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BRIDGE FAILURE RATES, CONSEQUENCES, AND PREDICTIVE TRENDS

by

Wesley Cook

A dissertation submitted in partial fulfillment
of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

in

Civil and Environmental Engineering

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2014

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ABSTRACT

Bridge Failure Rates, Consequences, and Predictive Trends

by

Wesley Cook, Doctor of Philosophy

Utah State University, 2014

Major Professor: Dr. Paul J. Barr
Department: Civil and Environmental Engineering

A database of United States bridge failures was used to ascertain the failure rate of bridge collapses for a sample population with associated rates by causes. By using the National Bridge Inventory bridge counts, the bridge population, from which the collapsed bridge came from, was determined. The average number of bridge collapses based on the sample population was approximately 1/4,700 annually. The geometric distribution was determined to be a valid model for the number of bridge failures per annum through multiple methods. Based on the data extrapolation and 95% confidence interval, the estimated average annual bridge collapse rate in the United States is between 87 and 222 with an expected value of 128. The database showed hazards that have caused bridges to collapse historically, throughout the United States. Conditional probabilities of collapse rate with consideration for the features under the structures were constructed. The most likely cause of collapse was determined to be hydraulic in nature when adjusting for the features under the structure. The collapse rate of hydraulic causes was unknown from past investigations; however, the value was determined to be an annual rate of $1.52E-4$. Collapse rates were also quantifiably established for other causes. The consequences

coupled with the rate of failure by cause were quantitatively evaluated. A benchmark, set by the United States Army Corps of Engineers interim guideline for dam safety, was used to show that bridge collapses within the United States are within a tolerable range comparing collapses to life loss.

To enhance risk-based and data-driven approaches to bridge management systems in compliance with Moving Ahead for Progress in the 21st Century Act, efficacious bridge collapse data collection is examined for this investigation. Trends obtained from statistical analysis of existing data show 53% of collapsed bridges were structurally deficient prior to collapse, and a failure rate of structurally deficient bridges to be 1/1,100 annually. Age and structural deficiency are related, structural deficiency and collapse are related, and age at collapse is contingent on collapse cause. It was determined that deterioration-caused and overload-caused bridge collapses are age related, but hydraulic-caused and collision-caused bridge collapses are not. Based on the desired results, trends seen in existing collapse data, improved collection efforts and data fields of interest are assessed with recommendations for analytical methods and consequence assessment while maintaining concise data. A national repository of bridge collapses at the federal level is paramount for effective bridge collapse risk analysis. Currently, bridge failure data is incomplete and insufficient to enable in-depth lifetime data analysis for improved bridge preservation. However, the frequency of collapses is often enough for large amounts of data to be collected in relatively few years.

(115 pages)

PUBLIC ABSTRACT

Bridge Failure Rates, Consequences, and Predictive Trends

The intent of this investigation is to assess the number of bridge collapses in the United States, describe, in a numerical form, negative impacts resulting from collapsed bridges, and, last, analyze conditions of bridges prior to collapse and note similarities. Bridge collapse data is scarcely recorded, as such; an isolated region (New York State) over a period of time (25 years), wherein data has been collected of this nature, was used to determine the number of bridge collapses in the region annually. Probability and statistics were used to estimate the average number of bridge collapses throughout the United States and a value of 128 annually was determined with a range between 87 and 222.

The causes of bridge collapses were numerically determined and associated with adverse effects of loss of life and average amount of traffic per day using the structure. Life loss occurred on about 4% of bridge collapses.

Similarities among collapsed bridges include bridges being classified as structurally deficient, bridges which have had the load carrying capacity lowered below the normal legal limit of vehicles, and bridges which have limited vertical clearance under the structure and a roadway under the structure. Age influences bridge collapses for only specific causes of collapse.

Wesley Cook

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Special thanks to New York State Department of Transportation and Winchell Auyeung for the use of their bridge collapse database. Obtaining the bridge collapse database was a critical part to this research and was not feasible without it.

I'd like to thanks to my mother, Lois, for encouragement to return to school for a MS and subsequent PhD. Special thanks to my in-laws, Dale and Lisa, for similar encouragement. Thanks to Dr. Kevin Womack for providing the opportunity to do a PhD and Dr. Paul Barr for taking me, for a second time, as a guide and advisor. Thanks to the members of my graduate committee, Dr. Paul Barr, Dr. Marvin Halling, Dr. James Bay, Dr. Joseph Caliendo, and Dr. Gilberto Urroz.

Lastly, I'd like to thank my wife, Laura, and daughters, Kelsey and Jocelyn, for their unwavering love and support. Thank you; I love you.

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CHAPTER I

INTRODUCTION

On December 15, 1967 the Silver Bridge between Point Pleasant, West Virginia and Kanauga, Ohio catastrophically collapsed due to corrosion and fracture of a suspension link, 46 fatalities and nine injuries resulted (Lichtenstein, 1993). In 1971, the San Fernando earthquake was responsible for the collapse of seven highway bridges in the region, particularly the Antelope Valley Freeway Interchange, causing two fatalities (Housner and Jennings, 1972). In 1980, the Sunshine Skyway Bridge over Tampa Bay, Florida was struck by a marina vessel dislodging a span from the supports, totaling 35 fatalities (Wuttrich et al., 2001). In 1983, the I-95 over Mianus River Bridge hinge connection failed due to fatigue and corrosion causing the collapse of the span, three fatalities and five injuries resulted (Lichtenstein, 1993). In 1987, the I-90 New York Thruway over the Schoharie Creek collapsed due to scour of the foundation soils, causing ten fatalities (Lichtenstein, 1993). In 1989, the Loma Prieta Earthquake caused the I-880 Cypress Street Viaduct, a two tiered bridge, to collapse, sandwiching the lower tier, and resulted in 41 fatalities (Housner and Thiel, 1990). On September 15, 2001 the Queen Isabella Causeway Bridge connecting South Padre Island, Texas to the main land was struck by a barge and collapsed two spans, eight fatalities were recorded (Wilson, 2003). In 2007, the Minneapolis I-35W Bridge over the Mississippi River collapsed due to a construction overload and under designed gusset plates in the trusses, 13 fatalities and 145 injures (Hao, 2010). Notice how the time lapses between major bridge failures are somewhat regular. Lichtenstein (1993) depicts significant bridge collapses, and academia funding for preventative investigations, as a swinging pendulum. If a pendulum

effectively portrays bridge failures as a function of chance and time, then probability will as well.

The bridge collapses described above are an abridged list of failures that resulted in life loss and public outcry for preventative measures. A plethora of investigations of significant bridge collapses or even the same collapse abound, when in fact, the number of bridge failures within the United States is significantly larger, though the consequences are typically less severe and the general population is unaware. It may seem obvious that in any given year, events will occur that test the resilience of infrastructure in the United States. In many cases, extraordinary events produce loadings on structures that surpass their capacity, resulting in their collapse. The probability of such extraordinary occurrences is low and the probability of structural capacities, being exceeded, is even lower. However, with the number of bridges within the United States in excess of 600,000, it is no surprise that a certain number of collapses are expected annually. In order to measure the risk of bridge collapses and consequence severity, risk assessment methods can be employed.

Research Objectives

A predictive model of failures based on historical evidence has the potential to become a highly effective method of risk management for bridge owning entities and decision makers. When probability methodologies are applied, the results directly comparable, while consequences can be linked in the model. When multiple risks are assessed as event and consequences, decision makers are more informed and thereby

better empowered to evaluate risk reduction measures. Specific objectives of this research include:

- Determine the collapse rate of bridges in a sample population through failure analysis.
- Proportion the failure rates for different causes of collapse.
- Couple bridge collapses with consequences.
- Evaluate trends in pre-collapse national bridge inventory data.
- Judiciously recommend improved data collection efforts and associated data fields of interest.

Scope and Organization of Report

This dissertation is divided into three distinct investigations, for publication purposes, and additional chapters with appurtenant information. It is organized as follows:

- Chapter II provides a breadth of risk analysis methods, and described risk analysis specific to bridges from previous investigations.
- The first study, consisting of Chapter III, uses historical data in a failure rate analysis method to assess the collapse rate of bridges. This is accomplished with a sample population through determination of the annual expectation and identifies a discrete distribution to model the sample with a corresponding 95% confidence interval. Discussion is then presented of the model selection implications, annual bridge collapse rate for given populations, and preventative measures related to inspection and the AASHTO LRFD Bridge Design

Specifications (2010). This investigation omits consequences and uses significant and less significant bridge collapses to show the rate of collapse.

- The second investigation, consisting of Chapter IV, describes the current collapse rate for bridges and proportioned for different causes of failure. For example, the collapse rate due to collision is unknown from past research; however, the numerical value is determined in this study. Parallel calculations are performed for other causes of collapse. The investigation evaluated bridge collapses and consequences qualitatively and quantitatively.
- The third investigation (Chapter V) formulates the level of data collection needed to assist in the further development of failure and lifetime data analytical methods. Existing bridge collapse data is evaluated to show trends in the national bridge inventory pre-collapse data. Deficiencies in the existing data have been observed in the former investigations. Therefore, improved collection methods have multiple advantages. Establishing specific data fields will improve predictive capabilities, and show trends, while maintaining concise data.
- Chapter VI summarizes the conclusions from Chapters III, IV, and V.

CHAPTER II

LITERATURE REVIEW

Risk Analysis Methods

Risk assessment is commonly analyzed by one of three techniques: expert opinion; reliability analysis; and failure analysis (Sundararajan, 1995). The first method is used when data is scarce and the demand for probabilistic analysis of failures is high, or the consequences are extensive. In this situation, expert opinion and/or Bayesian probability (Bulleit, 2008) is used in the development of failure probability for components, of a system and resulting consequences. A second risk method, when historical failure data is not available, is reliability analysis which is the premis of the LRFD design philosophy. Reliability analysis uses simulation, analytical or numerical inegration, moment –based methods, or first and second order methods of approximate limit states, with loadings and resistance data in determination of reliability indices and probability of failure for limit states (Pate-Cornell, 1996). This method is an inductive logic or bottom up approach that can be performed in the design phase to investigate all possible failure modes (MacDiarmid and Bart, 1995). A third risk assessment technique, referred to as failure analysis, uses frequentistic (Bulleit, 2008 and Pate-Cornell, 1996) or class statistical philosophy to determine the failure rate from historical data, or a retrospective analysis of a group of failures. Each of the three risk assessment processes have advantages and disadvantages.

Risk Analysis: Expert Opinion

The nuclear power industry developed risk assessment methods based on expert opinion and utilized fault tree risk analysis (Henley and Kumamoto, 1981) in the 1970s. Nuclear power plant risk assessment was performed on potential hazards with the associated probability of occurrence and consequences (Rasmussen, 1975). This, and related work, revolutionized the nuclear power industry by prioritizing risk mitigation efforts. In the field of dam engineering, analysis of breach data demonstrated that the cause of half of all failures was the result of piping, slope instability or an earthquake, with piping failures accounting for a majority of the failures. Ascertaining the cause and frequency of failure has been used to determine the probability of dam failures (Foster et al., 2000). This knowledge has empowered dam owners, designers, and researchers to more efficiently focus resources on dam failure mitigation. In both of the above cases, failure data is rare and expert opinion is necessitated in the development of numerical values for the component performance. Whenever opinion is used the analysis is subjective and results are debatable. Thus, this type of analysis is viable when scarcity of data issues arise.

Risk Analysis: Reliability Analysis

Akgul and Frangopol (2006) evaluated the load rating and reliability of a network of bridges with probability of failure for each bridge. The values obtained constitute one parameter of Liu and Frangopol's (2006) study of the transportation network reliability for the Northwestern Denver, CO metropolitan freeway system. Reliability through modeling or simulation tends to inevitably exclude certain types of uncertainty. The types of uncertainty from some sources, like tornados, are, and realistically ought to be,

omitted. The researchers (Nowak and Collins, 2013), involved in the LRFD Bridge Specifications calibration, has stated that the LRFD design philosophy is a theoretical model and does not include all sources of uncertainty. Akgul and Frangopol's (2006) model was more advanced than the LRFD methodology with the inclusion of deterioration rates for member components, which is critical for overload caused bridge failures. However, the leading cause of failure, hydraulic, is not fully addressed above the LRFD limit states, nor have vehicle collisions been included in the model which was found to be the second leading cause of failure (Wardhana and Hadipriono, 2003). Therefore, when the two leading causes of failure are poorly integrated, large discrepancies between reliability and actual failures are expected. Liu and Frangopol's (2006) study is an excellent demonstration of the level of complexity and use the probability of failure for bridge failures can bring to fruition.

Nowak and Collins (2013) stated the bridge probability failure rate in the United States is between 10^{-3} and 10^{-5} annually, but has limited supporting evidence. At this failure rate the theoretical LRFD specified probability of failure differs from the actual by an order of magnitude or more. Historical data commonly has the predicament of being insufficiently large. While the effect of an addition or subtraction of a bridge failure to the dataset significantly alters the failure probability rate. In an effort to circumvent the issues arising from small samples, reliability assessment is used; whereas, historical data has inclusion of uncertainties from all sources.

Risk Analysis: Failure Analysis

The intent of failure analysis is to assess how a system performed by collecting data and analyzes parameters, such as, failures per time interval or cycles per failure

(Scheaffer and McClave, 1995). The provisions which enable failure analysis techniques to be performed are if the sample sizes are sufficiently large and can probabilistic distribution model these data (Pate-Cornell, 1996).

Bridge Risk Analysis

Current methods for bridge risk assessment vary with the type of event or risk and transportation department. The method most commonly used is reliability analysis, the basis of LRFD design philosophy. Reliability analysis, in this context, focuses on, how a system *will* perform. Reliability analysis is a preconstruction method for safety assessment; however, it is an incomplete model, neglecting uncertainty from sources such as human error (Nowak and Collins, 2013). Additionally, consequences are addressed by an importance factor that alters the reliability index and effectually decreases the probability of failure. In current practice, the AASHTO LRFD Bridge Design Specifications (2010) for marine collision annual frequency of collapse has a probability of failure that can be based on failure analysis. New York State uses vulnerability assessment, which requires expert opinion on individual bridge risk, and results are relative to the population investigated (Shirole, 1995). Comparison of subsets, in this method, is an area of continued research. Scour hazard analysis is assessed department by department and no uniform data collection or application method nationally exists besides HEC-18 (2012), but it has the capability to be either reliability or failure based. Challenges persist in all of these methods with inclusion of consequence evaluations and in the results.

Structural engineering has a unique challenge in design, in that, structures have to be visualized, and hazards conceptualized prior to construction. As a result, levels of uncertainty occur throughout the design, construction, and use of the structure. Uncertainty is dealt with on a case by case basis. Examples include, concrete compression strength, loading, error in design, construction error, structure misuse, etc. Some are explicitly addressed in design specifications, while others are accounted for in calculation checks or quality control. More commonly in current practice, case studies are performed for significant failures, where life loss occurred. Case study failure results are frequently incorporated into design codes or specifications as lessons learned. However, the need for design codes or specifications to adequately address the most common or most likely causes of collapse remains uncertain. Failure analysis focuses on, how *did* a system perform. Therefore, failure analysis includes all uncertainty of constructed facilities by assessing trends in a group of failures.

Qualitative Causes of Bridge Collapses

The cause of bridge collapses is an issue of interest to bridge owners, designers, and the general population. The AASHTO LRFD Bridge Design Specifications (2010) states, “A majority of bridge failures in the United States and elsewhere are the result of scour” (C2.6.4.4.2). Scour was the foremost cause of bridge failure as initially declared by Smith (1976), who analyzed the cause of bridge collapses by searching published works for collapses. The reviewed material ranged from national investigations and disciplinary journals to news media. Smith’s data consisted of bridge failures from multiple counties from 1847 to 1975. This process, even when extremely thorough, has been shown to have omitted significant quantities of bridge collapses. When the

researcher reduced this dataset down to the years 1961 to 1975, it was determined that 86 total failures occurred, 48 of those were caused by flood (60%) with scour (46 bridges) being the predominant mode of failure.

Harik et al. (1990) performed a similar study, restricting the years of bridge failures from 1951 to 1988, collecting data for the United States as a whole, and focusing on the State of Kentucky. Data collection was performed by searching, primarily, three sources: an engineering journal, a nationally distributed newspaper, and a statewide distributed newspaper. Because a statewide newspaper was utilized, 35 bridge failures in the State of Kentucky were identified. The leading cause of failure among these was by vehicles exceeding the load limit (60%). Excluding Kentucky, 79 bridge failures were identified in the United States. The leading cause among these was collision (37%). The researchers work suggests the leading cause of bridge failures is not necessarily hydraulic in nature. It is also a demonstration that numerable less significant bridge collapses occur.

