. As good practice dictates, the higher and more refined the quality of the data, the more supportable the justification for extrapolation becomes. As far as extreme precipitation phenomena are concerned, the issue of frequency estimation has been debated by several US federal agencies and entities involved with hydrologic applications. A good summary of the state-of-the-art is provided in the 1999 joint report by Utah State University and the US Bureau of Reclamation titled "A Framework For Characterizing Extreme Floods for Dam Safety Risk Assessment," where the limits of credible extrapolation for annual exceedance probabilities are set at 1/100,000 with the inclusion of optimal data inputs (i.e., best combination of data), beyond what is presented in NSAC/60.

Dam Failure Rate Calculation

The Bayesian approach for the dam failure rate estimate follows a similar methodology to the PMP frequency extrapolation. The functional form used in this case is $L(t) = a \cdot b^{-t}$, where *a* and *b* are the functional parameters, and *t* is time measured in dam-years. This assumes that dam failure rates are continuously decreasing with time. The likelihood function derived for use in Bayes' Theorem measures the probability that a number of failures occur within a certain period followed by no failures up until the present time considered for the analysis. Another assumption stated as fundamental for this analysis in NSAC/60 is that *"the failure frequency in a particular year for a certain dam (regardless of its age) is identical with the failure frequency of a new dam built in that same year. In other words, the dams that survive up to a given year are just as "good" as the dams built in that year."*

The data used in the analysis was developed from an effort to build a catalog of dams and dam failures applicable to Jocassee Dam based on the following characteristics: (i) large US dams, (ii) Earth-rockfill dams, (iii) age, (iv) failure mode, and (v) construction date. Multiple sources are used and the authors acknowledge the unfeasibility in building a complete catalog that fits the attributes of Jocassee Dam exactly. The failure modes considered are (1) piping, (2) seepage, (3) embankment slides, and (4) structural failure in foundation or embankment (NSAC/60 states that seismic failures are addressed elsewhere). These were selected by a qualitative screening excluding all failures assumed to not be physically possible at Jocassee Dam. Dam failures occurring within 6 years of construction are eliminated based on the age of Jocassee Dam. Additionally, only failure events involving dams built since 1900 were to be considered.

Due to the lack of data, dam-years were estimated based on the rate of construction, and the number of dam failures considered applicable was chosen from available case studies (Table 9-20 and 9-21 in NSAC/60). From these, a table with the dam-years at each failure date was derived. Examination of these failures using current databases such as the National Performance of Dams Program (NPDP) and the National Inventory of Dams (NID), indicates the following information on these failures:

Dam	Failure Year	Year Completed	Type	Height (feet)	Event Description
Goodrich	1956	1900	Earthfill	65	Limited piping due to seepage caused a void and abnormal weight of ice or ice pressure over void caused failure
Lake Towaxay	1916	1902	Earthfill	62	Piping into rock fissures
Sinker Creek	1943	1910	Earthfill	92	Complete failure after many years of saturation of downstream slope and leakage through upper portion of dam
Baldwin Hills	1963	1951	Earthfill	160	Piping into foundation from fault movement
Walter Bouldin	1975	1967	Earth Gravity	170	The dam may have failed due to piping in the downstream shell

The analysis used in NSAC/60 was used to estimate the dam failure rate of a dam operating in 1981 (as was the case of Jocassee Dam) for dams built after: (i) 1900, (ii) 1940, and (iii) 1960. It is unclear what is the main basis for the chosen overlapping time periods, but these are later used in NSAC/60 to validate the assumption that the failure frequency in a particular year for a certain dam is identical with the failure frequency of a new dam built in that same year.

Grid 1

a = [0.0002 0.0004 0.00075 0.0015 0.003 0.006 0.012 0.016 0.02 0.024 0.03 0.04 0.05 0.06 0.075 0.1] (irregular increments)

b = [0.1 0.15 0.2 0.25 0.3 0.35 0.4 0.45 0.5 0.55 0.6 0.65 0.7 0.75 0.8] (increments of 0.05)

Grid 2

a = [0.0002,..., 0.1] (increments of 0.0005)

b = [0.1,..., 0.8] (increments of 0.0035)

The results for dams built after 1900 (see Figure 3) show that the analysis with the original grid compares well with the NSAC/60 results. However, using a more refined grid indicates that the Bayesian updating used is sensitive to the grid arrangement. The 95th percentile with the more refined grid is 4.3E-5/year, compared to the NSAC/60 value of 5.5E-5/year. Overall, the results for the dam failure rate and the PMP frequency are close enough for the purposes of validating the result and the noted differences are not significantly different, despite the discrepancies observed. Additionally, the different periods considered in the study were compared to the results presented in NSAC/60 (see Figure 4), where at each overlapping period interval only those failures applicable are considered (i.e., 5 failures between 1900 and 1981, 2 failures between 1940 and 1981, and 1 failure between 1960 and 1981), with a recalculated number of dam-years is derived for each period.

