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Estimated Rates of Failure for Dams in the United States

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ABSTRACT

Annual rates of failure which consider the effect of dam type, construction era, and dam age were estimated for dams in the United States by examining the National Inventory of Dams and the Worldwide Historical Dam Failures Database. Based on information from these databases, there has been a total of 5,628,516 dam-years (sum of years in service for all dams), 2,694 dam failures, and thus 0.00048 dam failures per dam-year. Concrete and earthfill dams both have less than 0.0005 failures per dam-year; masonry and rockfill dams have more than 0.001 failures per dam-year and timber dams have more than 0.0035 failures per dam-year. For all dam types, failures per dam-year are greatest in the first five years after construction and steadily decrease with increasing dam age except for earthfill and rockfill dams. Earthfill and rockfill dams reach the lowest rates of failures per dam-year when they are between 20-50 years old with an increase in failure rate, especially for earthfill dams, after 50 years after construction. Results from this study are predicated by the available data, which likely does not include information for all dams or dam failures.

I.INTRODUCTION

Dam safety programs in the United States, particularly those for hydropower dams regulated by the Federal Energy Regulatory Commission, are transitioning to a risk-informed approach to dam safety assessments. This transition has been motivated in part by expert recommendations following reviews of recent high-profile dam safety incidents, most notably the service and auxiliary spillway failures at Oroville Dam in 2017 [4]. Risk-informed dam safety assessments are based on the explicit goal of reducing the societal risk to *As Low As Reasonably Practicable* (ALARP) with the implicit understanding that some amount of risk must be tolerated. A fundamental component of risk-informed dam safety assessments is an estimate of annual probability of failure for various failure modes identified through a potential failure modes analysis. Such estimates are difficult to make for complex dam systems, typically resulting in large uncertainties, and there is little data to validate the estimates. Therefore, historical rates of failures for dams of various types, construction eras, and ages may be used as a component to complement risk-informed dam safety processes, which seek to estimate the annual probability of failure for dams. Previous studies have estimated the rate of failures of dams e.g., Foster et al [3], and Ingles [6], but have not considered the effect of dam age or construction era. Engemoen [2] completed a similar study which investigated the historical rates of failures for Bureau of Reclamation embankment dams and dikes and considered the effect of dam age on failure rates and failure type. This study attempts to supplement the existing body of work by providing additional estimates, which consider the effect of dam type, construction era, and dam age.

II.BACKGROUND

We used two datasets for this analysis:

- National Inventory of Dams [7]
- Worldwide Historical Dam Failures Database [1]

The National Inventory of Dams contains data for over 90,000 dams in the United States; the Worldwide Historical Dam Failures Database contains data for 3,861 dam failures from around the world but is filtered to only include dam failures in the United States, resulting in 2,543 recorded dam failures. The focus of this paper is on permanent, engineered water dams, so all data for landslide dams, test dams, cofferdams, and tailings dams are removed.

The two datasets contain measurements of various dam characteristics such as dam height, dam length, reservoir volume, etc. The Worldwide Historical Dam Failures Database also contains information on failure consequences: e.g., fatalities and economic impact; however, this information is incomplete, therefore, it is not considered for this study except to complete a catalogue correction. Similarly, we do not attempt to match dam failures from the Worldwide Historical Dam Failures Database to dams in the National Inventory of Dams. Instead, this study uses categorical data attributes, which were available for each dam and each dam failure: dam type, construction era, and dam age.

The failures database includes recorded instances of dam failures from 1848 to present. These failures vary significantly in their consequences. A variety of dam safety incidents are included in the failures database: disasters, internal erosion, overtopping, quality problems, and only a subset of these resulted in fatalities, N. In this study, all types of failures are given equal weight regardless of their severity. This approach is generally consistent with that of the Federal Energy Regulatory Commission in that it includes the recorded uncontrolled release. However, for risk-informed analyses, catastrophic failure is the primary consideration, and thus the definition of failure differs from that in this study because there is an opportunity for intervention to prevent catastrophic failure once uncontrolled release is observed.

III. DATA COMPLETENESS, CATALOGUE CORRECTION, AND IMPUTATION

This study does not differentiate between dam failures based on their economic or human costs. However, it is likely that some older records of dam failures that resulted in no fatalities (N = 0) were not recorded. This is analogous to the catalogue completeness issue in earthquake ground motion databases for which a magnitude of completeness, M_c, is used to express the minimum magnitude for which all earthquakes are recorded [8]. In this study, we adopt a similar approach and assume a fatality of completeness, N_c, where the failures database is assumed complete for all failures which resulted in at least one fatality. We experimented with using various fatality thresholds for which the catalogue is assumed complete, e.g., $N_c = 1$, 10, and 100, and did not find significant sensitivity. The data in this study is limited, therefore we did not explore geographical variation of catalogue completeness and assumed that geographical effects are negligible.