Wardhana and Hadipriono (2003) used a dataset obtained from the New York State Department of Transportation (NYSDOT). This study included the analysis of 503 bridge failures for the entire United States with the years ranging from 1989 to 2001. Results show the most common bridges to collapse are steel construction and beam/girder bridge types. The leading cause of bridge collapse is shown to be hydraulic in nature (53%). This study acknowledges the deficiency of the dataset, which is non-comprehensive in that numerous less significant bridge collapses may not have been contained in the dataset.

Quantitative Causes of Bridge Failures

Availability of data for bridge failure analysis rarely exists in published works up to this point. The most common failure analysis is for geographical hazards like marine vessel collisions (Larson, 1983) and hurricane damage (Sobanjo et al, 2013). Often bridge collapse data is incomplete and insufficient to enable statistical analysis of bridge failure probability rate and life loss from historical data. Data driven risk analysis is unique because the severity, based on current data, is demonstrated and validates statistical results through multiple means. Additionally, consequences have been linked to the collapsed bridges and pre-collapse trends have been observed.

CHAPTER III
A BRIDGE FAILURE RATE¹

Abstract

A regional bridge failure database was used to determine the bridge failure rate with associated causes. Using a sample population, from one DOT over a 25 year period, the average number of bridge failures was approximately 1/4,700 annually with a 95 % confidence interval from 1/6,900 to 1/2,700 annually. The number of bridge failures per year was modeled with a geometric distribution which requires a constant failure rate. Based on a validation analysis with bridge failures from six separate DOTs, other DOTs have bridge failure rates within the determined sample population 95% confidence interval. Analysis of the failed bridges by year of construction show no apparent era of construction that is more susceptible than another to failure. Correspondingly, the determined constant failure rate ascertained in the model selection indicates that the changes in bridge design specifications and maintenance regulations do not appear to have significantly reduced bridge failure rates. Based on the data extrapolation, the estimated average annual bridge failure rate in the United States is between 87 and 222 with an expected value of 128.

¹Cook, W., P. Barr, M. W. Halling, *A Bridge Failure Rate* – ASCE Journal of Performance of Constructed Facilities (accepted for publication).

Introduction

On December 15, 1967 the Silver Bridge between Point Pleasant, West Virginia and Kanauga, Ohio catastrophically collapsed due to corrosion and fracture of a suspension link, 46 fatalities and nine injuries resulted (Lichtenstein, 1993). In 1971 the San Fernando earthquake is responsible for the collapse of seven highway bridges in the region particularly near the Antelope Valley Freeway Interchange, causing two fatalities (Housner and Jennings, 1972). In 1980, the Sunshine Skyway Bridge over Tampa Bay, Florida was struck by a marina vessel which severed a span from the supports, totaling 35 fatalities (Wuttrich et al., 2001). In 1983, the I-95 over Mianus River Bridge hinge connection failed due to fatigue and corrosion causing the collapse of the span, three fatalities and five injuries resulted (Lichtenstein, 1993). In 1987, the I-90 New York Thruway over the Schoharie Creek collapsed due to scour of the foundation soils, causing ten fatalities (Lichtenstein, 1993). In 1989, the Loma Prieta Earthquake caused the I-880 Cypress Street Viaduct, a two tiered bridge, to collapse sandwiching the lower tier and resulted in 41 fatalities (Housner and Thiel, 1990). On September 15, 2001 the Queen Isabella Causeway Bridge connecting South Padre Island, Texas to the main land was struck by a barge and collapsed two spans, eight fatalities recorded (Wilson, 2003). In 2007, the Minneapolis I-35W Bridge over the Mississippi River collapsed due to a construction overload and under designed gusset plates in the trusses, 13 fatalities and 145 injures (Hao, 2010). Most recently on May 23, 2013 the I-5 bridge over Skagit River in Washington, see Figure 1, injuring one after being struck by a tractor trailer (Valdes and Baker, 2013). Bridge failures are unfortunate and tragic. Lichtenstein (1993) depicts significant bridge failures and academia funding for preventative investigations as a

swinging pendulum. If a pendulum effectively portrays bridge failures as a function of chance and time then probability will as well. It may seem obvious that in any given year, events will occur that test the resilience of the infrastructure in the US. In many cases, extraordinary events produce loadings on structures that surpass the capacity of the structure and result in the failure or collapse of the structure. Though the probability of occurrence of extraordinary events is low and probability of the structural capacity being exceeded even lower, with the number of bridges within the United States in excess of 600,000, it is no surprise that a certain number of failures are expected annually. The intent of this investigation is to quantifiably determine the bridge failure rate.

George Santayana an early 20th century philosopher and poet stated, “Those who cannot remember the past are condemned to repeat it.” The bridge failures described above are narratives to Santayana’s quote; only, those described are an abridged list of failures that resulted in life loss and public outcry for preventative measures. In effort to not repeat the past, a plethora of investigations of significant bridge failures or even the same failure abound, when in fact, the number of bridge failures within the United States is significantly larger, though the consequences are typically less severe and the general public is unaware. This investigation uses significant and less significant bridge failures to show a trend of failures. Consequences have been omitted from this investigation noting the need to learn from past less significant bridge failures.

This study uses historical data to assess the rate of bridge failures for a sample population through the annual expectation and identifies a discrete distribution to model the data with corresponding 95% confidence interval. Pate-Cornell (1996) refers to this method of uncertainty computations as a branch of risk assessment from a frequentistic

philosophy. Frequentistic based probability removes the subjectivity of expert opinion by using historical data to justify conclusions. Probability of this philosophy circumvents the challenge of how to compare multiple risks hazards, because failure results are directly comparable. Probability theory also allows for the combination or removal of subsets of bridge failures. In contrast, advanced bridge management decision making models, such as vulnerability assessment, Bayesian probability and other risk methodologies in engineering risk assessment typically require expert opinion in the quantitative analysis and results are thus subjective and debatable with comparison of multiple risks hazards is an area of continued research. In addition, use of historical data has the potential to answer many age old questions regarding improvements to bridge design and maintenance regulations. Design manuals for structural engineers have grown exponentially in size and complexity since their advent, and the question of whether the numerable additions made a significant impact on the resilience of these structures needs to be answered. Also, with changing bridge inspection practices from a biannual frequency to a rationally based frequency will the resilience of bridges decrease? Risk assessment based on a frequentistic philosophy has the capability to answer these questions and more pending the collection of data and time by tracking trends with failures.

Risk Analysis

Risk analysis and risk assessment have been applied to many disciplines from the aerospace industry to the chemical industry (Henley and Kumamoto, 1981). For nuclear power plants an assessment was performed of potential hazards with the associated probability of occurrence and consequences (Rasmussen, 1975). This, and related work,

revolutionized the nuclear power industry by prioritizing risk mitigation efforts. In the field of dam engineering, analysis of breach data demonstrated that the cause of half of all failures was the result of piping, slope instability or an earthquake, with piping failures accounting for a majority of the failures. Ascertaining the cause and frequency of failure has been used to determine the probability of dam failures (Foster et al., 2000). This knowledge has empowered dam owners, designers, and researchers to more efficiently focus resources on dam failure mitigation. One of the crucial steps in risk assessment is validation of the failure rate and the causes of failure.

Risk can be generally defined as the probability or likelihood of an undesired outcome, bridge failures with time in this study. By identifying the cause and bridge failure rate, designers and managers of bridges can more accurately focus resources on risk reduction measures with quantitative results. A probabilistic model of risk can combine or remove subsets of bridge failures for individual or group risk, and has the potential to numerically estimate the consequences of undesired outcomes.

The scope of this investigation is to analyze a sample population of bridge failures, determine the failure rate and then model the expected number of failures. From the selected model, the multiple causes of failure are combined into one probabilistic model, which is then expanded to the entire bridge population of the United States with a statistical confidence limit. The causes of bridge failures for the sample population are compared to the causes found in other investigations. Justification of the model selection was provided through linear regression analysis of the sample population and additional sample sets having means within the confidence limit of the model. Discussion is then presented of the model selection implications, annual bridge failure rates for given

populations, and preventative measures related to maintenance and the AASHTO LRFD Bridge Design Specifications (2010).

Bridge Risk Analysis

The cause of bridge failures is an issue of interest to bridge owners, designers, and the general public. The AASHTO LRFD Bridge Design Specifications (2010) states “A majority of bridge failures in the United States and elsewhere are the result of scour” (C2.6.4.4.2). Scour was the foremost cause of bridge failure as initially declared by Smith (1976), who analyzed the cause of bridge failures by searching published works for failures. The reviewed material ranged from national investigations and disciplinary journals to news media. Smith’s data consisted of bridge failures from multiple counties from 1847 to 1975. This process, even when extremely thorough, has been shown to have omitted significant quantities of bridge collapses. When the researcher reduced this dataset down to the years 1961 to 1975 it was determined that 86 total failures occurred, 48 of those were caused by flood (60%) with scour (46 bridges) being the predominant mode of failure.

Harik et al. (1990) performed a similar study, restricting the years of bridge failures from 1951 to 1988, collecting data for the United States as a whole, and focusing on the State of Kentucky. Data collection was performed by searching primarily three sources: an engineering journal, a nationally distributed newspaper, and a statewide distributed newspaper. Because a statewide newspaper was utilized, 35 bridge failures in the State of Kentucky were identified. The leading cause of failure among these was by vehicles exceeding the load limit (60%). Excluding Kentucky, 79 bridge failures were identified in the United States. The leading cause among these was collision (37%). The

researchers' work suggests the leading cause of bridge failures is not necessarily hydraulic in nature. It is also a demonstration that innumerable less significant bridge failures occur.

Wardhana and Hadipriono (2003) used a dataset obtained from the New York State Department of Transportation (NYSDOT). This study included the analysis of 503 bridge failures for the entire United States with the years ranging from 1989 to 2001. Results show the most common bridges to fail are steel construction and beam/girder bridge types. The leading cause of bridge failure is shown to be hydraulic in nature (53%). This study acknowledges the deficiency of the dataset, which is non-comprehensive in that innumerable less significant bridge failures may not have been contained in the dataset.

Based on a compilation of data, Nowak and Collins (2013) stated the bridge probability failure rate in the United States is between 10^{-3} and 10^{-5} annually. Further stating, historical data has in the past had the predicament of being insufficiently large and the effect of an addition or subtraction of a single bridge failure to the dataset significantly alters the failure probability rate. It is also known that the theoretical LRFD specified probability of failure differs from the actual by an order of magnitude or more. Nowak and Collins attributed the difference to an incomplete theoretical model that does not include human error in the analysis. Whereas, historical data has inclusion of uncertainties from all sources and computes actual failure probability rates rather than a reliability index that theoretically relates to the probability of failure.

Bridge Failure Rate Analysis

Failure Definition

For this study, the word failure was taken by applying the definition of the NYSDOT. The NYSDOT categorizes bridge failures as either total (see Figure 1) or partial (see Figure 2) collapse. Total Collapse (TC) is defined as “structures which all primary members of a span or several spans have undergone severe deformation such that no travel lanes are passable.” Partial Collapse (PC) is defined as “structures on which all or some of the primary structural members of a span or multiple spans have undergone severe deformation such that the lives of those traveling on or under the structure would be in danger” (NYSDOT, 2004). Figure 2 is an example of PC of a bridge over I-10 in Southern New Mexico.



Figure 1 Total collapse of I-5 and Skagit River Bridge Span.



Figure 2 Partial collapse of I-10 underpass in Southern New Mexico.

Bridge Failure Dataset Description

The Thruway Bridge over Schoharie Creek in New York collapsed due to foundation scour and others in the same flood event led to the establishment of the NYSDOT's bridge failure database. The goal of creating this database was to document all bridge failures throughout the United States. As a result, the NYSDOT database is updated depending on two primary sources of information. One data source is obtained by sending questionnaires to every DOT in the nation at four year intervals. The questionnaire currently requests six pieces of information for collapsed bridges: identification (location and features over/under), year built and failed, principal material, bridge type, cause of failure, and type of collapse (TC/PC). The database is also updated

by NYSDOT personnel who hear of and validate bridge failures through any viable source. This is the only agency, including federal organizations, that collects and maintains a national bridge failure database (Wardhana and Hadipriono, 2003). However, despite the best efforts this dataset is still described as non-comprehensive (Winchell Auyeung, personal communication, 2011).

The lack of comprehensiveness of the NYSDOT bridge failure database is evident in two forms; incomplete information on a failure and unrecorded failures. Both may be due to various DOTs' reluctance to allocate resources to reporting the requested data and particularly anything beyond the National Bridge Inspection Standards (NBIS) stipulations, especially at the cost of public perception. At the DOT level, bridge failure data is rarely compiled, stored, or allocated resources for time to respond to the NYSDOT quad-annual questionnaire. In 2008, only 18 responses were returned from all the DOTs in the nation (Winchell Auyeung, personal communication, 2011). On more than one occasion, DOTs that did respond to the questionnaire reported no updates to the existing failure database, when in fact bridge failures did occur in these DOT regions and were documented in other published works. Many such cases were found to occur between 2004 and 2009. Incompleteness often occurs when not all the information data fields are compiled. This is true even for the State of New York bridge failures. In order to better determine the bridge failure rate, most probabilistic causes and modes of failure, in addition to mitigating failures in the design and maintenance processes, a more robust data collection system is required. Echoing Harik et al. (1990) recommendation, a data collection system of this nature is best suited at the federal level with firm regulations in place.

In an attempt to quantify the bridge failure rate for this study, a sample national bridge population was taken by using the data from the NYSDOT database. Wardhana and Hadipriono (2003) describe the quantity of bridge failures reported in the database for the State of New York as seemingly higher than any other state. This is due to the fact that the NYSDOT is the organization managing the data and is more apt to report a bridge failure. The data collected from the State of New York is also the most complete. Therefore, the bridge failure sample population will consist of the bridge failures within the State of New York over the period of years since the database was initiated. This subset to the national dataset will be referred to hereafter as the Sample Population (SP).

A second dataset from the National Bridge Inventory (NBI) was utilized from the Federal Highway Administration (FHWA). The NBI contains data of all publicly owned bridges in the nation of length 6.1 m (20 ft.) or more. This inventory was used for total bridge counts as necessary. NBI records are on the public domain through the FHWA (2012).

Failure Rate

The bridge failure probability rate in this investigation is determined with Eq 1 as follows:

$$\bar{P} = \frac{n}{N} \quad (1)$$

where \bar{P} is the estimated failure rate, n is the observed number of bridge failures in a given population and period of time, and N is the given population count multiplied by the number of time intervals in the time period.

Bridge Failure Data

The SP has recorded 103 bridge failures in the last 25 years, using the most recent data from 1987 to 2011. Of the 103 failures, one was a railroad bridge, 10 were pedestrian/footbridges, and the remaining 92 are believed to be publicly owned roadway bridges. For analysis of the failure rate, the SP is restricted to the 92 bridge failures. Of the 92 failures, 52 are PC and 40 are TC. Compared to other studies, the 92 bridge failures in this investigation have been collected over more years, come from more recent data, are from a more geographically isolated region, and are segmented to only include vehicle bridges. A sensitivity analysis of the failure rate will further demonstrate the uniqueness of the dataset. The data is presented in the following forms: the number of failures by year, by age, and by year built.

To assess the number of failures annually, the SP was organized into the number of occurrences by calendar year. Table 1 lists the numbers and Figure 3 is a plot of the number of bridges failed per given year. For example, from 1987 to 2011 there were four years in which no bridge failures occurred. The maximum number of bridge failures in a year was 11. The average annual failure rate is 3.68, with a median of 2, a mode of 2, and a standard deviation of 3.46. With the median being 2, half of the years had 0, 1, or 2 failures or rather infrequent occurrences. In other years, through stochastic processes, multiple failures occurred. In 2011, the NBI bridge population for the state from which the SP was taken is 17,300. For the SP, n is 92 and N is roughly 17,300 per time interval (year) for 25 years or 432,500. With 92 bridges failures in total and approximately 432,500 bridge-years, the failure rate is $2.13E-4$ or $1/4,700$ annually. Again, this SP is

Table 1 Bridge failure frequencies and rates

Frequency of Failures	Bridge Failures in a Year						
	Sample Population (1987 to 2011)	Midwest State I (1990 to 2008)	Midwest State II (1990 to 2008)	Southwest State (1996 to 2008)	Southern State (1990 to 2008)	Mid-Atlantic State I (1990 to 2008)	Mid-Atlantic State II (1990 to 2008)
0	4	3	2	6	4	12	7
1	4	4	7	3	5	2	6
2	6	1	–	3	1	1	5
3	2	2	6	–	3	2	1
4	–	2	2	1	1	1	–
5	2	1	–	–	–	–	–
6	–	1	–	–	–	–	–
7	3	2	–	–	–	1	–
8	–	–	1	–	2	–	–
9	2	2	–	–	–	–	–
10	1	–	–	–	1	–	–
11	1	1	–	–	1	–	–
more	–	–	1	–	1	–	–
Population	17300	24200	24400	3900	13300	5140	6560
Bridge Failures	92	74	97	13	79	21	19
Annual Failure Rate	1/4,700	1/6,200	1/4,800	1/3,900	1/3,200	1/4,700	1/6,600

Note: – means the value is zero or undefined in all tables.