Posterior References to NSAC/60

After the publication of NSAC/60, the issue of risk contributions due to dam failures was revisited in a NUREG published in 1987, NUREG/CR-5042 "Evaluation of External Hazards to Nuclear Power Plants in the United States." The objective of the report was to perform an evaluation of external event initiators and their contributions to core damage or radioactive release to the environment with state-of-the-art tools available at the time. Under the river flooding scenarios, the following discussion on dam failures is included (underline added):

"There seems to be no single generally accepted methodology for analyzing the frequency F_F of a dam failure that would produce a PMF-sized flood at a downstream reactor site. Such an analysis must be entirely dam-specific (meaning river-specific also), and depends on dam construction, spillway design capability, conditions of the reservoir and embankments, and other such factors. Realistic calculations of the dam failure probability of a specific dam as a function

of extreme conditions are difficult to find in the literature; bounding calculations are more common, and would be fully acceptable if based on defensibly conservative models and data. Some bounding calculations provide values of F_F that are quoted as being in the range of 10^{-6}/year or even smaller, especially for modern well-engineered dams [Ref. 5.7 Oconee PRA, 1984]. On the other hand, some dam failures could easily be in the range of about $F_F = 10^{-3}$/year, since the mean value of the data base for FF for all dams is in the range between 10^{-4}/year and 10^{-5}/year (according to a survey published in the Oconee PRA [Ref. 5.7, Oconee PRA,1984])."

The statements in NUREG/CR-5042 balance some of the findings in NSAC/60. Nonetheless, the reference is made and the statement that some modern well-engineered dams may warrant failure rate values of 1E-6/year or less provide a sense that bounding calculations may be justifiable under the NSAC/60 approach. It should be noted that, for the most part, NSAC/60 results are above 1E-6/year and no quantitative attempt is made to justify lower estimates even for Jocassee Dam. Only the result for the 1960-1981 period appear to exhibit lower percentiles in the 1E-6/year order of magnitude and the scarcity of the data used (1 failure event) would hardly justify using these ranges.

After publication of NUREG/CR-5042, ONS revisited the PMP frequency and dam failure rate values as part of the 1990s effort in developing Individual Plant Examinations of External Events (IPEEEs), as a response to the US NRC request of an evaluation of plant-specific severe accident vulnerabilities initiated by external events contained in Generic Letter 88-20.

The PMP frequency values were copied verbatim from the original report. The dam failure frequency, however, was revisited and a new value of 1.3E-5/year was obtained by recalculation of the dam-years in order to consider the additional operating experience up to 1993 (when the ONS IPEEE was developed). The initial period of applicability is considered to be dams built after 1940, although Jocassee was completed in 1972. The only events included for this period are Baldwin Hills Dam and Walter Bouldin Dam, and an updated total value of 154,380 dam-years is obtained for dams built between 1940 and 1993. The Bayesian updating approach in NSAC/60 is not reproduced and the dam failure rate derived is a point estimate (i.e., 2/154,380 = 1.3E-5/year). The data included in the ONS IPEEE (Table 5-16) is replicated here for discussion. The basis for the updated value is referenced as being discussed in internal ONS documents which are not included in the IPEEE.

Event Year	Event	Cumulative Dam-Years	Failure Rate Point Estimate (/year)
1963	Baldwin Hills Failure	32,207	3.10E-05
1975	Walter Bouldin Failure	74,782	2.67E-05
1987	No Failure	126,435	1.58E-05
1993	No Failure	154,380	1.30E-05