The assumption of a constant background rate, as is done for seismicity, is not valid for dam failures due to changes in dam safety and dam populations over time. We assumed a self-similarity in the consequence profile (F-N plot shape) over time, which is analogous to a constant Gutenberg-Richter curve, and that the ratio of failures which cause fatalities (i.e., lethality) is constant over time. Therefore, we used the rate of dam failures in 2022 determined from a first-order ordinary least squares regression to back-project a corrected failure rate curve based on the trend of failures with lives lost, and then compute a corresponding transfer function, as illustrated in Figure 1. The transfer function, which is dependent on failure year, is applied to all failures in the failures database to scale up the number of failures to current levels of failure reporting and therefore address the catalogue completeness issue. The effect of this catalogue correction was investigated; it was found to increase the total number of failures by 6%, from 2,543 to 2,694 failures.

In addition to the catalogue completeness correction, missing categorical data in the two datasets is imputed based on the ratios of available data. This is done to mitigate bias in the analysis due to missing data when the effects of multiple categorical characteristics are examined.

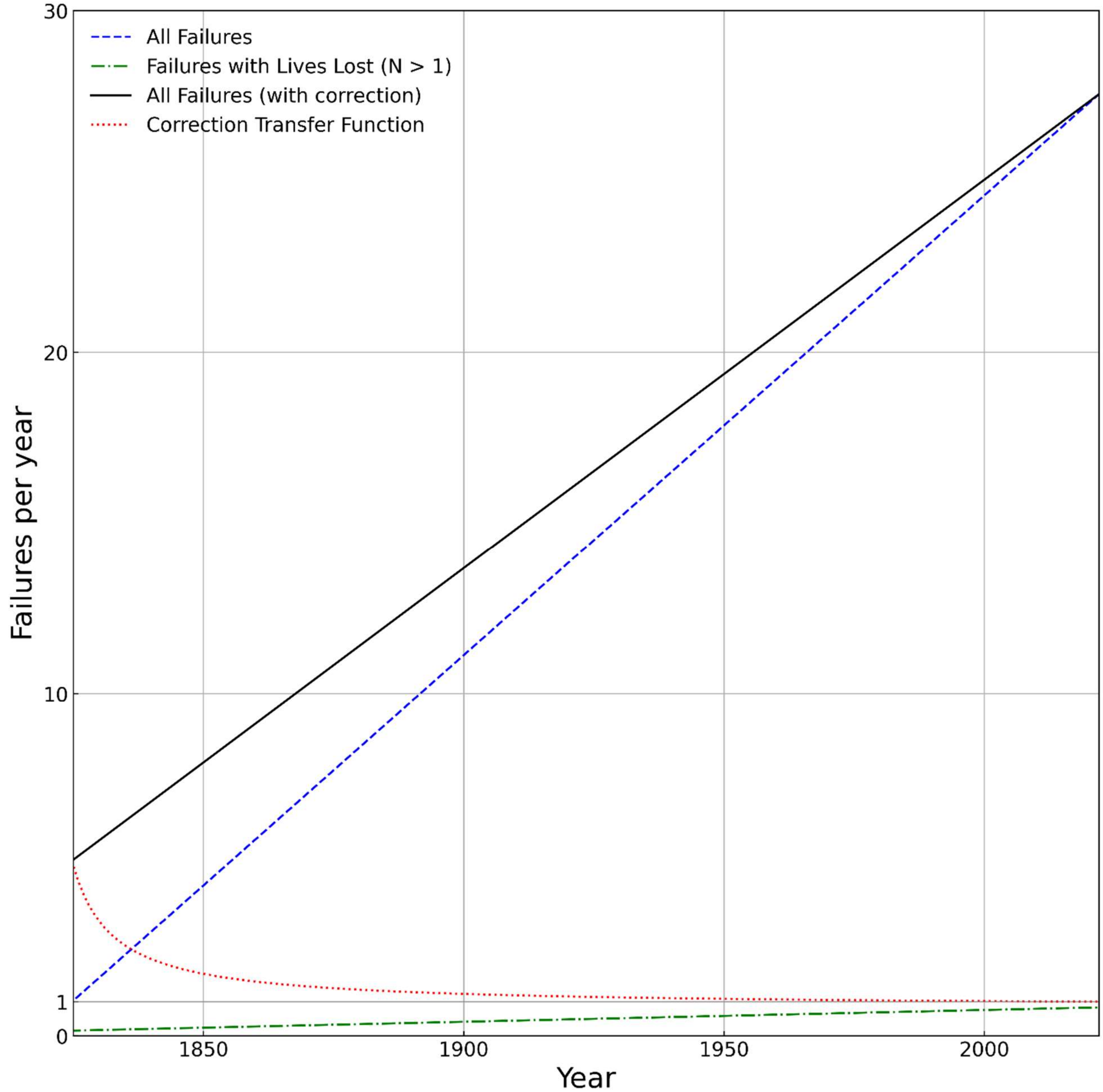

Figure 1. First-order ordinary least square regression showing dam failures per year as a function of year for all failures (uncorrected), failures resulting in fatalities (N > 1), the corrected back projection for all failures based on the N > 1 failure curve, and the resulting transfer function used to correct the catalogue for missing historical failures.