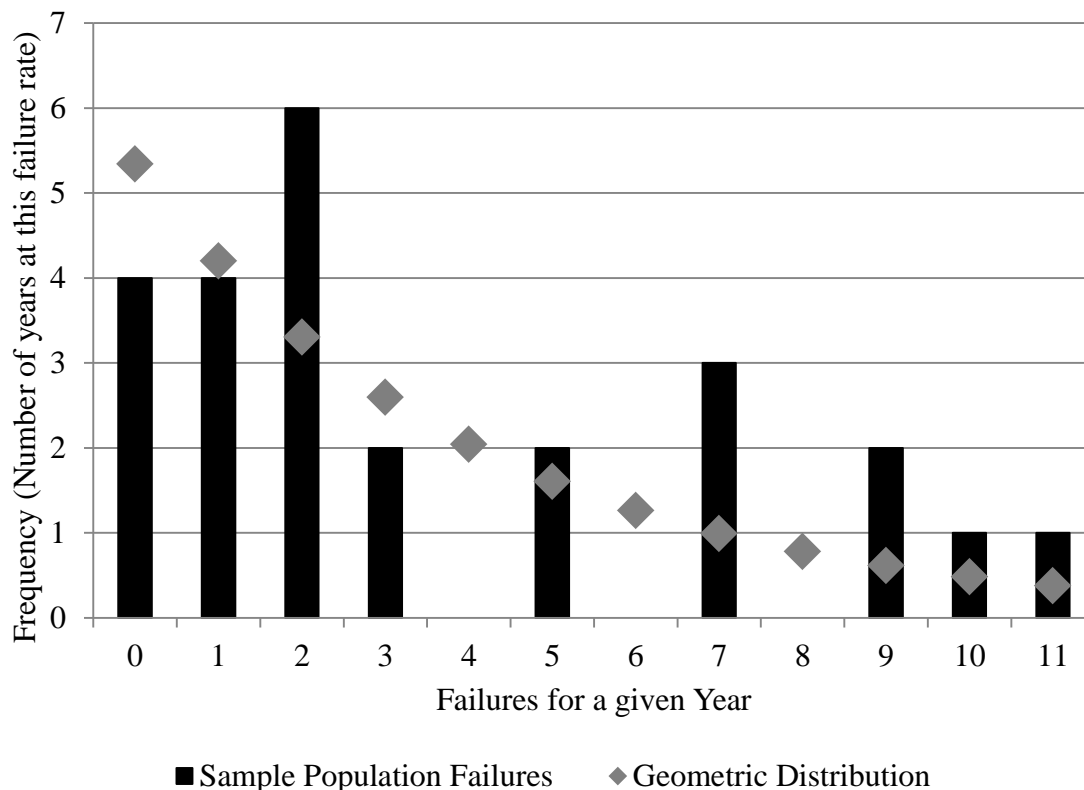


Figure 3 Bridge failure frequency in years from 1987 to 2011.

if anything non-comprehensive, suggesting that the actual failure rate is more severe than these numbers depict.

Ages of the failed structures range from during the first year (construction) to 202 years, with 11 having an unrecorded year built. A histogram of the age at failure is shown in Figure 4. In this histogram, the age is separated into 10-year periods compared to the bridge count. The mean age at failure is 54.8 years and median is 50.5 years. The data is right skewed signifying half of the bridge failures occur when the bridge is at or before the 51st year (median) and the other half of failures have an age of 51 to 202 years, which is clearly beyond their design service life. This dataset lacks a presumed significant number of bridges that were decommissioned or demolished prior to being classified as having failed. With this portion of data unaccounted for, the SP is expected

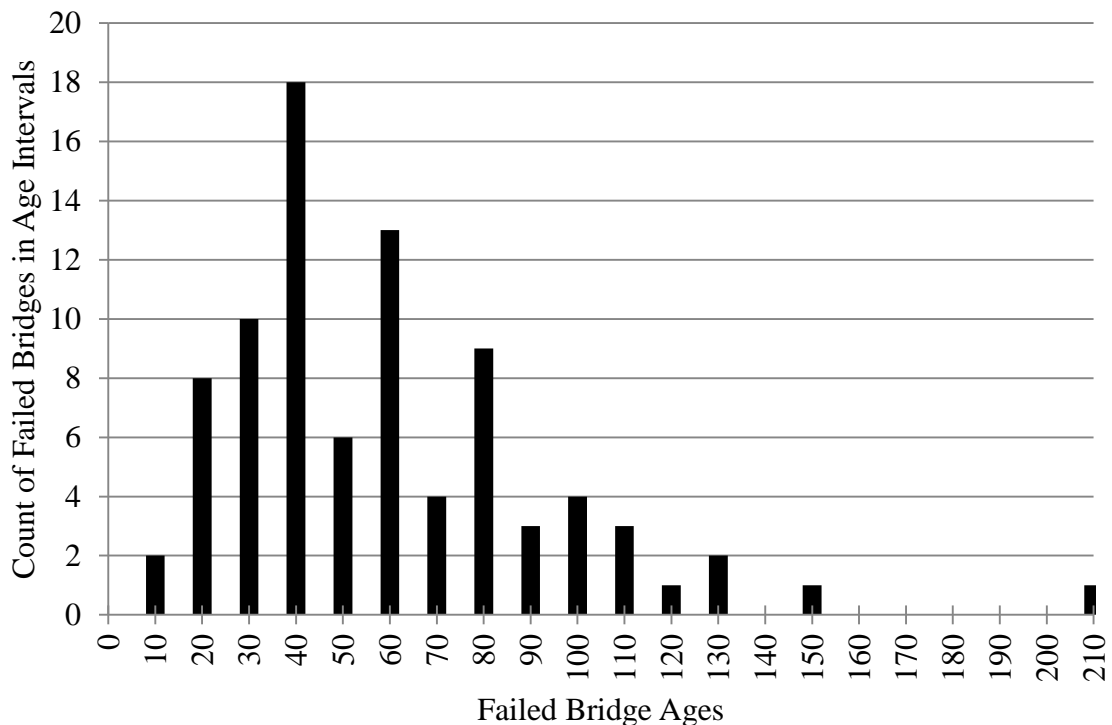


Figure 4 Distribution of bridge failures by age.

to include more failures due to stochastic extreme events. This is evident in the right skew of the data. From this observation, age does not appear to be a factor or is less significant in determining the cause of failures of in use bridges.

Analysis of the failed bridges by the year built show a range from 1800 to 1994 and five different modes. The modes are 1900, 1934, 1940, 1955, and 1959. Each mode has four failures from each year. From the wide range of modes for the year of construction, there does not appear to be any significant time period of construction that is more susceptible to failure than another. It can be noted that three bridges failed with the year built of 1973. As a result, there is insufficient evidence that increased bridge design regulations since their advent have significantly reduced the failure rate.

Description of Failure Causes

The 92 bridge failures, believed to be publicly owned, are categorized by cause of failure, as shown in Table 2. Failure types include: hydraulic total, collision total, overload, deterioration total, fire, construction, fatigue-steel, bearing, soil, and miscellaneous. Hydraulic total, collision total, and deterioration total are divided into subcategories to distinguish the exact cause of collapse when the SP is specific enough to do so. Hydraulic caused failures account for 52% of the collapses, collision of some type accounts for 20% of the failure causes, overload failures are nearly 12% of the causes, and deterioration of some sort represents 7% of the failure causes. Therefore, the majority of causes are a result of extreme or hydraulic events, not human error as

Table 2 Percentages of cause of bridge failures

Cause of Failure	Partial Collapse	Total Collapse	Total Count	Percentage of Total
Hydraulic Total	21	27	48	52.17%
Hydraulic	–	2	2	2.17%
Flood	8	18	26	28.26%
Scour	12	7	19	20.65%
Ice	1	–	1	1.09%
Collision Total	17	1	18	19.57%
Collision	14	1	15	16.30%
Auto/Truck	3	–	3	3.26%
Overload	3	8	11	11.96%
Deterioration Total	4	2	6	6.52%
Deterioration	–	1	1	1.09%
Steel deterioration	2	1	3	3.26%
Concrete deterioration	2	–	2	2.17%
Fire	3	–	3	3.26%
Construction	1	1	2	2.17%
Fatigue-steel	1	–	1	1.09%
Bearing	–	1	1	1.09%
Soil	1	–	1	1.09%
Miscellaneous	1	–	1	1.09%
Total	52	40	92	100.00%

suggested by Nowak and Collins (2013). The percentages of causes reported in Table 2 are fairly congruent with percentage of bridge failure reported by Wardhana and Hadipriono (2003). Because the sample size of the entire NYSDOT dataset used by Wardhana and Hadipriono (2003) is sufficient to draw conclusions on the causes of failure and the SP is comparable, therefore, the failure rate is comparably consistent with the entire nation.

The cause of failure that accounts for the largest percent of failures (52%) is hydraulic in nature, inclusive with for example, scour, flood, tidal, debris buildup, with the presumed foremost being scour. The definition of scour is, “erosion of streambed or bank material due to flowing water; often considered as being localized,” according to Hydraulic Engineering Circular No. 18 (HEC-18), (Arneson et al., 2012). Past investigation of scour by Chang (1973) depicts bridge failures due to hydraulic events in 383 cases; 25% involved pier damage and 72% involved abutment damage. In 1993, flooding of the upper Mississippi caused 28 highway bridge failures with 22 resulting from scour 79% (Kamojjala et al., 1994). Based on this study nearly 80% of all hydraulic failures are expected to be due to scour. Current data lacks clarity to affirm scour as the highest rate, but does consist of scour failures at 40% or more in hydraulic total causes.

Collision or lateral impact is the second leading cause of bridge failure. In this category, TC is rare in the data at 6% with the remaining 94% for PC. All 18 collisions of the 92 failures were listed with a highway underneath them. None of these collisions appear to be the result of marine vehicles. The current data is insufficient to further the understanding of why this type of cause is so high. More information would be required to determine how to mitigate this type of failure in design. Feasible predictors are

vertical clearances, height/size of impacting objects, vehicle classifications and quantities on the highway beneath, oversized load permits, posted speed limits, and estimated velocity of impacting vehicles.

An overload failure cause is distinctly different from deterioration in name, although the two are related as infrastructure ages. For the overload caused failures, PC occurred three times and eight TC failures occurred. The year built ranges from 1895 to 1955 with one unknown. Six are some type of truss bridge, four are girder or multi-girder, and the remaining one is an unknown bridge type. All these bridges have water as the common feature underneath them. This sample is insufficient in size for definitive statements on the reasons for overload failures. However, it appears that some relation exists between age, redundancy in load paths, and overload caused failures. Failures caused by deterioration have two cases of TC and four of PC. The year built of these range from 1914 to 1973. Five are girder type bridges and the remaining one is a culvert. One is labeled concrete deterioration/overload, and the cause was assumed deterioration. Items of interest to better ascertain the difference between deterioration and overload causes of failure are: mode of failure, redundancy in load path, posted weight limit (if applicable), vertical impact loading from uneven approach, presence of water or adverse environment, and climate, to name a few.

Construction accounts for a comparatively limited number of bridge failures. This indicates that the AASHTO LRFD Bridge Design Specifications (2010) and generally accepted construction checks and balances of design and erection methods over the years have sufficiently mitigated this cause of failure, in spite of the complexities of construction and the varying entities involved.

Pedestrian and footbridges that failed in the SP consist of nine pedestrian bridges and one footbridge. PC occurred on four occasions and TC on all others. All nine failed pedestrian bridges spanned over an expressway, interstate, United States or State highway. The cause of failure for eight of the bridges was a result of collision (89%) and one was lack of lateral bracing during construction (11%). The collisions are a result of unsecured travelling loads under the structure at 67% or more. Many of these failures had notes to the effect of, “dump truck with dump body in air.” The footbridge failed as a result of snow and ice overload which spanned a creek. It can be recognized that the mass of a pedestrian bridge is less than the mass of a vehicular bridge and is therefore more vulnerable to TC due to lateral impact 89%. This leads to the understanding of the susceptibility of pedestrian bridges to lateral impact and human error of improperly secured loads.

Modeling of Failures

The 92 failed bridges in the SP were analyzed with a linear regression model ($Y=mX+b+\epsilon$) with Y being the number of failures, X the predictor variable as the year, m is the slope of the line, b is the intercept, and ϵ represents the variability around the line. This computation was performed in attempt to show decreased bridge failures with time. With the advent of bridge design regulations, and ever increasing standards and design checks, it is generally anticipated that the bridge failures follow a declining trend with time. Figure 5 shows the linear model that was obtained. The slope (m) of the line is negative indicative of the above hypothesis. However, the 95% confidence interval or

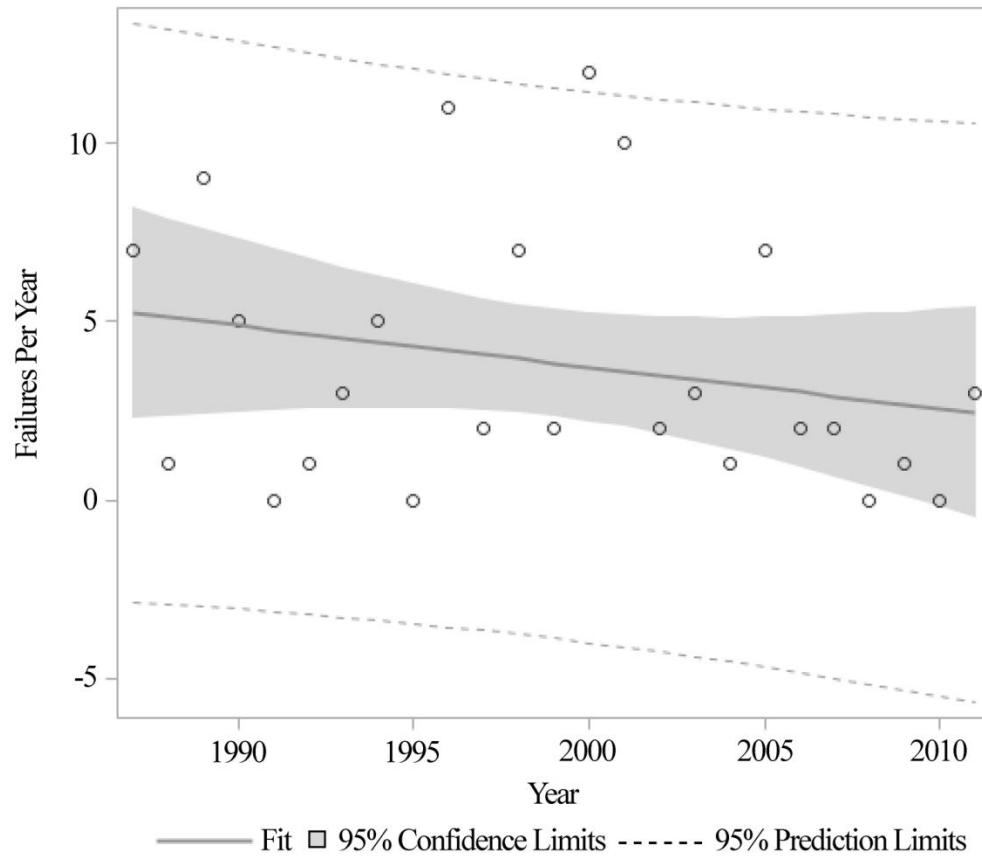


Figure 5 Bridge failures per year linear model.

confidence band around the estimated slope contains the slope of zero, as can be visually inspected in Figure 5. When a zero slope is feasible within the 95% confidence interval, it is evidence against this hypothesis and a constant, increasing, or decreasing failure rate are all viable with time. Thus the data is insufficient in showing increase of bridge resilience over the 25-year period.

Assuming that the variable x_i where ($i=0, 1, 2, \dots$) is the average or expected number of bridge failures in a given year, then x_i can be modeled as a random variable. Parameter estimation and goodness of fit tests were carried out on multiple feasible distributions. The geometric distribution, described in Eq 2, was selected for this investigation. The geometric distribution models (x) the number of bridge failures

annually with a constant expected failure rate, and is accurately based on the linear regression analysis described previously.

$$f(x) = (1 - p)^x p, \quad 0 < p \leq 1, \quad x \geq 0 \quad (2)$$

Following the Maximum Likelihood Estimate (MLE) method for the parameter estimation, p is determined by $E(X) = \bar{x} = (1-p)/p$ or $p=1/(1+\bar{x})$. Pearson chi-squared goodness of fit test determined a probability of 0.24, which fails to reject this distribution and parameter as a model of the 92 bridge failures in the SP. The calculated parameter p was found to be 0.213. The geometric probability mass function is overlaid on the bridge failures per year in Figure 3. Visual inspection shows the distribution to be a mild fit. Other distributions examined in exchange of a geometric distribution lacked improvement, as a result the geometric mode was applied to this study.