Another plant that referred explicitly to the NSAC/60 analysis for dam failures in its IPEEE is Fort Calhoun Station (FCS), which quotes a value of 5E-5/year as applicable to the dams located upstream of the site. Copper Nuclear Station (CNS), located downstream of FCS, quotes NSAC/60 indirectly, by referring to NUREG/CR-4767, "Shutdown Decay Heat Removal Analysis of a General Electric BWR 4/Mark 1," published in 1987, which directly quotes NSAC/60 as the basis for its estimate. Additionally, multiple other sites refer to either NUREG/CR-5042, NSAC/60, and/or and other references as sources of external event screening bases without clear indication whether the dam failure rate was used in the screening analysis itself. The potential for further indirect referencing (as in the case of CNS) makes it particularly challenging to fully establish how much the NSAC/60 assessment percolated through the industry, although it is clear that it has been used by more than one site. As an example, the McGuire and Catawba sites use the following language in the introduction of their IPEEE submittals:

"All natural and man-made external events were identified using other PRAs, NSAC/60 (Ref. 2.2), ANSI/ANS-2.12 (Ref. 2.3), and the aforementioned NUREG/CR-2300."

NRR/DRA Generic Failure Rate Approach

In March 2010, NRR/DRA staff documented a generic dam failure rate analysis applicable to Jocassee Dam (ML100780084), as part of an insights assessment of the limitations and challenges in deriving an estimate based on historical data. Input information included (i) an assessment of the overall US dam population for those with features corresponding to a large rockfill dam, and (ii) a study of U.S. dam performance information for failure events that may be applicable to this subset of the overall population (along the lines of the NSAC/60 boundaries for the Bayesian analysis). The two best available databases were used to obtain the total number of dam-years for large dams and documented failures: (i) the National Inventory of Dams (NID), maintained by the US Army Corps of Engineers, and (ii) the NPDP database mentioned previously, developed by Stanford University. A point estimate calculation produced a value of 2.9E-4/year for the period covering dams built between 1940 and 2005. While the inclusion or exclusion of certain dam failure events is a significant source of uncertainty and debate, the most significant insight (via a simple sensitivity analysis) is that significantly lower estimates cannot be reasonably supported by the use of historical data alone.

Additionally, a Bayesian updating analysis with the subset of dam-years and failures corresponding to rockfill dams was also performed by NRR/DRA staff and documented in this effort. This approach had a significantly different framework than used by NSAC/60. Rather than assume a functional form for the dam failure rate with respect to dam-years, an assumed prior distribution is developed based on the considerable knowledge on average failure rates of large dams. A conjugate prior-posterior analysis is then performed using data specific to dams with the same attributes as Jocassee Dam, resulting in a posterior distribution with a mean of 2.8E-4/year with a narrow 90^{th} confidence interval of (1.3E-4/year, 4.8E-4/year). A literature review of similar published statistical studies of dam failures corroborated the conclusion that a generic dam failure rate for large dams is in the order of magnitude of 1 in 10,000 dam-years (see ML100780084 for references).

In summary, while limitations in historical data represent a challenge to ascertain a more precise estimate, it is clear that screening this hazard exclusively via this methodology does not appear justified. Analog to the previous discussion on credible extrapolation of PMP frequency values, if the ambiguity and lack of precise historical data to characterize dam failure rates precludes the estimation of a site-specific value with a high confidence, then a bounding or screening value should not be based on the same approach to justify estimates orders of magnitude lower than the average dam failure rate produces. This is not to say that a higher degree of confidence cannot be achieved by alternate methods, such as more detailed dam risk assessment techniques, or that all dams should be assumed to have equal attributes when this is clearly not the case. However, there is sufficient evidence of dam failures and a large population of dams in the US to justify an average value with a reasonable uncertainty spread.

Issues with NSAC60 Input Data

By parsing the information applicable to Jocassee Dam by various attributes, the use of the methodology in NSAC/60 immediately excludes a significant amount of information available in databases (both dam-years and failure events). This practically ensures that almost no failures can be considered as representative of a rockfill dam such as Jocassee. Instead, NSAC/60 takes the approach that all earthfill, rockfill, and earth-rockfill dams be counted as part of the analysis, while restricting the consideration of failures to "other than overtopping and earthquake ground shaking." It further narrows the failure modes to piping, seepage, embankment slides, and foundation/embankment structural failures. The resulting list of dam failures consists primarily of earthfill dams, which is further trimmed by setting an applicable period of dam construction to 1940-1981. The result is a significantly reduced number of failures and a large number of dam-years which is responsible for the lower estimates observed in NSAC/60 and ONS IPEEE.