IV.METHODS

Both datasets contain categorical labels of the type of dams, which were harmonized into the following dam types: concrete (including gravity, roller-compacted, buttress, multiple-arch, and arch), earthfill, masonry, rockfill, timber, and other (including stone, steel, and others). We consider five construction eras, roughly delineated by transitions in dam design and construction practice: Practice-Based (pre-1920), Standards-Based (1920-1950), Improved Standards-Based (1950-1970), Criteria-Based (1970-1990), and Risk-Informed (post-1990) [5]. Dam ages are grouped into stages of dam life: 0-5 years, 5-10 years, 10-20 years, 20-50 years, 50-100 years, and 100-200 years. Dams in all 50 states as well as Guam and Puerto Rico are included in the analysis.

We group each dataset into categories and sub-categories. From the National Inventory of Dams, we count the cumulative number of dam-years in each category, where dam-years are the product of the number of dams and their respective ages (i.e., 10 dams constructed in 1923 would constitute 1,000 dam-years by 2023). From the Worldwide Historical Dam Failures Database, we count the number of dam failures in each category, and we then compute the historical rates of failures in units of failures per dam-year in each category.

V.DATA SUMMARY

There has been a total of 5,628,516 dam-years, 2,694 dam failures, and thus 0.00048 dam failures per dam-year in the history of dams in the United States (once catalogue completeness has been adjusted for and missing data has been imputed). Table I through Table III provide summaries of the combined dam inventory and dam failures dataset partitioned by dam type, construction era, and dam age; the totals from each table differ slightly due to the application of the catalogue correction, imputation of missing data, and rounding errors. For reference, the number of failures without the catalogue correction applied are provided in parentheses.

As shown in Table I, historical failure rates range between 0.00031 and 0.00392 failures per dam-year when aggregated by the type of dam. Dam types with the highest failure rates (i.e., timber, rockfill, and masonry) appear to be those which were common in the earliest construction eras, which tended to have higher rates of failures as shown in Table II. A portion of the higher relative failure rates for early-era timber, rockfill and masonry dams appears attributable to both the era of construction, and to these dam types being inherently more failure prone.

TABLE I

Summary of dam failures by dam types, failures without the catalogue correction applied are shown in parentheses

Dam Type	**Dam-years**	**Failures**	**Failures per dam-year**
Concrete	530,391	187 (174)	0.00035
Earthfill	4,857,697	2,196 (2,086)	0.00045
Masonry	91,994	115 (103)	0.00126
Rockfill	77,274	111 (104)	0.00144
Timber	16,163	63 (57)	0.00392
Other	53,765	16 (16)	0.00031

TABLE II

Summary of dam failures by construction era, failures without the catalogue correction applied are shown in parentheses

Construction Era	**Dam-years**	**Failures**	**Failures per dam-year**
Practice-Based (pre-1920)	1,018,081	1,223 (1,065)	0.00120
Standards-Based (1920-1950)	1,166,655	508 (476)	0.00044
Improved Standards-Based (1950-1970)	2,291,867	440 (423)	0.00019
Criteria-Based (1970-1990)	916,653	254 (246)	0.00028
Risk-Informed (post-1990)	235,258	337 (331)	0.00144

The high number of failures per dam-year for dams constructed in the Risk-Informed (post-1990) era (Table II) is initially surprising. We believe this finding reflects changes in reporting through the history of dams in the United States, with much more diligent documentation of dam safety failures in the modern eras relative to eras prior to 1970.

As shown in Table III, the dams demonstrate the highest rates of failures when they are in the earliest stages of their life cycles, especially in the first 5 years after initial filling of the reservoir. The rate of failures steadily declines up until 20-50 years of age with a very slight increase in failure rate for very old dams (i.e., 50-100 years and 100-200 years). As shown in Figure 2, the slight increase in failure rate for old dams does not appear to occur for all dam types; only rockfill and earthfill dams demonstrate increased failure rates while all other dam types exhibit steadily declining rates of failures as they age beyond 50 years. Concrete dams appear to age particularly well.