The expected annual failure rate \bar{x} can be scaled by population size and the probability (p) of bridge failures annually for any population can be obtained. The geometric probability mass function (Eq 2) being a discrete distribution, can be used to solve a probability of a specific number of failures by substituting x with an integer. For example, if a generic bridge population is 10,000 bridges, scaled \bar{x} is 2.13 and equivalently p is 0.320, the probability of no failures, also written as $P(X = 0)$, can be solved by substituting x with zero in Eq 1. $P(X = 0) = 0.32$ or about one out of three year zero failures will occur. The complimentary solution $1 - P(X = 0) = 0.68$ or about two out of three years, one or more failures will occur. For any bridge owning entity the expected annual bridge failure rate can be estimated with an associated rate, as long as the population is defined. Given the bridge population, from which the SP came, is 17,300, expected failures per year is found to be $E(X) = \bar{x} = 3.68$. If a congruent failure

rate is applied to the 2011 NBI 600,000 bridges in the United States, the average number of failures would be 128 bridges annually.

A 95% confidence interval for the geometric distribution parameter p follows the relationship shown in Eq 3 where, $E(X) = \bar{x}$ is the expected number of failures (3.68), n is the number of years (25), and p is the annual bridge failure rate for the population. Solving for p , p has a range from 0.136 to 0.285, therefore, the confidence interval of the expected value is between 2.51 to 6.36 bridges failures per year. Dividing the confidence interval by the bridge population (17,300), the result is a bridge failure rate between $1.45E-4$ to $3.68E-4$ or $1/6,900$ to $1/2,700$ annually. Scaling this confidence interval to the United States bridge population provides statistical evidence of an average bridge failures rate in the United States in the range from 87 to 222 annually.

$$[np\bar{x} - n(1 - p)]/\sqrt{n(1 - p)} = \pm 1.96 \quad (3)$$

Justification of Failure Rate

Some argument exists in applying the calculated failure rate of $1/4,700$ annually of a regional dataset to the entire nation. Elms (1999) states, threats of various causes to bridge failure are not uniformly addressed in design codes. This suggests the failure rate will change as the threats change from region to region. Dunker and Rabbat (1990) suggest the NBI structural and depreciation rates vary regionally with climate, environment, and possibility due to quantity of truck traffic over time. These studies indicate a differing failure rate based on location.

To validate the SP bridge failure rate, six other states were selected from the NYSDOT database that have responded to the quad-annual questionnaire more than once,

and many are from different regions of the United States. The first is a Midwest state (Midwest I) with a bridge population of 24,200. This particular Midwest state has recorded in the dataset 74 bridge failures in 19 years from 1990 to 2008. The average number of failures is 3.89 annually. This computes to $1.61E-4$ or $1/6,200$ annually, see Table 1. This calculated failure rate is within the 95% confidence interval obtained from the SP which ranges from $1/6,900$ to $1/2,700$ annually. Annual failure rates were calculated, similar to above, for five additional states and are shown in Table 1. The states were a second Midwest state, a Southwest state, a Southern state, and two Mid-Atlantic states, each having an annual failure rate within the determined SP 95% confidence interval. Table 1 shows the bridge failure annual frequency by number per year, year range, total failures, and summarizes the annual failure rates for each. Failures rates are presumed to vary from state to state, but a significant difference from one DOT to another is unsubstantiated. Considering that the SP has the longest duration and can be considered the most complete in the entire database, it is reasonable to conclude that the $1/4,700$ remains the expected failure rate and reasonably applicable to any region within the United States.

Bridge Failure Rate Sensitivity

Insufficient population of bridge failures, discussed previously, has also been termed the “Principle of Consistent Crudeness” by Elms (1999). Defining the Principle of Consistent Crudeness as, “The quality of the output of a model cannot be greater than the quality of the crudest input or of the model itself, modified according to the sensitivity of the output to that input.” The crudest input according to Nowak and Collins

has been the addition or subtraction of a single bridge failure to the dataset which in the past significantly alters the failure probability rate.

The application of the Principle of Consistent Crudeness in this investigation is to show what the crudest or most sensitive input is. Based on Nowak and Collins' logic the sensitivity analysis is adding and then subtracting a bridge failure to the SP. The failure rate of 93 and 91 failures out of 432,500 bridge-years is $2.15E-4$ or $1/4,650$ and $2.10E-4$ or $1/4,750$ annually, respectively. Thus a change in the number of bridge failures within the SP is anticipated to alter the magnitude in the millionth integer or third significant digit. In contrast to the uncertainty of the count of bridge failures is the variance of the model. Numerical confidence interval for the model was determined to be $1.45E-4$ to $3.68E-4$ or $1/6,900$ to $1/2,700$ annually, changing the ten thousandth integer or first significant digit. Therefore, in this study the failure rate is more sensitive to confidence limit or uncertainty of the model than the number of failures contained in the SP. It can be concluded that the order of magnitude for the bridge failure rate has been identified with a confidence limit.

Regulation Implications

The use of the geometric distribution and the validation methods indicate a constant failure rate is a fair assumption. A constant failure rate is viable and anticipated with the dominant causes of failures being due to extreme events. This indicates preservation and maintenance schedules are keeping pace with deterioration. It also means design regulations fail to show decreased bridge failure rates.

Among the most recent design changes are the adoption of the AASHTO LRFD Specifications and HEC-18. Similarities exist between the LRFD Specifications and the

former ASD design methodologies. One method of LRFD factor calibration was used in the ASD factors of safety (Brown et al., 2010). Regardless of the design philosophy employed, the member size selection is not exactly the same but often similar. Because no significant design change has occurred, a change in the failure rate is unlikely based on the code used during the era of design. Duckett (2005) stated similarly, “For many reliability based codes the most straightforward approach [to calibrate a new code] is calibration to existing codes. This is based on the presumption that structures in service today have an acceptable level of safety against structural failure.” Future investigations will attempt to demonstrate the consequences to the failure rate and if it is safe enough. Since the Thruway Bridge collapse over Schoharie Creek in New York, scour type bridge hazards have had numerous new publications and regulations. HEC-18 (Richardson et al., 1991) and related documents were first published in 1991. It can be noted that the most recent year constructed among the SP bridge failures is 1994 which failed from a hydraulic cause. Insufficient time has elapsed to quantitatively determine a decreased failure rate from scour related design improvements or the effects are marginal.

Significant regulation changes have taken place in regard to underwater inspections with the FHWA Technical Advisory T 5140.20 in 1988 and T 5140.23 in 1991 (Willett). These regulations initiated underwater inspections as part of routine bridge inspection for scour assessment. Still, the majority of bridge failures after 1988 resulted from hydraulic causes. Insufficient data exists to quantitatively determine a decreased failure rate from increased inspection criteria.

The cause of failure that has the most potential to reduce the overall rate of failure is hydraulic caused failures. A reduction of half the hydraulic caused failures would

result in a decreased annual failure rate from 1/4,700 to 1/6,400. As a result, hydraulic, and particularly scour, should continue to be a primary focus to mitigate failures.

Conclusions

A sample dataset of bridge failures was analyzed for the cause and rate failure. The sample dataset consists of 103 bridge failures from 1987 to 2011. Of the 103 failed bridges, 92 are believed to be publicly owned roadway bridges, nine are pedestrian bridges, one is a footbridge, and the remaining one is a railroad bridge. From the 92 publicly owned roadway bridges failures and bridge population of 17,300 an overall failure rate was determined. In addition, six other state failure rates were evaluated from different DOTs in the United States. Results show the failure rates of the other states to be within the 95% confidence interval determined from the sample set. The following conclusions were obtained from the data analysis.

- A linear regression analysis demonstrated a constant, increasing, or decreasing failure rate by year are all feasible. A geometric distribution was used to model the expected number of annual roadway bridge failures. The expected bridge failure rate is 1 out of 4,700 annually. The sample population bridge failure rate had a 95% confidence interval of 1/6,900 and 1/2,700 annually. Six additional state datasets were studied and the failure rate of each is within 1/6,900 and 1/2,700 annually. As a result from the DOTs investigated, the United States projected average failure rate is between 87 to 222 bridges annually with an expected value of 128.

- Based upon the year constructed, a wide range of statistical modes were discovered. From these determined modes, there does not appear to be any significant era of design and construction that is more susceptible to failure than another. Enhanced bridge design regulations do not appear to significantly reduce bridge failures. In addition, inclusion of underwater inspections does not appear to have reduced the failures due to hydraulic causes.
- The causes of the 92 bridge failures (excluding pedestrian and railroad bridges) in the dataset were 52% hydraulic, 20% collision, 12% overload, and 7% deterioration. All other causes are less significant. If the hydraulic caused failures could be reduced by half the annual rate of failure could potentially be reduced to 1/6,400.
- Pedestrian bridges that failed in the dataset were due to lateral impact in 89% of occurrences and the remaining 11% during construction.
- A more robust data collection system is required to better trace trends, refine the bridge failure probability rate model, most probabilistic causes and modes of failure, and to mitigate failures in the design and maintenance processes. Such a regulation or mandate is best suited at the federal level.

CHAPTER IV

PROPORTIONING OF BRIDGE COLLAPSE CAUSES AND CONSEQUENCES

Introduction

What makes one bridge more susceptible to failure than another and what are the predictors that cause failures to occur? If a particular bridge does collapse, what are the consequences? These questions are at the forefront of design codes, regulations, specifications, maintenance practices, etc. In fact, the intent of the Load and Resistance Factor Design (LRFD) design philosophy is the establishment of minimum requirements at a set probability of failure or reliability index through various limit states. However, the LRFD design philosophy is theoretically based and has inevitably excluded certain types of uncertainty like human error (Nowak and Collins, 2013) or system performance. Additionally, consequences are addressed by an importance factor that alters the reliability index and effectually decreases the probability of failure. In an effort to transform the above questions from theoretical to data driven computational results, risk management methods can be applied to quantitatively ascertain such queries. Similar risk management methods and decision making models are utilized in the nuclear power industry and United States military operations (Munger et al., 2009).

The primary function of risk analysis is to obtain the likelihood of undesirable events in terms of probabilities and the corresponding consequence (Bowles, 2007). In a fault tree model, the undesired outcome (failure) is assessed on the binary condition of collapse or no collapse by what mechanisms attribute to it. One example is a superstructure failure due to a meteor strike. While it is possible, it has an extremely low

probability, and, therefore, a meteor strike has limited significance. On the other hand, failure, due to foundation erosion from flooding, is several orders of magnitude more likely, and, therefore, is more likely. As an illustration, if the substructure of a bridge fails the bridge fails. A substructure failure due to a hydraulic event is hypothetically 1/5,000. For the collapse scenario, the number of individuals in peril can be deduced with probability when parameters like traffic characteristics are known. From this process a fault tree is formulated. Once the fault tree is constructed in terms of probabilities and the corresponding consequences have been coupled, the analysis is used in relation to value judgment and preferences in decision making models.

A failure devised model has the potential to become a highly effective method of risk management for bridge owning entities and decision makers with the computations being in terms of failure rate. In current practice, where an advanced bridge risk assessment is used, hazard calculations are relative to themselves and are subjectively compared to other hazards or hazards are part of an incomplete model. When hazards are quantified in terms of probability, the values range from 0 to 1 and are directly comparable. Additionally, when probability methodologies are applied, events and consequences can be linked in the model. Examples include failure rate and loss of life. When multiple hazards are assessed with consequences, decision makers are more informed and, thereby, better empowered to evaluate risk mitigation measures.

Nowak and Collins (2013) have stated that the annual bridge probability failure rate is between $1.0E-3$ to $1.0E-5$, but has limited supporting evidence. In a previous work performed by the authors (Chapter III), the bridge failure rate was quantifiably determined from a historical data sample population using a frequentistic philosophy

(Pate-Cornell, 1996). The failure rate for a sample population was determined to be $1/4,700$ or $2.13E-4$ per annum. A geometric distribution was used to model the number of failures annually, which requires a constant failure rate, and a confidence interval was formulated on the expected number of annual collapses. Six additional sample sets had failure rates within the confidence interval, along with other validation methods the failure rate results for the investigation. The two leading causes of bridge failures were found to be due to hydraulic events and collisions. Both are random extreme loading events independent of age. With the assumption that all bridges fail randomly, the importance or significance of the bridge was omitted to enable grouping bridge collapses together regardless of consequences.

This investigation describes the current failure rate for bridges and constructs the numerical framework for fault tree risk analysis. For example, the failure rate of bridges due to collision is unknown from past research; however, the numerical value is determined in this study. Parallel calculations are performed for other causes of failure. The analysis performed herein moves from the frequentistic approach of the authors' former investigation (Chapter III), to a more subjective philosophy, due to the lack of information on failures and the need for proportioning of failure rates causes into subsets. Therefore, proportions have been used from existing data to perform computations. Due to the subjective nature, results are consistent based on the assumptions made and justification is provided as requisite for others to compare. An account of the present state of bridge failure probability has a threefold application. The first is, since the advent of bridge design specification and regulations additions have been introduced with the prospect of improvement to safety with balanced economics. However, have these

alterations effectively influenced the failure rate for bridges? The answer is currently unknown; however, computing the failure rate provides the current state. Furthermore, any future significant changes to design or maintenance regulations can track the failure rate, pending data collection and time. The second application permits comparison of consequence with the failure rate and thereby aids risk management decisions. Last, the resulting computations construct the numerical framework for a fault tree risk analysis. In effort to achieve these goals, this investigation will evaluate quantitatively the historical failure rate into subcategories of cause of failure that are coupled with consequences.

Definitions

Various definitions are presented in this section to establish the frame of reference to be used throughout this investigation.

Risk

Risk is defined as (ICOLD, 2005) a measure of the time dependent probability and severity of an adverse effect to life, health, property, or the environment. Within this definition, the consequence is considered an integral part of an event. Risk analysis is the determination of the probabilities of undesirable events. Consequences are the results of an event; life loss, injury, economics, environmental distress, etc., and all are considered in the adverse effects. Risk assessment is the nexus between risk analysis and consequences.

Failure

For this study, failure was taken by applying the definition of the New York State Department of Transportation (NYSDOT). The NYSDOT categorizes bridge failures as either total or partial collapse, “Total Collapse (TC): structures which all primary members of a span or several spans have undergone severe deformation such that no travel lanes are passable. Partial Collapse (PC): structures on which all or some of the primary structural members of a span or multiple spans have undergone severe deformation such that the lives of those traveling on or under the structure would be in danger” (NYSDOT, 2004).

Tolerable Risk

The tolerable risk definition was taken by applying the interim tolerable risk guideline of the United States Army Corps of Engineers (USACE). The USACE defines tolerable risks “as risks that society is willing to live with so as to secure certain benefits, risks that society does not regard as negligible or something that it might ignore, risks that society is confident that are being properly managed by the owner, and risks that the owner keeps under review and reduces still further if and as practicable” (Munger et al., 2009).

Dataset Descriptions

In 1987 the Thruway Bridge over Schoharie Creek in New York collapsed due to foundation scour with tragic consequences (Lichtenstein, 1993). This bridge collapse led to the establishment of this NYSDOT’s bridge failure database. The goal of creating this database was to bridge failures document not only in New York but throughout the

United States. As a result, the NYSDOT database is updated by sending questionnaires to every DOT in the nation at four year intervals or validation of new articles or periodicals. The database in general, lacks comprehensiveness due to missing less significant bridge failures and poor responses from many DOTs. Additionally, the NYSDOT bridge data obtained through news agencies are more likely to be cataclysmic events in which public outcry is high, life loss resulted, or a large number of structures were affected, or was tragic. The same can be stated for the questionnaires received and therefore the data could be skewed as such. The questionnaires request the following information for collapsed bridges: identification (location and features over/under), year built and failed, principal material, bridge type, cause of failure, type of collapse (TC/PC), and fatalities and injuries. Bridge failures that occur within the state of NY are typically associated with the National Bridge Inventory (NBI) structure numbers in the data. The NYSDOT database is partitioned herein for various analysis procedures and each is described for every instance.

The NBI from the Federal Highway Administration (FHWA) is also used in various forms throughout this investigation. The NBI contains data of all publicly owned bridges in the nation of length 6.1 m (20 ft) or more. NBI records are on the public domain through the FHWA (2012). The New Mexico Department of Transportation in a joint venture with FHWA has developed software, Special Application Bridge Information System (SABIS), which has enabled data mining with map and query interfaces for the NBI records. Through the SABIS software, nearly all of the bridge failures that occurred in the State of NY have been associated with NBI data.