Additionally, the applicability to other sites or dams without careful reconsideration of the assumptions used in NSAC/60 is questionable. Primarily, because the number of failures considered to be applicable to the site-specific characteristics may not apply to other sites (such as the screening of failure modes). Additionally, because the dam-years derived for NSAC/60 cover a wide range of embankment dams to account for the lack of rockfill-specific data, the direct use of this analysis to an earthfill embankment dam may be non-conservative.

Table 1. Input data used in PMP frequency estimation in NSAC/60

Data Point	Rainfall Duration (hours)	Precipitation Depth (inches)	Observed Storm Frequency (/year)
1	12	3.5	1
2	12	4.2	0.5
3	12	4.8	0.2
4	12	5.8	0.1
5	12	6.7	0.04
6	12	7.5	0.02
7	12	8.1	0.01
8	24	4.2	1
9	24	4.7	0.5
10	24	6.5	0.2
11	24	6.8	0.1
12	24	8.5	0.04
13	24	9.2	0.02
14	24	10.5	0.01
15	48	6	0.5
16	48	7	0.2
17	48	8	0.1
18	48	9.5	0.04
19	48	10	0.02
20	48	11.5	0.01
21	96	7	0.5
22	96	8.5	0.2
23	96	10	0.1
24	96	11	0.04
25	96	12	0.02
26	96	14	0.01
27	168	8.5	0.5
28	168	10	0.2
29	168	13	0.04
30	168	14	0.02
31	168	16	0.01

Figure 1. Cumulative precipitation depth vs. observed storm frequency used in NSAC/60

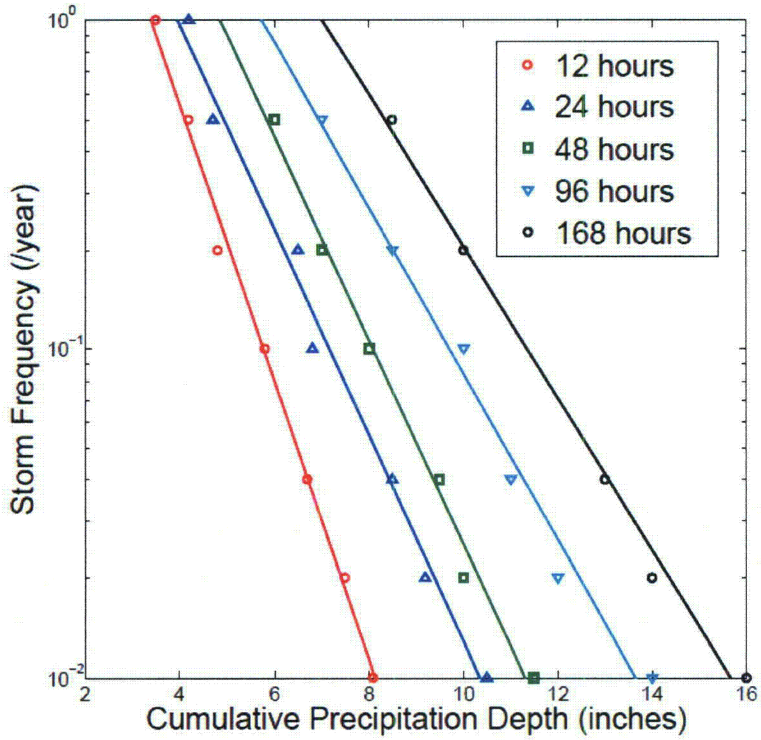
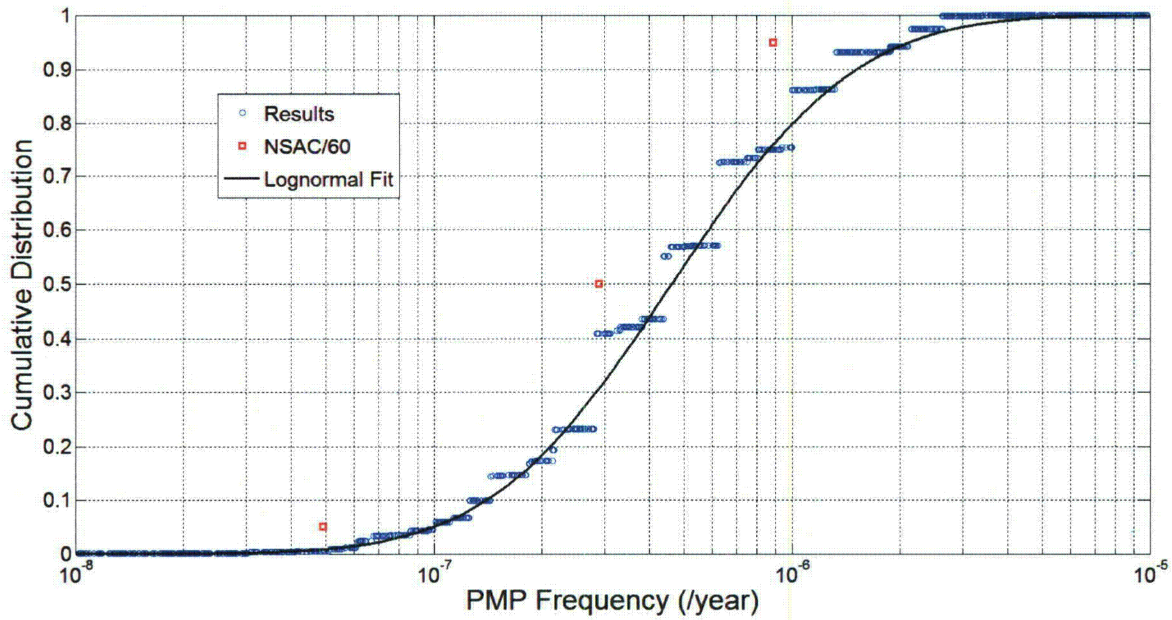