TABLE III

Summary of dam failures by dam age, failures without the catalogue correction applied are shown in parentheses

Dam Age	Dam-years	Failures	Failures per dam-year
0-5 years	452,584	829 (756)	0.00183
5-10 years	451,014	310 (282)	0.00069
10-20 years	886,601	316 (286)	0.00036
20-50 years	2,327,418	613 (559)	0.00026
50-100 years	1,286,753	548 (525)	0.00043
100-200 years	224,142	136 (132)	0.00061

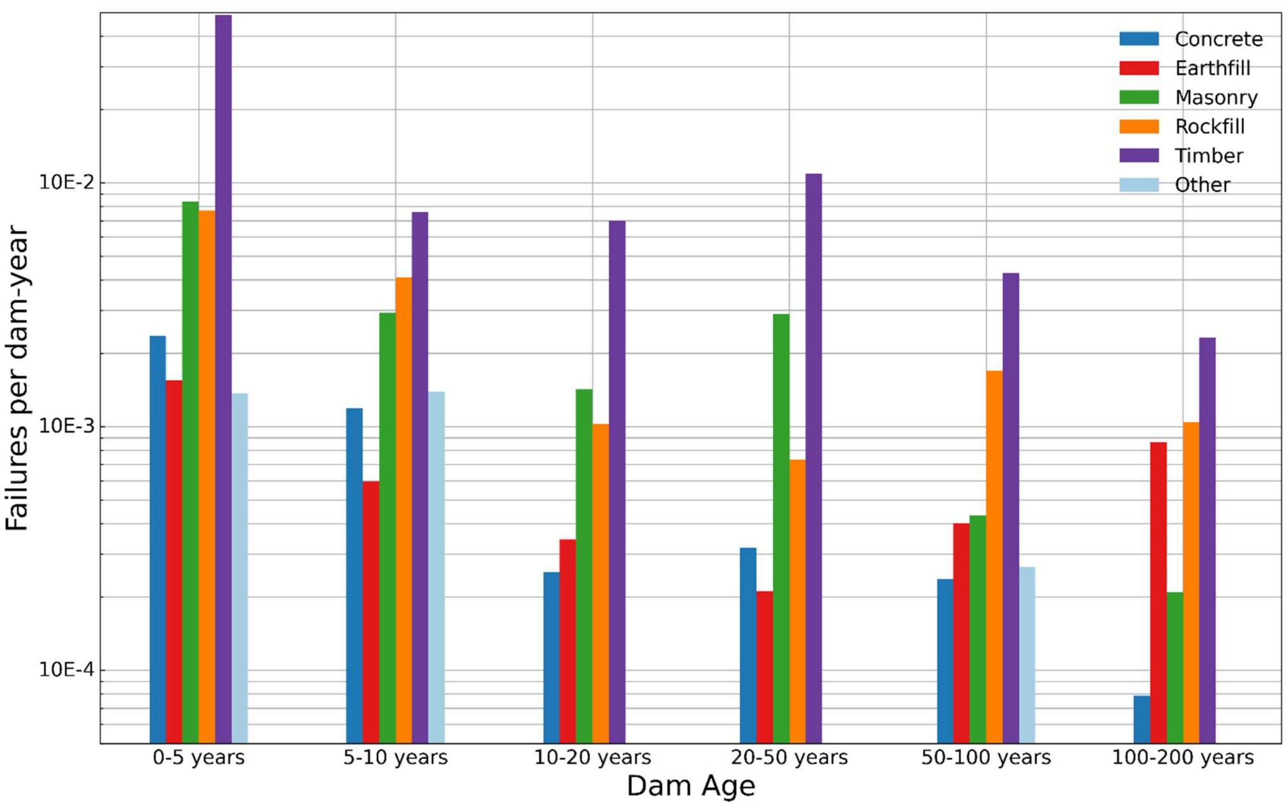

Figure 2. Failures per dam-year grouped by dam age for various types of dams.

The decline in failure rates as dams age appears to be consistent for all construction eras, as shown in Figure 3, with very significant reductions in failure rates occurring for dams constructed in modern eras between 1970-1990 and post-1990. High failure rates observed for dams constructed post-1990 (Table II and Figure 3) are initially surprising; however, the higher failure rate may be attributed to more rigorous reporting in recent years.