Bridge Collapse Cause Proportioning

Bridge Collapse Datasets

The NYSDOT database has been assembled into three distinct datasets, see Table 3. One, to be referred to here after as All Data (AD), consists of the entire record which has 1,745 bridge failures within the United States and extends from 1920 to 2011 regardless of use, railroad, pedestrian, or the like. The second dataset is a confined portion of AD obtained by truncating the years to include failures from 1987 to 2011 (25 years). For this dataset, the inclusion of bridges is restricted to vehicular bridge failures and precludes railroad and pedestrian bridges. This dataset is referred to as the Restricted Data (RD). The RD dataset has 691 vehicular bridge failures. Of the 691 failures 190 are PC, 240 are TC, and 261 lack the type of collapse distinction. The final assemblage includes 92 bridge failures within the State of New York (NY) of the RD 691 and will be referred to as the Sample Population (SP); acknowledging NYSDOT is the most apt to report and record a failure of any another entity and therefore the most complete sample set (Wardhana and Hadipriono, 2003).

Table 3 Datasets description

Dataset Name	Acronym	Region	Period Covered	Years Covered	Number of Collapses	Bridge Uses
All Data	AD	US	1920-2011	92	1,745	Pedestrian, RR, & Vehicular
Restricted Data	RD	US	1987-2011	25	691	Vehicular
Sample Population	SP	NY State	1987-2011	25	92	Vehicular

Hazards

In an effort to identify the hazards that cause bridges to fail, the AD dataset was reviewed. Table 4 provides a list of all the causes of failure that were compiled. The compilation of hazards describes the initiating events that have caused bridges to fail from historical data, without ranking or probability. The hazards are divided into categories representing the major causes of failure with subcategories where the data is specific enough for the designation. Knowledge of potential hazards for bridges is an effective method of risk management when remedial action is low costs or obvious (Pate-Cornell, 1996). However, when public sensitivity to large magnitude events is critical more advanced risk management methods of risk assessment are warranted.

Proportioned Bridge Collapse Cause Failure Rates

For a more advanced risk management than only knowing the hazards resulting bridge failure, an evaluation of the rate due to specific causes of bridge failures is addressed. To determine the failure rates by cause, the expected or average annual failure

Table 4 Bridge collapse hazards

<i>Category</i>	<i>Subcategories</i>
<i>Hydraulic</i>	Flood, Scour, Debris, Ice, Drift, & Dam Failure
<i>Collision</i>	Auto, Truck, Barge or Ship, Train Collision or Derailment, & Airplane
<i>Geotechnical</i>	Slide Plane Failure, Foundation Instability, Abutment Collapse, Sink Hole, Consolidation, Anchor Failure, Unreinforced Piers, & Inadequate Soil Compaction
<i>Fire</i>	Fire, Explosions, & Fire and Collision
<i>Deterioration</i>	Concrete, Steel, Decay, Pier, Pile, & Abutment
<i>Overload</i>	Posted, Overload with Deterioration
<i>Nature</i>	Storm, Hurricane, Wind, Tornado, Earthquake, Volcanic Eruption, Avalanche, Freezing, Insect Attack, & Tree Fall
<i>Other</i>	Fatigue, Design Error, Construction, Bearing, Cable Rubbing, Miscellaneous, or Unknown

rate (1/4,700) established in the authors previous investigation (Chapter III) is used herein, without consideration of the confidence interval range. The average annual failure rate (1/4,700) is proportioned by cause types into categories and subcategories using proportions. The proportions are assessed from the RD dataset. All failures in the AD dataset encompass an unknown time frame due to poor records prior to 1987, as such; the RD dataset is the most reliable dataset available. The RD can only determine a failure rate for subsets for which a failure has occurred and is represented in the data, otherwise this method omits small probability occurrences due to lack of comprehensiveness and time lapse of the dataset. By constructing the data in this form, the causes of failure can be ranked by rate. Table 5 presents the proportioned failure rate determined by cause. They are shown in descending order of categories and subcategories. The types of collapse (TC/PC if indicated in the record) are tabulated and summed for total counts. Percentages by cause are also provided.

Conditional Probability

It is improbable that a bridge spanning a roadway will fail due to a flood event. Conversely, a bridge spanning a river is not susceptible to vehicular collisions. In previous investigations, the two leading causes of bridge collapse were found to be hydraulic and collision (Wardhana and Hadipriono, 2003). Therefore, the highest two causes of failure are due to what travels under the structure as opposed to over. The observation that the feature under the structure has a significant influence on the cause of failure allows for a distinction of the failure rate based on the feature under and assists in the fault tree analysis. This type of distinction is a conditional probability. Two

Table 5 Cause-proportioned failure rate for bridges in the United States (1987-2011)

Mode of Failure	Partial Collapse	Total Collapse	Not Indicated	Total Count	Percentage of Total	Proportion of Failure Rate
Hydraulic Total	82	115	182	379	54.85%	1.17E-04
Flood	26	56	116	198	28.65%	6.10E-05
Scour	46	41	44	131	18.96%	4.03E-05
Debris	1	5	17	23	3.33%	7.08E-06
Hydraulic	6	8	0	14	2.03%	4.31E-06
Ice	3	3	5	11	1.59%	3.39E-06
Drift	0	2	0	2	0.29%	6.16E-07
Collision Total	47	24	18	89	12.88%	2.74E-05
Collision	35	13	14	62	8.97%	1.91E-05
Auto/truck	9	4	1	14	2.03%	4.31E-06
Barge/Ship	3	5	3	11	1.59%	3.39E-06
Train	0	2	0	2	0.29%	6.16E-07
Overload	11	44	23	78	11.29%	2.40E-05
Deterioration Total	25	12	24	61	8.83%	1.88E-05
Deterioration	23	11	15	49	7.09%	1.51E-05
Steel-deterioration	2	1	9	12	1.74%	3.69E-06
Fire	6	9	4	19	2.75%	5.85E-06
Storm/Hurricane	1	16	0	17	2.46%	5.23E-06
Geotechnical	7	4	1	12	1.74%	3.69E-06
Construction	3	7	0	10	1.45%	3.08E-06
Miscellaneous	1	2	4	7	1.01%	2.16E-06
Earthquake	0	5	1	6	0.87%	1.85E-06
Fatigue-steel	4	0	1	5	0.72%	1.54E-06
Design Error	2	1	1	4	0.58%	1.23E-06
Tree Fall	0	0	2	2	0.29%	6.16E-07
Bearing	1	1	0	2	0.29%	6.16E-07
Sum	190	240	261	691	100.00%	2.13E-04

questions need to be answered. If a bridge is over water what is the failure rate?

Similarly, if a bridge is over a roadway what is the failure rate? To answer these

questions, the SP was separated by the features under the bridge. The conditional failure

rate can be defined by the following equation:

$$P(F + |W +) = \frac{P(F+\cap W+)}{P(W+)} \quad (4)$$

where $P(F + |W +)$ is the probability ($P[\cdot]$) of failure ($F+$) given ($|$) that the bridge is over water ($W+$). To solve this conditional probability, the intersection (\cap) of the number of bridge failures that were over water is needed as well as the probability the bridge is over water. The SP was used for this computation because the underlying population was known. Of the 92 failures in the SP 74 were over water, therefore $P(F + \cap W +)$ was changed to a probability and annualized when 74 is divided by 17,300, the underlying bridge population, and 25 years or 432,500. $P(F + \cap W +)$ was determined to be $1.71E-4$. For NY State 69.95% of the bridges are over water ($W+$) (obtained through NBI data). When one of the features under a bridge was water, the failure rate was calculated to be $2.44E-4$ or 1/4,100 annually. Similarly, the conditional probability of the probability of failure given a bridge is over a roadway or railroad can be solved. Nineteen bridges in the SP that failed are over a road or railroad. Note that the sum of 74 and 19 is greater than 92. This is due to bridges spanning multiple items. The SP underlying population has 30.63% of bridges with a roadway, railroad, and/or miscellaneous as a feature under. For the SP when accounting for the feature under the failure rate when over a roadway is $1.43E-4$ or 1/7,800 annually. Therefore, a bridge is more likely to fail when it is over water than if it is over a roadway. It has been found that scour/hydraulic is the principal cause of failure but not just because most bridges (83.08%) in the United States are over water.

The conditional failure probabilities determined, if a bridge spans over a waterway and/or over a roadway, are proportioned in Table 6 by cause types into categories and subcategories causes of failures using proportions. The values determined can be directly applied in a fault tree risk analysis depending on the bridge configuration

under consideration. Some judgment is required in the failure rate selection for specific causes. For example, the cause deterioration; if a bridge spans a waterway the failure rate can be taken from Table 6 at a value of $2.21E-5$. However, present research is insufficient to state that a bridge spanning water has an increased deterioration rate and, therefore, should be modeled with a general bridge failure rate determined off of Table 5, at a smaller and less likely value of $1.88E-5$. It is at the discretion of the fault tree creator(s) to justify the selection of the failure rate based on the conditions of a specific bridge.

The data further discretized into failure type (TC and PC) assists in understanding the consequences associated with the extent of damage. Considering the hydraulic total causes category, omitting “not indicated,” 41.6% are PC and 58.4% are TC. Thus, the distinction of TC proportionally is the product of $1.52E-4$ and 58.4%, which is $8.87E-5$ or 1/11,300 annually, see Hydraulic Failures in Figure 6. Overload failure are the second leading cause of failure when the bridge is overwater. It can be assumed that a correlation exists for the increased failure rate over water opposed to over a roadway. However, the data is currently insufficient to quantify the value, therefore, the failure rate was taken from the proportion in Table 5 as $2.40E-5$ annually and TC (80.0%) the product is $1.92E-5$ or 1/52,000. This value was plotted in Figure 6.

Consequences

The discussion of bridge failure consequences, especially life loss, is a sobering topic and must be approached with the right intent of improving safety and mitigating risk. Bridge failures historically speaking in the United States have taken numerous

Table 6 Cause-proportioned conditional failure rate for bridges in the United States

Cause of Failure	Over Water			Over Roadway & RR		
	Count	Proportion	Failure Rate	Count	Proportion	Failure Rate
Total	609	100.00%	2.44E-04	87	100.00%	1.43E-04
Hydraulic Total	379	62.23%	1.52E-04	7	8.05%	1.15E-05
Overload	69	11.33%	2.77E-05	3	3.45%	4.94E-06
Deterioration Total	55	9.03%	2.21E-05	6	6.90%	9.89E-06
Collision Total	42	6.90%	1.68E-05	52	59.77%	8.57E-05
Storm/Hurricane	17	2.79%	6.82E-06	–	–	–
Fire	12	1.97%	4.81E-06	6	6.90%	9.89E-06
Geotechnical	9	1.48%	3.61E-06	4	4.60%	6.59E-06
Construction	7	1.15%	2.81E-06	4	4.60%	6.59E-06
Fatigue-steel	4	0.66%	1.60E-06	1	1.15%	1.65E-06
Earthquake	3	0.49%	1.20E-06	2	2.30%	3.30E-06
Design	3	0.49%	1.20E-06	–	–	–
Tree Fall	2	0.33%	8.02E-07	–	–	–
Bearing	1	0.16%	4.01E-07	1	1.15%	1.65E-06
Miscellaneous	6	0.99%	2.41E-06	1	1.15%	1.65E-06

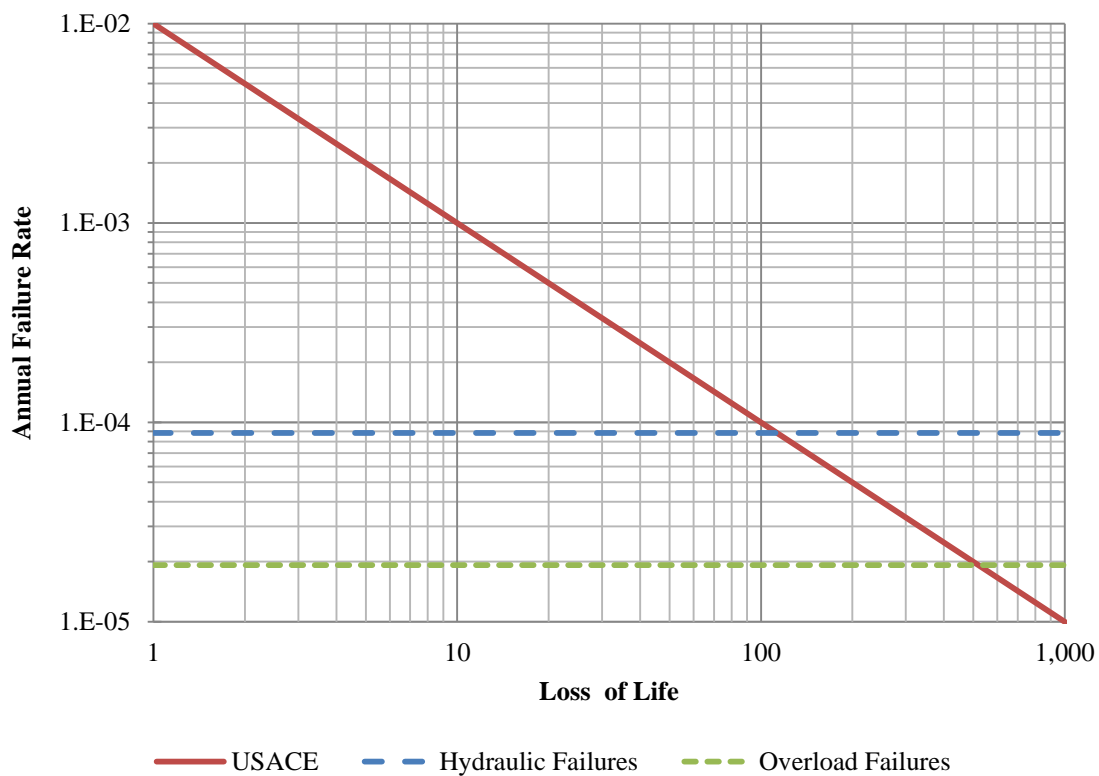


Figure 6 Bridge collapse annual failure rate and loss of life compared with United States Army Corps of Engineers (USACE) dam safety interim tolerable risk guideline.

lives. Instances include: the Silver Bridge of 1967 which was a corrosion and overload catastrophic collapse, 46 fatalities resulted (Lichtenstein, 1993), Tampa Bay Sunshine Skyway Bridge of 1980 which was a barge collision catastrophic collapse causing 35 fatalities (Wuttrich et al., 2001), New York Thruway Bridge over Schoharie Creek scour foundation failure in 1987 resulting in 10 fatalities (Lichtenstein, 1993), gusset connection failure of the Minnesota I-35W bridge in 2007 with a total of 13 fatalities (Hao, 2010), and others. When assessing bridge risk potentials for failure managing the outcomes is also of interest. When a bridge fails that has an Average Daily Traffic (ADT) of one, the general public will be unalarmed or might not even be aware, however, when the ADT is high and/or life loss occurs for a failed bridge the public outcry is substantial. For any bridge failure the question is; what is at risk? Bridge failure rate needs to be assessed on the level of risk posed to society; the greater the risk the lower the failure rate ought to be. Bridge failures have caused public outcry depending on the magnitude of the consequence and are considered an involuntary risk, when life loss is due the collapse of the structure. This investigation will present a hierarchy of consequences, evaluate ADT, detour length and life loss for the 92 bridges that failed in the SP, life loss with the 691 bridge failures in the RD set, and assesses loss of life consequences qualitatively and quantitatively.

Consequences Hierarchy

Consequences are diverse, naming a few: life loss, injury, critical or emergency routes, economic loss, environmental concerns, and historical significance. When considering decision management alternatives, a hierarchy is sure to exist on the potential

outcomes if a bridge or portfolio of bridges were to experience extreme loadings. Ethical issues arise with comparison of consequence categories but are applicable within a judgment of a hierarchy. Preference of what routes are critical in the event of a major earthquake, is an example of how a hierarchy can be utilized in risk management. Each category has both direct and indirect effects. For example, economic loss can have direct cost through litigation and expedited bridge replacement while indirect loss could be stifled economic development and high user cost. Direct consequences are often simpler to measure and records exist of this nature. On the other hand, indirect consequences are inclined to be onerous to collect and complex, as such records are rare at best. Assessment of consequences in this investigation is a framework for evaluating direct life loss in a fault tree risk analysis.