Figure 2. Comparison of results for the cumulative distribution of the PMP frequency

Grid 1



Grid 2

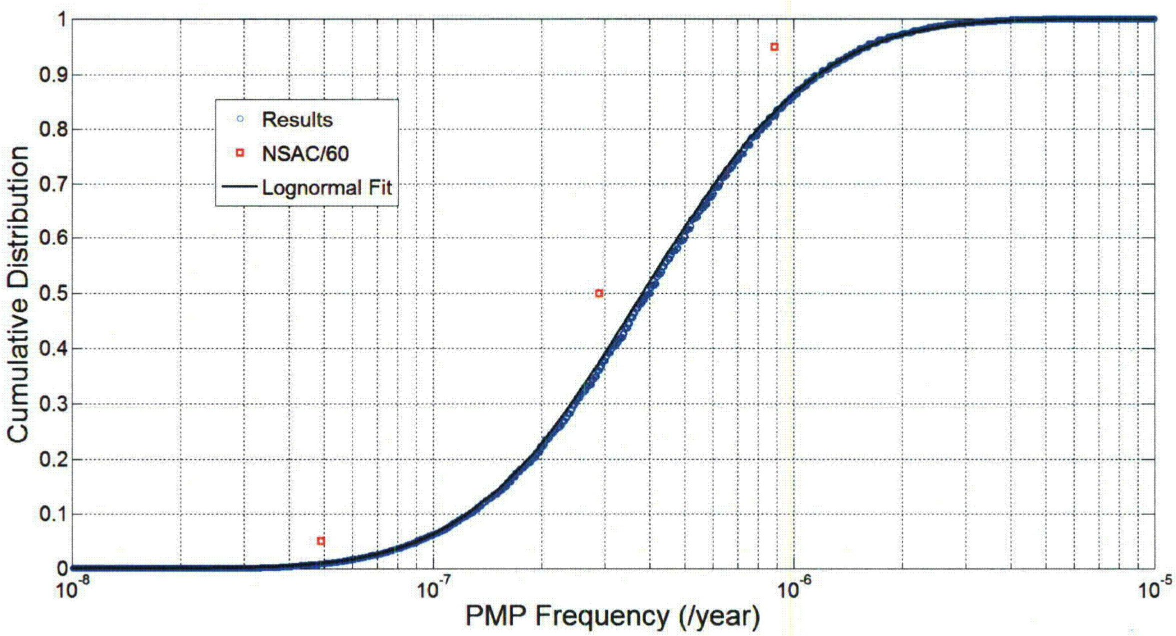
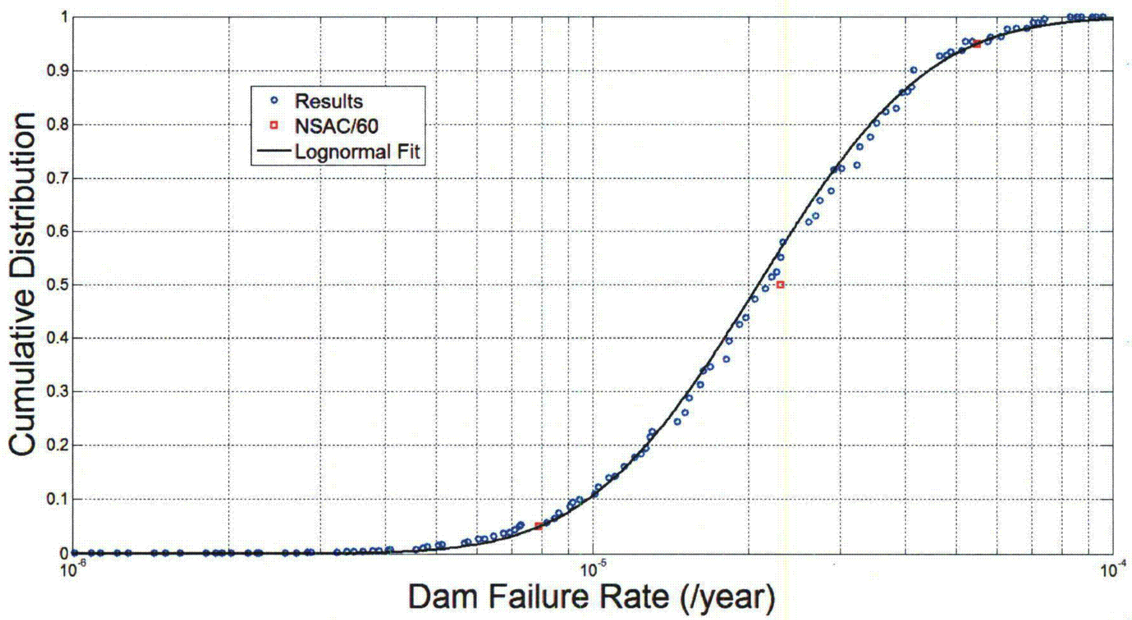