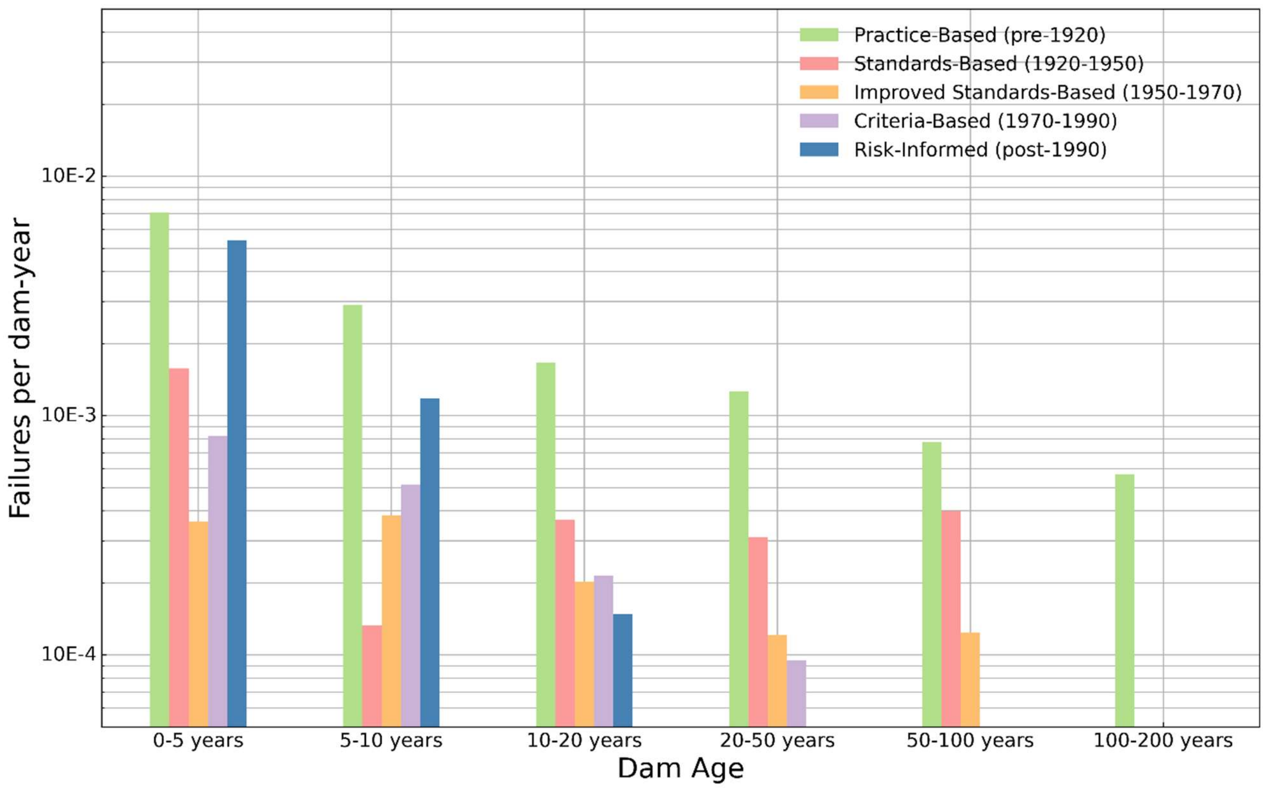

Figure 3. Failures per dam-year grouped by dam age for various construction eras.

Figure 4 and Figure 5 show the total failures, failures per dam-year, and total dam-years in each dam type-construction era and dam type-dam age subcategory, respectively. Masonry, rockfill, and timber dams have demonstrated the highest historical rates of failures; however, most historical failures are earthfill dams. When partitioned by dam type and construction era, the subgroups have a median of 0.00061 failures per dam-year with a standard deviation of 0.00576. When partitioned by dam type and dam age, the subgroups have a median of 0.00112 failures per dam-year with a standard deviation of 0.00814.