Qualitative Consequences to Life Loss

Qualitatively life loss consequences for bridge failures are mainly a function of the failure cause, structural configuration and traffic characteristics. Failure cause and structural configuration are interdependent on the rate it takes a bridge to collapse, sudden catastrophic or ductile, and length of span(s) that failed. For instance, bridges with multiple girders or redundant load paths have the ability to transfer load to adjacent members and avoid TC in a particular span, whereas in the case of suspension bridges if one span fails the counter weight will cause instability and the other spans will eminently fail. Accordingly, the collapse progression is time dependent and also plays an integral part. In the event a sufficient deficiency is observed and authorities are notified, the bridge can be closed and traffic rerouted averting the ailing bridge's probability of life loss, otherwise lives are at risk. Once the probability and nature of failure are

determined, the traffic configuration dependent with bridge length or span lengths and width dictate the number of vehicles at risk. The composition of traffic, diurnal flow, vehicle lengths, persons per vehicle, flow rate, density, number of lanes, and stopping sight distance (SSD) all influence the number of individuals at risk in the event of a failure. Composition of traffic relates to the diversity of the traffic, whether it is semi-tractor trailers, transport busses, or passenger vehicles, and a mix. Vehicle length determines the maximum number of vehicles that can feasibility fit on a specific bridge length. Persons per vehicle values convert the vehicles at risk to the population at risk. The flow rate is an estimate of the number of vehicles per hour passing a point, whereas density refers to the number of vehicles on the road. The relationship between the two is the higher the density the lower the flow rate, with the maximum density being gridlock and flow is near zero. The number of lanes is independent of direction but multiplies the at risk vehicles per lane. Last is the SSD, which is the length necessary to stop before running off into the damaged, downed portion or void. The process can be duplicated in the event a bridge crosses another roadway with some alterations. Falling debris becomes an issue, and as such, the type of failure can change to no longer requiring span or total collapse of the structure but structural component disintegration. These criterions constitute a qualitative life loss in a generic form for the travelled way, and are by no means comprehensive.

Quantitative Consequences to Life Loss

Historically significant bridge failures that have resulted in extreme consequences are in general well researched. Two examples are the Queen Isabella Causeway and the I-35W Bridge in Minneapolis that failed in 2001 and 2007, respectively. The Queen

Isabella Causeway bridge failure is unique due to the route being the only vehicle access to the South Padre Island, Texas. Thus, when the failure occurred the residence of South Padre Island had no detour, became isolated and utilities crossing the bridge were severed. Not only were lives loss in the bridge collapse but the entire community became exposed to the consequences of the failure (Wilson, 2003). The Minneapolis I-35W Bridge had a relatively short detour length; however, the ADT of 140,000 is an example of life loss and high user cost from the ensuing metropolitan traffic congestion (Hao, 2010). Two major factors that lead to adverse consequences, that are also in the NBI data, are ADT and detour length. Analysis of life loss, ADT and detour length are shown for the 92 failures of the SP, then comparisons of the 92 to the entire NBI are conducted by simulation, and last the benchmark when the life loss parametric is likely to be intolerable is assessed.

Sample Population Bridge Collapse Data Consequences

The bridge failures in the SP have been associated with the NBI; estimates on consequential effects for ADT and bypass, detour length from historical data can be examined. In the SP, 92 bridge failures occurred within the State of NY in 25 years, 88 of those were identified in the NBI. The ADT for the 92 failed bridges had 10 to 50,383 as the range, 4,654 as the mean and 755 as the median. The median is telling of the data in that half the bridges had less than 755 ADT or are fairly insignificant failures. On the other hand the right tail is long with two bridges above 50,000 ADT, one in the 30,000 to 40,000 range, four in the 20,000 to 30,000 range, seven in the 10,000 to 20,000 range, all others are in the interval 755 to 10,000. The bypass, detour length for the 88 bridges has a range from 0 to 199 km. The coding requirements of Item 19 (bypass, detour length) in

the NBI are zero when the structure is bypassable and 199 when on a dead end road or of greater length than 199 km detour (FHWA, 1995). All values within the interval 0 to 199 km are the extra distance traversed by the detour. Thirteen of the 88 bridges were coded 199 km, and four were coded zero, the average is 33.5 km, median 4 km with a mode of 1 km. Life loss occurred in four different instances with two scour and two collision caused failures. The life loss and injuries of the two collisions are likely a result of the collision not the bridge collapse. The majority of these consequence is fairly low, half had less than 755 ADT, 95.7% had no life loss, and detour lengths were commonly under 5 km (3 miles). The RD set has 24 instances of loss of life and 96.5% have no life loss. However, in few instances roughly 3.5% resulted in high consequences. If the proportion is applied to the annual expected number of bridge failures in the United States approximately four can be associated with loss of life.

The ADT mean and median are fairly similar for both the entire NBI and SP. The entire NBI data from the year 2011 has 604,415 bridges and a mean ADT of 7,335 and median of 820 and the SP has a mean of 4,654 and a median of 755. Therefore, a Kolmogorov-Smirnov test, shown in equation 2, which evaluates if two empirical distribution functions ($F_{1,n}(x)$ & $F_{2,\hat{n}}(x)$) are from the same statistical distribution,

$$D_{n,\hat{n}} = \sup_x |F_{1,n}(x) - F_{2,\hat{n}}(x)| \quad (5)$$

was performed. The Kolmogorov-Smirnov statistic (D) is solved by evaluating the supremum (\sup_x) of the set distances of the two empirical sample distribution functions. If the two samples come from the same distribution $F(x)$ then D converges toward zero and a high probability is determined. A probability of 0.54 was determined which fails to reject the hypotheses that they are from the same distribution. From this evaluation a

valid assumption is that bridge failures are random events regardless of the ADT traversing the bridge and is applied in this investigation. If a bridge fails randomly in regard to the ADT, then a simulation can compare the NBI data to the SP. In simulations of the entire United States Bridge population 88 bridge were randomly selected, commonly at least one bridge will have an ADT of 50,000 or more. If the simulation is performed for the 128 expected number of bridge failures annually in the United States one or more bridges is likely to have an ADT of 70,000 or greater. Therefore, based on the expected number of annual failures and simulation, a bridge fails randomly and one is expected to have an ADT of 70,000 or more.

Tolerable Risk Comparison

Involuntary tolerable risk guidelines of the failure rate and loss of life (N) can be used as a benchmark in the risk management decision process. Both the USACE for dam safety and Federal Energy Regulatory Commission (FERC) have collaborated in an attempt to set tolerable risk guidelines (Munger et al., 2009). The USACE interim tolerable risk guidelines of the consequences regarding N is graphed with the failure rate, shown in Figure 6. Figure 6 is a log-log plot where the guideline is a diagonal line with a lower failure rate associated with higher N, representing the aversion of increased life loss to the likelihood of an extreme event.

A comparison of the USACE interim tolerable risk guidelines and the failure rate describes the current standing of bridge failures in the United States. The number of possible fatalities associated with hydraulic failure is unclear, unless, discussing a particular bridge or group of bridges that if failed pose a substantial threat to life. The number of feasibly exposed individuals (denoted N) from a hydraulic cause bridge failure

being unknown, unless discussing a bridge of interest, the bridge failure rate due to hydraulic causes was generally represented with a horizontal line in Figure 6. The intersection of the guideline and hydraulic caused TC, when a bridge is over water, failure rate is $8.87E-5$ or 1/11,300 annually and N is 113 persons. The second most likely cause of TC when a bridge is over water is overload which has a failure rate of $1.92E-5$ or 1/52,000 and intersects the guideline at 520 persons. Historically no twentieth or twenty first century bridge failure in the United States has had a life loss of either magnitude, with hydraulic caused failures being the foremost of all causes. This suggests that bridge failures, in regards to life loss, are in a tolerable range. An additional issue is if life loss is tolerable enough, which is beyond the scope of this investigation.

Conclusions

A database of United States bridge failure was used to compare consequence with the failure rate by cause. The failure rate by cause and consequence were evaluated qualitatively and quantitatively and can be utilized in future fault tree risk analysis and risk management decision making. A database of United States bridge failures was used to show the hazards bridges have failed from historically, determine the failure rate based on the cause of failure, and formulated a conditional probability of failure accounting for the features under the structure. Consequences of bridge failures were established qualitatively by engineering judgment. Quantitative consequences were assessed from historical data and compared with a benchmark set by United States Army Corps of Engineers interim guideline for dam safety. The following conclusions were obtained from the data analysis.

- Based on proportioning the annual failure rate of bridge collapses the annual failure rate by multiple causes were determined. The failure rate due to overload is $2.40E-5$, and for deterioration is $1.88E-5$ both values are illustrations of the failure rate by causes.
- The dominant causes of failure are due to the feature under or what travels under the structure, as such; a conditional failure rate was determined to account for features under. The conditional failure rate calculated the most likely cause of failure is hydraulic in nature ($1.52E-4$), adjusting for the fact the most bridges in the United States are over water.
- A framework of qualitative consequences is constructed for a hierarchy of risk management decision making. Additionally, life loss parameters for fault tree risk assessment evaluating are established.
- Historically, life loss occurred on about 4% of bridge failures. Analysis and simulation of ADT of historically failed bridges shows bridges fail randomly and in turn, high consequence bridge failures are expected. From simulation at least one bridge fails annually with an ADT of 70,000 or greater.
- A benchmark set by United States Army Corps of Engineers interim guideline for dam safety and Federal Energy Regulatory Commission show bridge failures probability of failure and life loss are in a tolerable range compared to the benchmark.

CHAPTER V

BRIDGE COLLAPSE TRENDS AND EFFICACIOUS DATA COLLECTION

Introduction

The Moving Ahead for Progress in the 21st Century Act, also called MAP-21, stipulates the application of ‘risk-based and data-driven approaches to infrastructure initiatives and other FHWA bridge program goals. Risk-based approaches are to factor in the importance of the structure, defined by the need to provide safe and reliable waterway crossings, and consider the economic consequences of failure’ (FHWA, 2013). A risk-based approach, or risk analysis, has been limited in the types and methods used for collapse assessment due to the scarcity of bridge collapse information. In effort to comply with the Map-21 requirements, recommendations are investigated herein for effective data collection and associated data fields of interest used in probabilistic based analysis. Deficiencies in the existing data have been observed in former bridge failure investigations (Wardhana and Hadipriono, 2003). A formulation of the type of data of to acquire and the analytical method to use is performed based on the feasibility and the results that are desired. The intent of this investigation is to show predictive trends from existing collapses data and extrapolate efficacious bridge collapse data by: establishing a desired analysis method for risk-based and data-driven approaches, specifying data fields to assist analysis and consequence assessment, and illustrating trends among collapses, while maintaining concise data.

Data Collection Current Practices

Risk analysis is the quantitative determination of the probability of loss or injury to people and property (Henley and Kumamoto, 1981). Risk analysis for structures is commonly analyzed by one of three techniques: expert opinion, reliability analysis, and failure analysis (Sundararajan, 1995). The first method is used when data is scarce and the demand for probabilistic analysis of failures is high, or the consequences are extensive. In this situation, expert opinion and/or Bayesian probability (Bulleit, 2008) is used in the development of failure probability for components of a system and the resulting consequences. A second risk method is reliability analysis which is the premise of the LRFD design philosophy. Reliability analysis uses simulation, analytical or numerical integration, moment-based methods, or first and second order methods of approximate limit states, with loadings and resistance data in determination of reliability indices and probability of failure per limit states (Pate-Cornell, 1996). This method is an inductive logic or bottom up approach that is typically performed in the design phase to investigate all possible failure modes (MacDiarmid and Bart, 1995). A third risk assessment technique, referred to as failure analysis, uses frequentistic (Bulleit, 2008 and Pate-Cornell, 1996) or classical statistical philosophy to determine the failure rate from historical data, top down, or retrospective analysis of a group of failures. Reliability analysis, in this context, focuses on, how a system *will* perform. Failure analysis focuses on, how *did* a system perform.

Expert Opinion and Bayesian Probability

Often bridge failure data is incomplete and insufficient to enable classical statistical analysis of bridge failure rates and risk to life from historical data. Menzies'

(1996) investigation is an example of insufficient available data. Menzies used expert opinion and assumed a lifetime bridge collapse rate in the United Kingdom of 1 in 5×10^5 and determined annum fatality risk of 1 in 5×10^8 . From the analysis, the annual risk to life was calculated to be satisfactorily low enough.

Reliability Analysis

Akgul and Frangopol (2006) used reliability simulation to evaluate the load rating and reliability indices for a network of bridges with a probability of failure for each bridge. The values obtained constitute one parameter of Liu and Frangopol's (2006) study of the transportation network reliability for the Northwestern Denver, CO metropolitan freeway system. Reliability through modeling or simulation tends to inevitably exclude certain types of uncertainty. The types of uncertainty from some sources, like tornados, are, and realistically ought to be, omitted. The researcher (Nowak and Collins, 2013), that was involved in the LRFD Bridge Specifications calibration, has stated the LRFD design philosophy is a theoretical model and does not include all sources of uncertainty. Some examples include human error like design errors and bridge strikes or exclusion of deterioration. Akgul and Frangopol's (2006) model was more advanced than the LRFD methodology with the inclusion of the deteriorated condition for member components, which is critical for overload caused bridge failures. However, the leading cause of failure, hydraulic, is not fully addressed above the LRFD limit states, nor have vehicle collisions been included in the model, which was found to be the second leading cause of collapse (Wardhana and Hadipriono, 2003 and Chapter III). Therefore, when the two leading causes of collapse are poorly integrated, large discrepancies between reliability and actual probability of failure are expected. Liu and Frangopol's (2006)

study is an excellent demonstration of the level of detail a probabilistic analysis for a network can bring to fruition.

Forensic Analysis

For high profile and large quantities of bridge collapses, case studies are frequently performed. Case studies involved with forensic engineering state why bridges have failed. Detailed forensic analysis is performed on a very limited number of bridge collapses (Chapter III). A wealth of information is understood and learnt from bridge collapses, but are often at a micro scale compared with the total number of collapses. Results for collapse case studies are frequently incorporated into design codes or specifications as lessons learned. However, the need for design codes or specifications to adequately address the most common or most likely causes of collapse remains uncertain. In addition, are certain areas, such as, seismic resistance overdesigned and others are insufficiently addressed. Forensic analysis tends to be of isolated incidences rather than risk-based.

Bridge Performance Data Collection

The current practice for collecting and storing bridge performance data is federally regulated and contained in the National Bridge Inventory (NBI). The NBI contains data of all publicly owned bridges in the nation of length 6.1 m (20 ft) or more. The record is 116 data fields for the 600,000 plus bridges in the United States. The information contained in the NBI relates to location, owner, use, condition rating, and more. NBI record creation is the data collected during regulatory inspections at an interval not to exceed 24 months.

The next most common practice is developing bridge element performance based records for bridge management systems. Records are created through bridge inspections with state by state preferences and many use AASHTOWare or the forerunner Pontis. According to Cambridge Systematics, 45 plus DOTs had licenses to Pontis in 2008 (AASHTOWare, 2013). AASHTOWare is a bridge management software developed to collect and store NBI and bridge element conditions with features for tracking preservation and maintenance, perform deterioration modeling, and assist the decision-making process through cost-effective optimization of allocations. Some DOTs enhance the element condition data through collection and analysis of advanced deterioration (Thompson et al., 2013). To a large extent, fatigue or fast catastrophic chains of events such as flooding are ignored by bridge management systems.

Failure Analysis

The intent of failure analysis is to assess how a system performed by collecting data and analyzes parameters, such as, failures per time interval or cycles per failure (Scheaffer and McClave, 1995). The provisions which enable failure analysis techniques to be performed are if the sample sizes are sufficiently large and can probabilistic distribution model these data (Pate-Cornell, 1996).

Nowak and Collins (2013) stated the bridge probability failure rate in the United States is between $10E-3$ and $10E-5$ annually, but has limited supporting evidence. Historical data commonly has the predicament of being insufficiently large. While the effect of an addition or subtraction of a bridge failure to the dataset significantly alters the

failure probability rate. In an effort to circumvent the issues arising from small samples, simulation based reliability is most commonly used.

Availability of data for bridge failure analysis rarely exists in published works. The most common failure analysis is for geographical hazards like marine vessel collisions (Larson, 1993) and event specific or bridge specific forensic analysis. Stearns and Padgett (2011) is one example of an event specific bridge analysis. A plethora of forensic investigations for significant bridge failures abound.

New York State Department of Transportation (NYSDOT) is a rare exception and collects and maintains a bridge collapse database. In 1987, the Thruway Bridge over Schoharie Creek in New York collapsed due to foundation scour leading to the establishment of this NYSDOT database. The goal of creating this database was to document bridge collapses not only in New York, but throughout the United States. Record creation of collapsed bridges in the NYSDOT database depends on two primary sources of information. One data source is obtained by sending questionnaires to every DOT in the nation at four year intervals. The questionnaire currently requests seven pieces of information for collapsed bridges: identification (location and features over/under), year built and failed, principal material, bridge type, cause of failure, injuries and fatalities, and type of collapse Total Collapse (TC) or Partial Collapse (PC). The database is also updated by NYSDOT personnel who hear of and validate bridge collapses through any viable source. This is the only agency, including federal organizations, that collects and maintains a national bridge failure database (Wardhana and Hadipriono, 2003). However, despite the best efforts, this database is described as non-comprehensive (Winchell Auyeung, personal communication, 2011).