Figure 3. Comparison of dam failure rate estimates for dams built between 1900 and 1981

Grid 1



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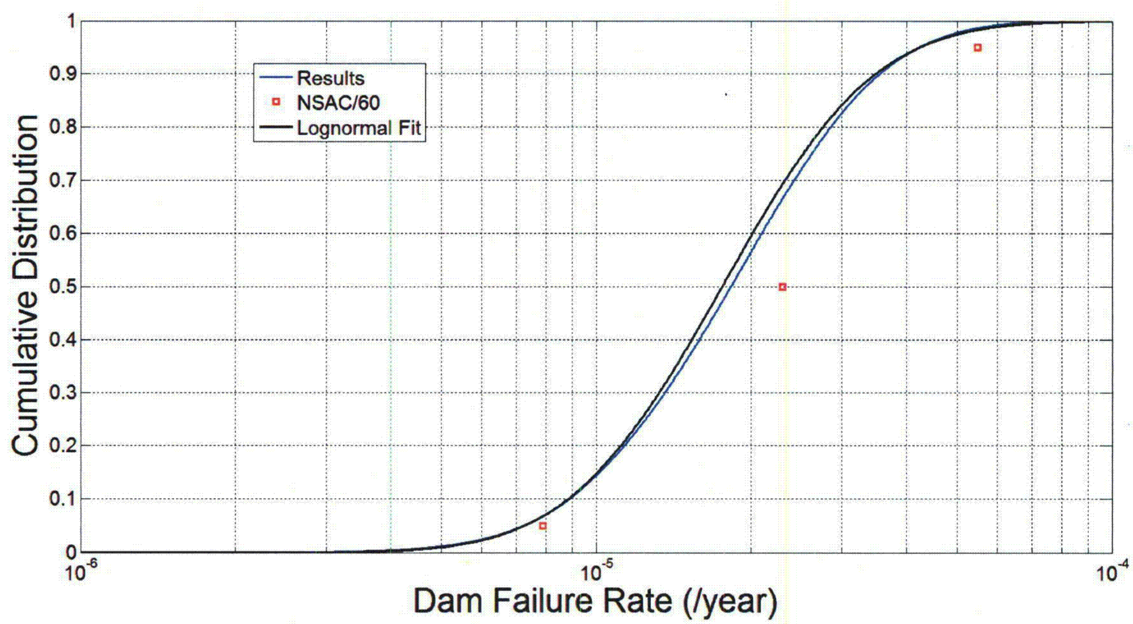

Figure 4. Comparison of results for dams built in different periods (until 1981)