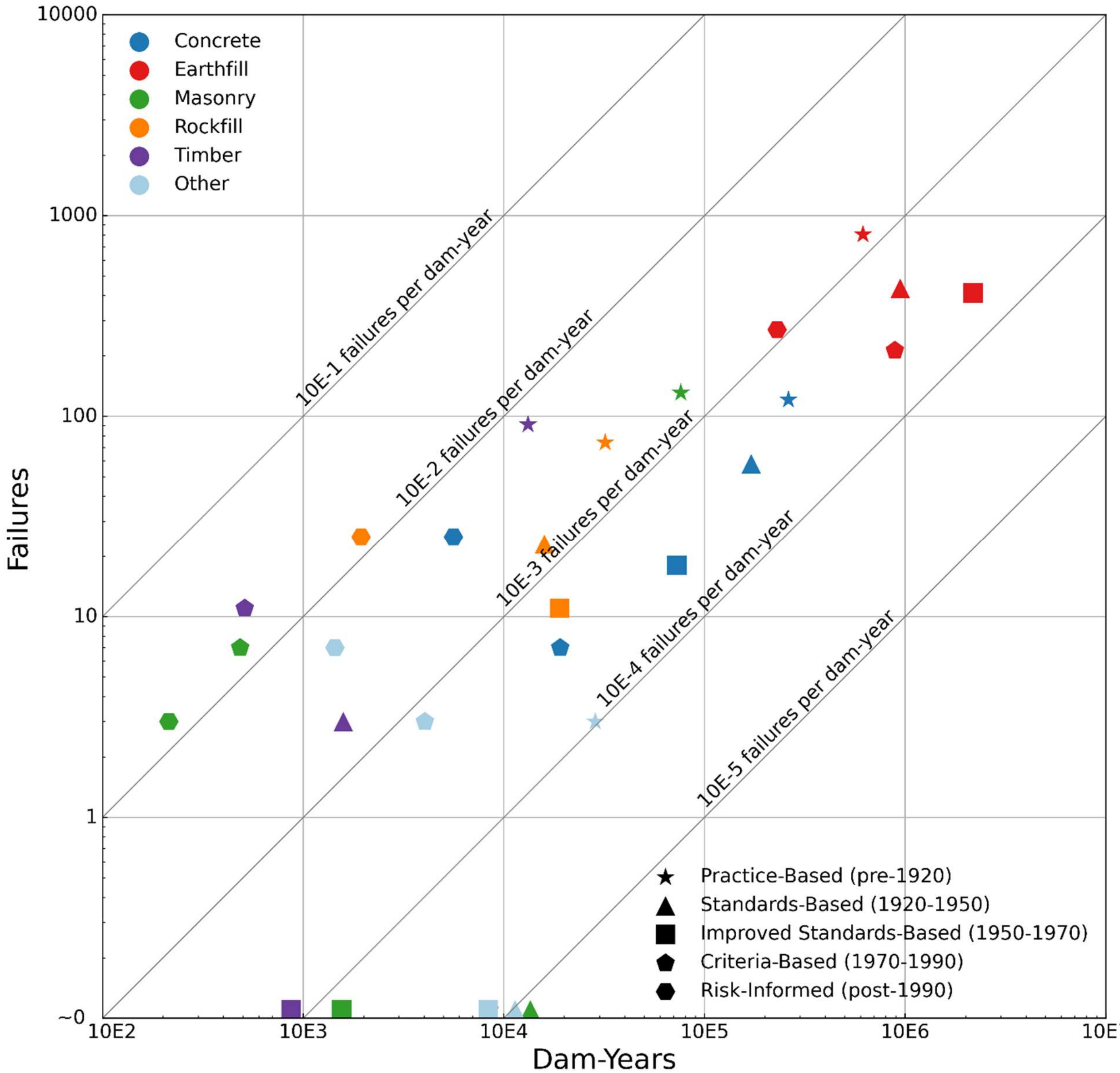

Figure 4. Failures, failures per dam-year, and dam-years for various dam types and construction eras.