The lack of comprehensiveness of the NYSDOT bridge failure database is evident in two forms; incomplete information on a failure and unrecorded failures. In 2008, only 18 responses were returned from all the DOTs in the nation (Winchell Auyeung, personal communication, 2011) for the quad-annual questionnaire. Additionally, on more than one occasion, DOTs that did respond to the questionnaire reported no updates to the existing failure database, when in fact bridge failures did occur in these DOT regions and were documented in other published works. Many such cases were found to occur between 2004 and 2009. Also, incompleteness often occurs when not all the information data fields are compiled. This is true even for the State of New York bridge collapses.

Despite the lack of comprehensiveness of the database observations have been made from sample populations of the database. A sample set of 92 bridge failures within the state of New York from 1987-2011 show a bridge collapse rate of 1/4,700 annually (Chapter III). In addition, failures based on the cause of collapse and consequences have been assessed (Chapter IV). The 92 bridge collapses occurring over a 25 year period of time are shown in Figure 7. Figure 7 identifies the location of the collapsed bridges in the state of New York with color coding by cause. The legend in Figure 7 is in descending order of collapse cause proportion.

The definition of bridge collapse according to the NYSDOT is categorized as either total or partial collapse, “Total Collapse structures which all primary members of a span or several spans have undergone severe deformation such that no travel lanes are passable. Partial Collapse structures on which all or some of the primary structural members of a span or multiple spans have undergone severe deformation such that the lives of those traveling on or under the structure would be in danger” (NYSDOT, 2004).

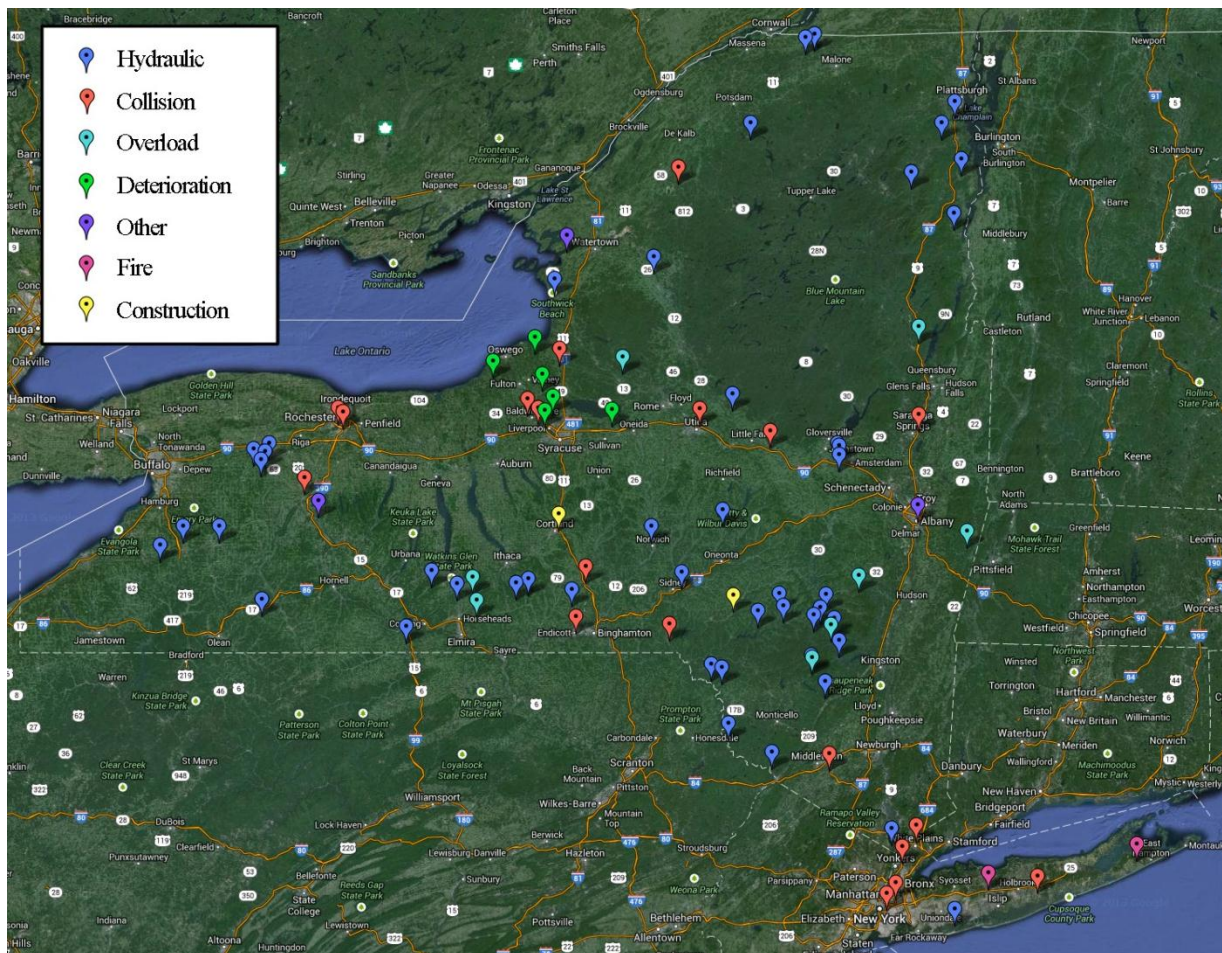


Figure 7 Total and partial collapsed bridges in New York from 1987–2011 (Google Maps, 2014).

Known bridge hazards from NYSDOT collapse database are shown below in Table 4. The compilation of hazards describes the events that have caused bridges to collapse from historical data. The hazards are divided into categories representing the major initiating causes of failure with subcategories where the data is specific enough for the designation.

Deficiencies in Current Bridge Collapse Data Collection

The item of upmost concern leading the decision for potential areas of improved data collection, at present, is the dearth of information regarding bridge

collapses. The NBI does indicate when a bridge has “failed” by assigning a condition rating of zero to bridge components. However, a condition rating of zero can also indicate the bridge is out-of-service and is, therefore, indistinguishable between the two cases. Failure data of bridge collapses are rarely collected or stored. Numerous reasons exist, but two conditions are evident from the responses

NYSDOT receives from various DOTs. DOTs are reluctant to allocate resources to reporting the requested data and, particularly, anything beyond the National Bridge Inspection Standards (NBIS) stipulations, especially at the cost of public perception. At the DOT level, bridge failure data is rarely compiled, stored, or allocated resources for time to respond to the NYSDOT quad-annual questionnaire. It is also evident in the database that some DOTs have responded to the questionnaire at some interval and not at others.

Of the data that is collected by the NYSDOT, the potential exists for biased data. Meaning, bridge collapse data could be skewed due to the collection methods. First, the data collected from news media has the potential to be of a more tragic nature, hence, the reason why the news is reporting it. The second potential source of bias is catastrophic sudden bridge collapses, where life loss is involved and agencies have better recollection for questionnaire responses. A third form of bias is due to large numbers of failures occurring from one event and is, therefore, more likely to be recorded in the database. A fourth form of bias can be due to articles being regionally specific and not representative of bridge collapses across the United States. Regional trends of data could be climate conditions, state-laws, maintenance strategies, exposure, humidity, deicing salts, earthquakes, hurricanes, marine collisions, permits for oversized loads, etc. A bridge

over a waterway is more susceptible to scour than a bridge over a roadway; therefore, the percentage of bridges in a region over water could influence the failure rate.

Significantly different failure rates by region, at present, are unsubstantiated (Chapter III). An example of potential bias is the percentage of failed bridges in New York State from 1987 to 2011, due to collision, is nearly 20% (Chapter III), whereas, the number of bridge collapses due to collision for the same time period over the entire United States is nearly 12%, (Chapter IV). A difference of 8% was observed; all other collapse causes are within 3%.

The NYSDOT database is a meso or medium level analysis, compared with the micro level analysis of forensic investigations, wherein the count of bridge collapses are sufficiently large to ascertain patterns and widen conclusions above a micro level analysis. Based on the expected number of collapse per annum the NYSDOT database contains roughly 22% of all the failures within the United States over a 25-year period of time. One of the end goals is to demonstrate the results that are feasible with a macro, statistical, analysis of failure data. Without a comprehensive database quantitative results are restricted to observations that exist within the known collapses.

Bridge Collapse Observations

Of the 92 bridge collapses which occurred in the state of New York between 1987 and 2011, pre-collapse NBI data has been associated with 66. Discrepancy between the 92 and 66 bridge collapse counts exist due to the lack of available NBI data before 1992; in addition, several collapses have insufficient information to be identified in the NBI. Of the 66 bridge collapses 36 were due to hydraulic, 16 were a result of collisions, seven

were due to overload, two were caused by deterioration, and the remainder is classified as “other”. For deterioration and “other” categories the populations are of a size that generalized statements are restricted. The pre-collapse data assessment, statistical analysis and observations, shows tendencies and identify metrics for future investigation.

Bridge collapses are associated with Structurally Deficient (SD) bridges. For the 66 bridge collapses, 35 or 53% of them were classified as SD. SD labeling of bridges is due to the condition rating of the deck, superstructure, substructure, or culvert, being 4 or less or the structural condition or waterway adequacy appraisal rating being 2 or less. The number of SD bridges in the state of New York was 12% in 2011. Even in the case of collisions caused collapses, that are thought to be random events, 31% were SD prior to collapse. Table 7 shows the number of deficient bridges by cause of collapse. Table 7 is also a contingency table setup to assess the probability of a difference between groups of collapse causes and SD classification. A chi-squared test has a p-value of 0.16; therefore, there is no statistically significant difference in the proportion of SD bridges to Non-SD bridge collapses based on the cause of failure.

A second point of interest is structural deficiency classification among in-service bridges compared with structural deficiency classification of bridges prior to collapse. The collapse and structural deficiency relationship was compared with a contingency table, shown below in Table 8. In Table 8, the quantity of Non-SD and SD bridges are listed for the entire state of New York and collapsed bridges which were Non-SD and SD prior to collapse. The p-value was less than 0.0001; therefore, a strong relationship exists between structurally deficiency bridges and collapsed bridges.

The age and SD relationship was assessed from an analysis of variance or ANOVA table. The ANOVA table compares the ages of all bridges to the ages of SD bridges within the state of New York. The p-value is less than 0.0001; therefore, a statistically significant difference exists between age of SD bridges and all bridges in the state. As shown in Figure 8, the median age of SD bridges is older than the median age of bridges for the entire state.

Figure 8 shows the age of bridges based on four categories, the first is the age of collapsed bridges caused by collision and hydraulic events (average 47.9 years), second is the age of all bridge in the NYSDOT inventory (average 45.5 years), the third is the age of collapsed bridges caused by overload and deterioration (average 61.3 years), and the fourth is the age of structurally deficient bridges in the state (average 64.5 years). An analysis of variance among the four categories shows at least one to be different from the others. Further investigation, either paired ANOVA for each set or Tukey's range test, shows age of hydraulic and collision caused collapse bridges to be related to the overall age of bridges within the state, and age of SD bridges is related to collapse bridges caused by overload or deterioration. Therefore, the age of SD bridges have a relationship

Table 7 Contingency table for bridge collapse cause and structural deficiency

	Hydraulic	Collision	Overload	Other	Σ
SD	22	5	5	3	35
Non-SD	14	11	2	4	31
Σ	36	16	7	7	66

Table 8 Contingency table for collapsed bridges and structurally deficient bridges

	All NYSDOT Bridges	NY Collapsed Bridge	Σ
Non-SD	15325	35	15359
SD	2067	31	2099
Σ	17392	66	17458

with age of overload and deterioration caused collapses. Dissimilarly, age of SD bridges has no apparent relationship with the age of hydraulic or collision caused collapses within the state. It is reasonable to conclude; hydraulic and collision caused collapses are independent of age and are due to random extreme loading events. Therefore, age and SD are related, SD and collapse are related, but only age and various causes of collapse are related.

Of the collapsed bridges due to hydraulic causes a few observations are of interest for future investigations. Underwater inspection was required for two bridges prior to their collapse, both at 60 month intervals, of the bridges that collapsed due to a hydraulic cause. Nearly all the bridges identified as having failed due to scour had a pre-collapse scour critical (Item 113) vulnerability rating of 8; “Bridge foundations determined to be stable for calculated scour conditions; calculated scour is above top of footing” (FHWA, 1995). Only one hydraulic event in the 25 year duration had a recurrence interval equal to or greater than 100 years (NOAA, 2014). The 100 year or more flood event occurred in 1996 with a total of 7 bridges collapsing. Figure 9 is a map showing the location of these collapsed bridges. All seven bridge collapsing during the 1996 flood event were rural routes coded as major collector (1 bridge), minor collector (1 bridge), and local (5 bridges), and no underwater inspections were required.

Of the bridges that collapsed due to overload, six of seven were load rated. The bridge posting (Item 70) ratings were one “5” rating or not posted, one “4” rating meaning up to 9.9% operating stress to legal load stress, and five “2” rating meaning up to 29.9% operating stress to legal load stress. In addition, five of seven were classified as

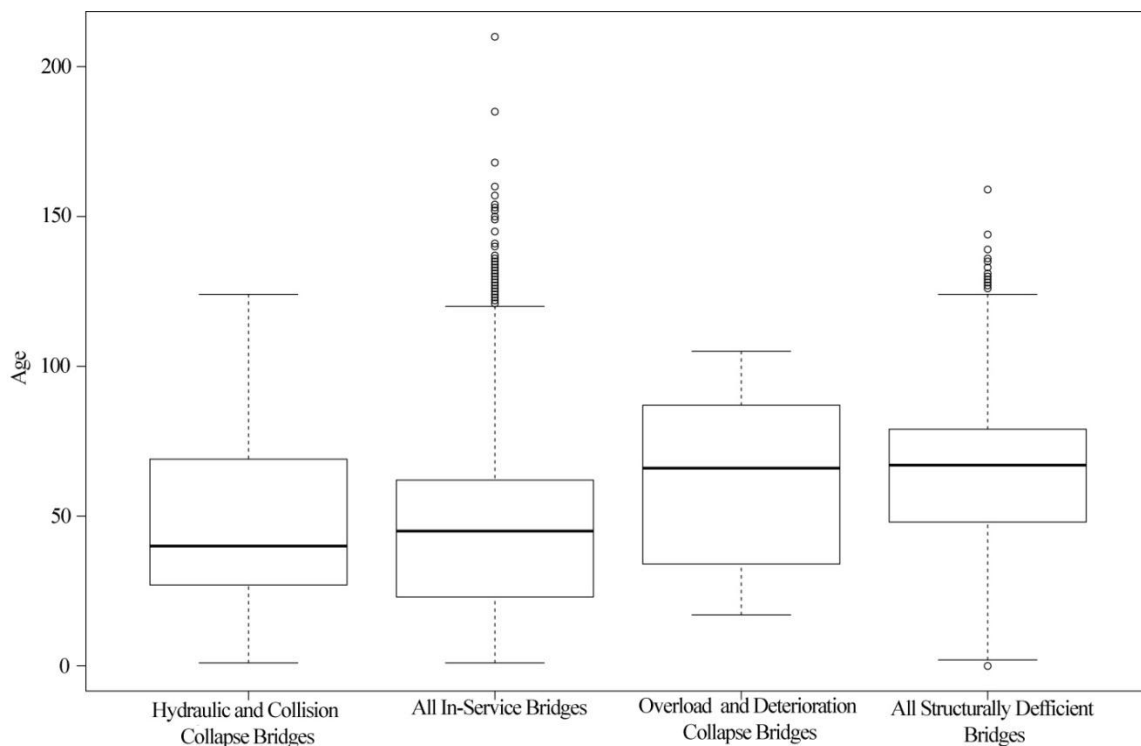


Figure 8 Age box plot of bridge sets from New York State.

SD prior to collapse. Overload cause bridge collapses appear to have a relationship with being load restricted.

Trends observed in the collapse cause of collision show the bridge vertical clearance over roadways, as well as, fracture critical bridges when over water appear related. Three bridges collapsed due to collisions that were over waterways. All three bridges were built during the 1930's and two of them were stated as fracture critical. Thirteen bridges over roadways collapsed due to collision, 12 (92%) had a vertical clearance between 4.26m (14 ft-0 in.) and 4.49m (14 ft-9 in.) and the remaining one at a height of 4.74m (15 ft-6 in.). Collision caused bridge collapses appear to be contingent on the vertical clearance when over a roadway and fracture critical bridges are susceptible to collision induced collapse.