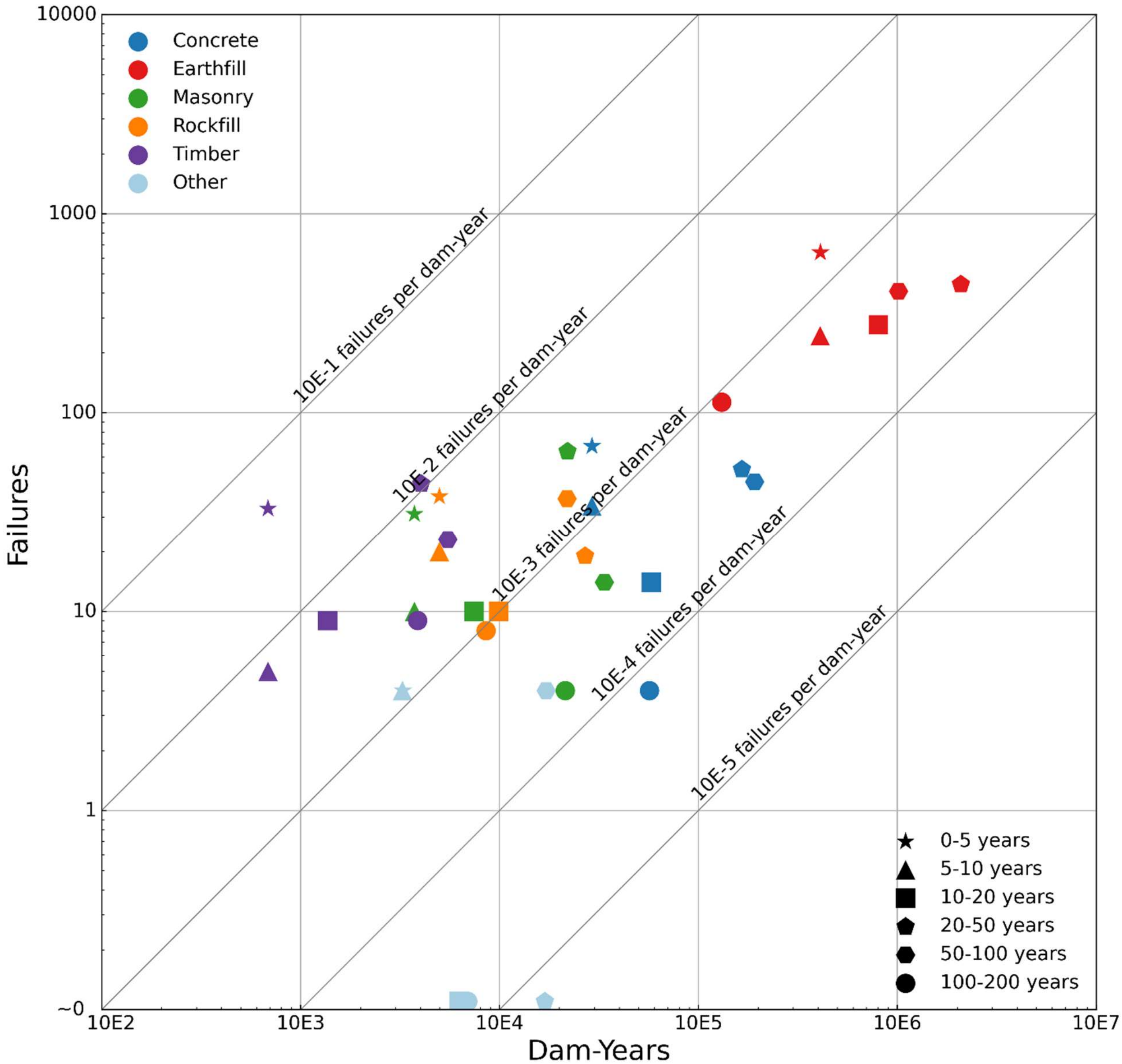

Figure 5. Failures, failures per dam-year, and dam-years for various dam types and dam ages.

VI.REGRESSION ANALYSIS

Dummy variables, with values of either 0 or 1, were used to replace each of the categorical variables for dam type, construction era, and dam age. Z-1 dummy variables were required for each; all dummy variables were set to 0 to indicate the Zth category. Ordinary least squares linear regression analysis was done in log-space with each subcategory constituting a single data point in the regression. Two different versions of this regression analysis were done, including different independent categorical variables: (i) considering dam type, construction era, and dam age as shown in Equation 1 and Table IV; and (ii) considering dam type and dam age only, as shown in Equation 2 and Table V.

$$Annual\ probability\ of\ Failure = e^{a+b+c+y_0} \quad (1)$$

TABLE IV

Coefficients and standard errors for the ordinary least squares linear regression including the effects of dam type, construction era, and dam age.

Dam Type Parameter, a	**Value**	**Standard error**
Concrete	-0.73	0.61
Earthfill	-1.16	0.59
Masonry	0.73	0.63
Rockfill	0.82	0.62
Timber	2.14	0.65
Other	0	0.62
Construction Era Parameter, b	**Value**	**Standard error**
Practice-Based (pre-1920)	-0.82	0.37
Standards-Based (1920-1950)	-1.28	0.44
Improved Standards-Based (1950-1970)	-1.67	0.47
Criteria-Based (1970-1990)	-0.41	0.44
Risk-Informed (post-1990)	0	0.43
Dam Age Parameter, c	**Value**	**Standard error**
0-5 years	3.09	0.51
5-10 years	2.08	0.51
10-20 years	1.31	0.52
20-50 years	1.35	0.51
50-100 years	0.97	0.52
100-200 years	0	0.51
Constant, y_0	**Value**	**Standard error**
All dams	-8.76	0.76

$$Annual\ probability\ of\ Failure = e^{a+c+y_0} \quad (2)$$

TABLE V

Coefficients and standard errors for the ordinary least squares linear regression including the effects of dam type and dam age only.

Dam Type Parameter, a	**Value**	**Standard error**
Concrete	-1.16	0.65
Earthfill	-1.70	0.63
Masonry	0.48	0.69
Rockfill	0.41	0.67
Timber	1.79	0.70
Other	0	0.67
Dam Age Parameter, c	**Value**	**Standard error**
0-5 years	3.30	0.53
5-10 years	2.15	0.53
10-20 years	1.47	0.55
20-50 years	1.21	0.53
50-100 years	0.74	0.56
100-200 years	0	0.53
Constant, y_0	**Value**	**Standard error**
All dams	-9.19	0.76

The results of the regression analysis indicate that dam age is the most important determinant of annual rate of failure, with generally declining rates of failure (in aggregate) as dams age. Earthfill and rockfill dams exhibit increased rates of failure for increased dam age; however, these dam-type specific effects were not handled by the ordinary least square regression. Timber dams appear to have high associated rates of failure, while concrete and earthfill dams exhibit the lowest rates of failure. Rockfill, masonry, and other types of dams have intermediate rates of failure.

The regression results for construction era are counterintuitive (Equation 1; Table IV), but are consistent with earlier observations for Table II, and show an apparently increased annual rate of failure for dams constructed after 1970, especially for dams constructed after 1990. We believe this is due to two main factors: (i) relatively diligent reporting in modern eras, especially post-1990; and (ii) records of historical dam failures being lost to history, which indicates that the catalogue completeness correction may not have fully addressed reporting biases throughout the history of dams in the United States. It is this finding that motivated the completion of a second ordinary least squares linear regression with the construction era parameter, b, removed (Equation 2; Table V). We recommend considering estimations from both regression equations. It should be noted that all parameters must be included for each equation, i.e., a, b, c, and y_0 for Equation 1 and a, c, and y_0 for Equation 2 because omission is equivalent to a value of zero which corresponds to the Zth category.

VII.LIMITATIONS

The analysis approach we use has several significant limitations; therefore, it is important that the historical rates of failures which we compute be interpreted as only rough order-of-magnitude approximations. Despite the catalogue correction and data imputation, the main limitation in this study is completeness, or lack thereof, of the two datasets considered. The catalogue completeness correction only addresses missing failures and does not address the possibility of missing dam inventory. It assumes a constant F-N curve throughout the history of dams in the United States and that the ratio of failures with fatalities to all failures has been constant over time. This assumption is dubious; modern dam inspection and reporting practices differ significantly from historical norms, and it is likely the portion of recorded failures which resulted in fatalities has decreased over time. We do not account for changes in reporting practices over time.

A further limitation is that no distinction between the types, causes, and consequences of dam failures is made in this study, except in determining the correction for catalogue completeness.

VIII.CONCLUSIONS AND RECOMMENDATIONS

We analyze two datasets containing data on dams and dam failures in the United States to calculate the historical rates of failures and make inferences on the estimated annual probability of failure for dams of various construction types, construction eras, and dam ages. We compute that there has been a total of 5,628,516 dam-years, 2,694 dam failures, and thus 0.00048 dam failures per dam-year in the history of dams in the United States (once a catalogue completeness correction is applied and incomplete data has been imputed).

Examination of variation in the rates of historical dam failures in the United States reveals various insights. There are significant differences in the historical rate of failures for different types of dams; timber, masonry, and rockfill dams have very high rates of failures while concrete and earthfill dams fare much better. The most risk-prone stage in a dam’s life is during the initial 5 years, which is followed by a steady decline in rates of failure for all dam types except for earthfill and rockfill dams, which demonstrate a resurgence in failure rates as they age beyond 50 years. Dams constructed in more modern eras demonstrate approximately an order of magnitude reduction in rates of failures compared with those constructed prior to 1920. High rates of failures are observed for dams constructed after 1990, however this may be attributed to higher reporting for such dams during their most risk prone years rather than a decline in the state of the dam engineering practice.

This study does not differentiate between the types, causes, and consequences of failures in the Worldwide Historical Dam Failures Database, i.e., every failure is treated the same although their consequences may vary greatly. Future work could further investigate the variation of these failures and the consequences of failure by producing F-N curves or through other methods.

IX.REFERENCES

[1] Bernard-Garcia, M., & Mahdi, T. F. (2020). A Worldwide Historical Dam Failure's Database, https://doi.org/10.5683/SP2/E7Z09B, Borealis, V1, UNF:6:+KL1E7ZRLuS6PvEGSb8mjQ

[2] Engemoen, W. O. (2017). Latest Compilation of Internal Erosion Incidents at Bureau of Reclamation Dams: U.S. Society on Dams.

[3] Foster, M., Fell, R., & Spannagle, M. (2000). The statistics of embankment dam failures and accidents. Canadian Geotechnical Journal, 37(5), 1000-1024.

[4] France, J. W., Alvi, I. A., Dickson, P. A., Falvey, H., Rigbey, S., & Trojanowski, J. (2018). Independent forensic team report: Oroville Dam spillway incident. ASDSO and USSD: Lexington, KY, USA, 1-584.

[5] Halpin, E. (2022). Planning for the Future: Modernizing Major Decisions for Dams & Levees. United States Society on Dams, San Diego, California, April 2022.

[6] Ingles, O. G. (1984). A short study of dam failures in Australia, 1857-1983. Civil Engineering Systems, 1(4), 190-194.

[7] U.S Army Corps of Engineers (2022). National Inventory of Dams. Available online: https://nid.usace.army.mil/#/ (accessed on 15 November 2022).

[8] Zúñiga, F. R., & Wyss, M. (1995). Inadvertent changes in magnitude reported in earthquake catalogs: Their evaluation through b-value estimates. Bulletin of the Seismological Society of America, 85(6), 1858-1866.

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