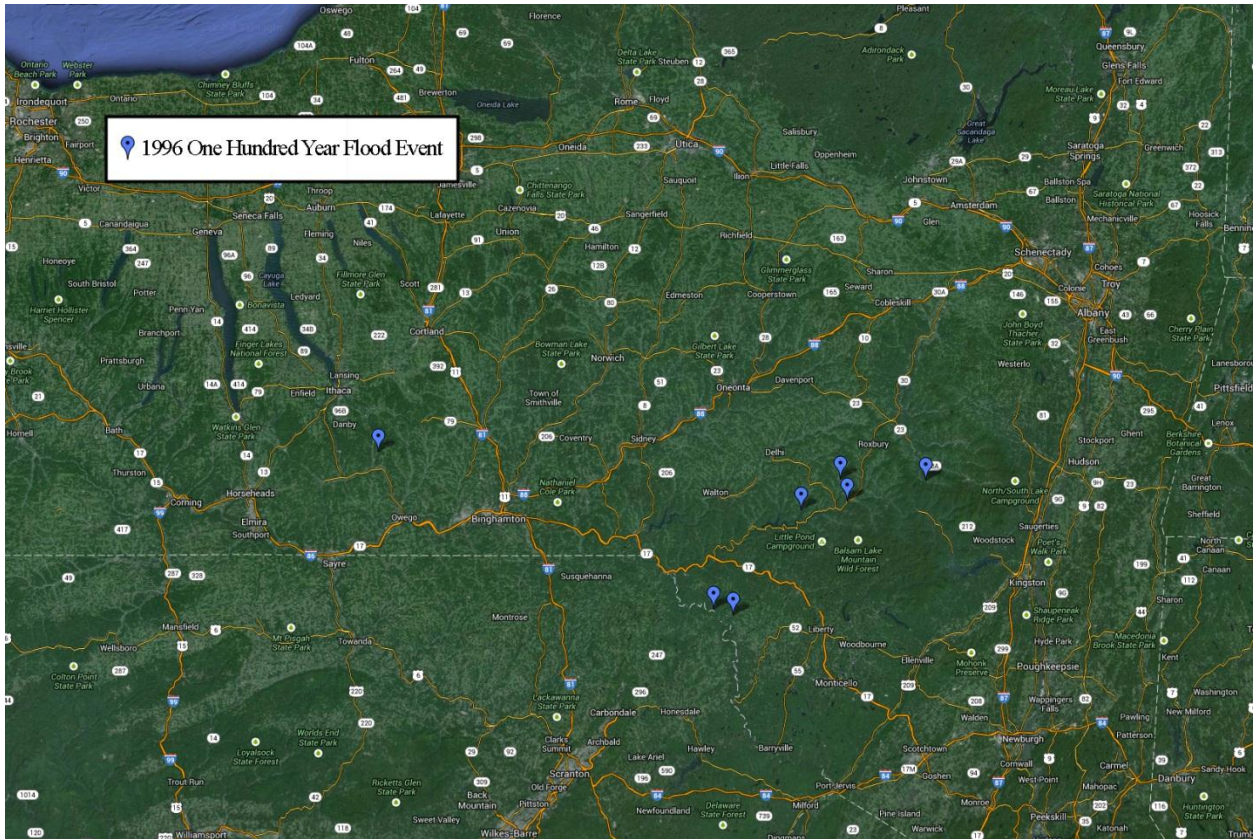


Figure 9 New York 1996 one hundred year flood event bridge collapses (Google Maps, 2014).

Due to the high proportion of SD bridges a conditional probability was used to examine the failure rate given a bridge is SD. A conditional failure rate is defined by the following equation:

$$FR(C + |SD +) = \frac{FR(C + \cap SD +)}{FR(SD +)} \quad (6)$$

where $FR(F + |SD +)$ is the failure rate ($FR[-]$) of collapse (C+) given (I) that the bridge is structurally deficient (SD+). To solve this conditional failure rate, the intersection (\cap) of the number of bridge failures that were SD is needed as well as the failure rate for bridges that were structurally deficient. Of the 66 collapsed bridges 35 were SD prior to collapse, therefore $FR(F + \cap SD +)$ was changed to a failure rate and annualized when

1/4,700 is multiplied by 53.0% and divided by the proportion of SD bridges. For New York State 12% of the bridges are SD (SD+) (obtained through NBI data). The failure rate for bridge collapse given the bridge was SD $FR(C + |SD +)$ was determined to be $9.40E-4$ or 1/1,100 annually.

The conditional failure rate for a bridge given it is load rated and collapses due to overload can be solve similarly to the above analysis. The failure rate is 1/4,700 multiplied by the proportion of collapse due to overload (0.113) and then divided by the ratio of loaded restricted bridges 1017 and number of bridges in the state 17300. The conditional collapse failure rate for a bridge that is load restricted due to overload is $3.52E-4$ or 1/2,800 annually.

Results Driven Data Collection

In order to determine what data to collect, the desired results should be drafted and then formulate the data collection and analysis methods. Bridge collapses are a function of numerous variables; each collapse type has a set of predictive variables or is a function of $f(x, y, z \dots n)$. Predictive modeling and potential variables could be acquired extensively. For example, the probability of a bridge being struck or collapsed due to an oversized load collision could be a function of the posted speed limit for the roadway below, the traveling speed of vehicles, the average daily truck traffic, height of the bridge, number of access points to roadway prior bridge, etc. The task is to determine which variables act as the most informative predictors and be concise in data collection. A correlated discussion to data collection is the analytical method used to achieve the Map-21 goals of risk-based and data-driven approaches. A range of methods exist for

probabilistic data analysis. The main three techniques are expert opinion, reliability analysis, and failure analysis (Sundararajan, 1995). Reliability analytical methods are common and data exists for many limit states, but does not included uncertainty for all sources. Expert option can provide probabilistic results where data is scarce, and has been used in the area of bridge collapses. In an effort to improve the analytical method over expert opinion failure analysis is recommended in this study. Advantages of failure analysis, over other current methods, include uncertainty from all sources and the removal of opinion based analysis. Therefore, in an effort to achieve Map-21 goals, failure analysis of collapsed bridges and links to consequences are recommended.

A variety of failure analysis methods are available, again, depending on the desired results and data. Two alternatives for failure analysis can be used: lifetime data or count of failures. Both types of data can be applied to quantify failure rates and probability of failure. Other alternatives are fault tree or event tree analysis and component or element failure analysis of a bridge as a system. A last option considered is service disruption data.

Lifetime data can be used to show the age effects on the failure rate, assist maintenance programs in tracking the useful life of bridges or components, and facilitate construction of the typical bathtub curve, see Figure 10. A bathtub curve states in the initial or early life failure rate (Infant Mortality, in this case construction) is high due to the complexities of erection and has historically received substantial recognition in published literature (Smith, 1976). As the useful life is used up, a higher failure rate is expected to occur, similar to human life expectancy (Henley and Kumamoto, 1981). In-between the two higher rates, is a plateau region in which the failures are considered

random events. Lifetime data requires records on all existing, collapsed, replaced, decommissioned, and/or rehabilitated bridges. The NBI contains some lifetime, rehabilitation, and consequences to user data, but is insufficient for analysis. Lifetime data requires extensive data counts on failed and successful bridges and is necessary due to the age dependence of overload and deterioration. In addition, other collapse causes or subsets of causes are age dependent and are presently unknown.

Failure Rate Analysis (FRA) of collapse data will prove occurrence rates and trends not seen in forensic analysis' isolated incidences. Trends and occurrence rates can assist the determination of the failure probability and most frequently exceeded limit states, and ultimately ameliorate bridge performance. FRA requires an unbiased and sufficiently large dataset of collapsed bridges, for which the total population of bridges, from which the collapse bridges came, and time duration, are known.

The Fault Tree Analysis (FTA) evaluates risk by tracing backwards in time or backwards through a cause chain. FTA is a common tool to ferret failure modes and root causes, as well as graphical depictions to aid descriptions of failures (Henley and Kumamoto, 1981). FTA has been used for individual bridge forensic analysis (LeBeau and Wadia-Fascetti, 2007) and ought to be continued. FTA requires bridge component descriptions or As-Built drawings and conditions.

Collection of element based data can further assist forensic analysis and demonstrate the role that bridge condition or defects influences in collapsed bridges individually and collectively. Lee and Sternberg (2008) assessment of catastrophic bridge collapse for both progressive failure of entire bridge systems and the failure of materials at the microscopic level can be continued with improved data.

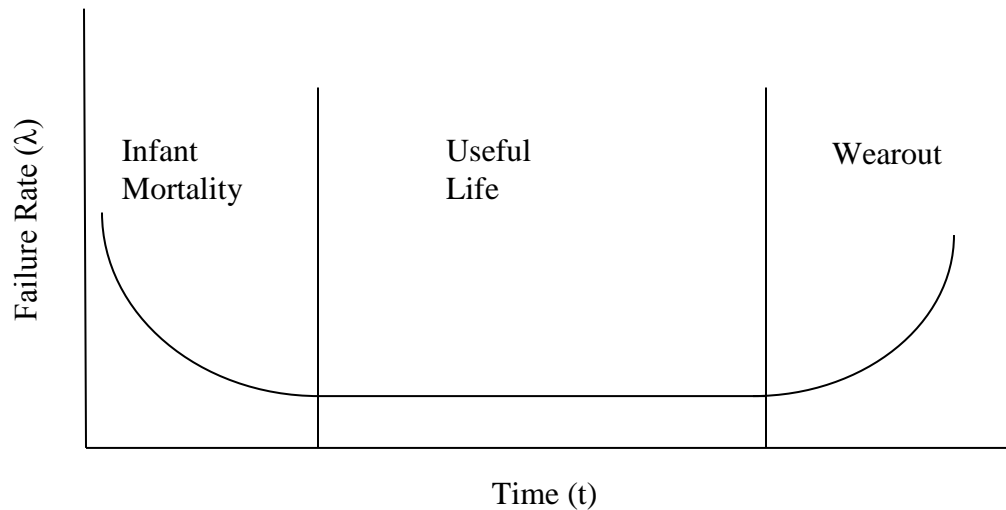


Figure 10 Typical bathtub curve.

In order to perform risk analysis, or consequence over a time interval, data of the actual bridge collapse or failures with associated negative impacts on society need to be gathered. The magnitude of consequences has a number of variables and can be viewed as a tiered approach. The more severe the effects of a bridge collapse, the more consequence data there should be.

Data Collection Improvements

The leading discussion on improvement to collection of bridge collapse data, which all others improvements are reliant upon, is the collection itself. The primary need is the development of a national repository of bridge collapses, potentially one that is updated continually. The number of states involved in supplying information can drastically alter the duration needed for datasets to be sufficiently large to enable classical statistical analysis. Also, the level that statistical significance data queries can achieve is dependent on data

counts. Thus, the longer the duration and the greater the population of bridges assessed, the more likely it is that a higher bridge collapses count will occur. As an example, the time duration required to obtain roughly 90 vehicle roadway bridge collapses within NYSDOT jurisdiction is 25 years (Chapter III). The duration required to obtain the same number in the United States is roughly one year (Agrawal et al., 2011 and Chapter III). The willingness of states to supply collapse data historically has been poor, as evident in the quad-annual questionnaires returned to NYSDOT, discussed previously. Therefore, unless a change is implemented, continued poor and false responses are anticipated. A bridge collapse data collection system is best suited at the federal level (Harik et al., 1990) to ensure a comprehensive database.

Based on analysis methods and desired results, data collection recommendations are divided into two main categories: general information and consequences, and subcategories for each. A subcategory on the general information is based on each of the common enabling and/or triggering causes that lead to bridge collapses is shown in Table 4.

With the current practice of bridge collapse evaluation and forensic investigation being limited, it is unlikely a change in the practice will be implemented until funding is available for agencies to perform such tasks. Forensic analysis is not intended to be performed on every bridge collapse. To ensure concise data, the most valuable information takes precedence. A tiered approach to data collection is, therefore, warranted based on the adverse effects of the collapsed bridge. As a result, the data collection efforts are prioritized by level of significance to failure analysis and enhanced risk assessment. The prioritization of recommended general information bridge collapse

data collection improvements is sequentially listed, beginning with the highest priority, as follows:

- National Repository Creation. The creation of a bridge collapse national repository is discussed above.
- Collapse and Failure Definition Endorsement. Acceptance of the definition of bridge collapse and bridge failure. Varying entities have deviating definitions for failure and collapse. Definitions are a requisite for soundness of data.
 - Bridge Collapse. Bridge collapse definitions are adopted from NYSDOT for TC and PC, previously discussed, are recommended.
 - Bridge Failure. Bridge failure is including any level of service disruptions as a functional state of a bridge is recommended.
- Cause Type. The cause type is a statement of what caused collapse to occur. Cause types can be distinguished between enabling, triggering, and procedural causes, see below. Past investigations and data collection group the three causes as one in the same. An example of correct term usage is the Minnesota I-35W Bridge that collapsed in 2007 during the rehabilitation construction efforts which exposed a design flaw of the gusset plate connection. Because forensic analysis was performed on this bridge, the cause can be stated with greater specificity, design defect of a gusset plate connection. The triggering cause was construction and the enabling cause was a design defect. It is not anticipated that all bridges will be studied to the same level of detail, as the above example illustrates. The Minnesota I-35W bridge collapse has been of interest due to the severity of consequences. Therefore, basic information, like the enabling cause and

triggering cause, are obvious and should be distinguished if possible. The cause types are as follows:

- Enabling Cause. An enabling cause is related to the condition of the bridge at the time of collapse. The enabling causes are issues related to design, detailing, construction, maintenance, and material related problems.
 - Triggering Cause. Triggering cause is an external loading event or atypical loading scenario that leads to collapse due to the reaction or element, component, or connection that fails as a result of the loading. The triggering cause can also be further classified as manmade or natural hazard.
 - Procedural Cause. Procedural cause is related to management issues of involved entities.
- Field Report Location. A field report location is a detailed description of the location. A site visit location description would be the only form of validation with a following recommendation (NBI record correlation), which also contains the location.
 - Date. The date is a record of the day, month, and year of bridge failure occurrence. For failure or lifetime analysis a measurement of the time interval or life span is required.
 - NBI Bridge Identification Number. The NBI identification number is a unique state assigned number for each bridge. If the link is made between the proposed bridge collapse repository and existing NBI the needed data for the repository is

significantly reduced. A few items of interest existing in the NBI are latitude and longitude, average daily traffic, structural deficiency, age, load limit posting, detour length, critical inspections, etc. Some NBI items are of interest to geographical information systems and the collapse probability and others relate to the consequences of collapse.

- **AASHTOWare Data.** AASHTOWare data, or predecessor Pontis, is an element conditions database. Element conditions can be collected initially for the previous inspection and then for the entire available history of element conditions for the bridge. AASHTOWare and Pontis contain detailed information for enhanced deterioration analysis or enabling caused detection compared to NBI alone.
- **Bridge Configuration.** The bridge configuration relates to component location, spacing, and materials used to construct the bridge. As-Built drawings or photographs will depict the bridge configuration.
- **Percent Damage of Deck.** The percent damage of deck area is the remaining useful portion of bridge deck post collapse. An indicator is also needed if restricted lane or weight use is viable in an emergency situation. The NYSDOT definition of TC classifies if one span of a multi-span bridge collapses the entire bridge as collapsed. Though the bridge, in this situation, is rendered unusable the effort required to restore the bridge to unrestricted operation varies with the extent of damage. An example is if an approach span fails of a long span bridge. PC of a bridge may render a portion or lanes unusable, but still in operation, especially for life critical routes.

- **Damaged Region(s).** Recording the damaged regions should include a details description of the damage components of the collapsed bridge (e.g. substructure, superstructure, deck). The damage region is a link between what failed and the resulting percentage of bridge deck damaged.
- **Development of Collapse.** Development of collapse is an estimated time indicator of warning to users. Bridge collapses resulting from fatigue or fast catastrophic chain of events, as opposed to ductile failures, is the difference between user awareness of avoiding danger and increased consequences.
- **Collapse Description.** A collapse description is a logical path of what failed, leading to the total amount of damage. If a brief description is provided, many of the other data fields can be validated. Observations of past databases have proven these comments to be of intrinsic worth.
- **Hazard Susceptibilities.** Hazard susceptibilities is an assessment of limit states addressed in design, rehabilitation, or maintenance efforts to avoid the site specific triggering causes from collapsing the structure. Data collection should involve hazard type and time or cost associated with hazard mitigations. Ideally, data will allow comparisons with other hazards and cost.
- **Optional Notes.** Optional notes are opinion based notes of investigator(s). A section should be permitted for data collectors to insert details not covered in a form, but appears to contribute to the collapse.

Enabling and Triggering Causes Categorization

The common enabling and triggering causes categorized for bridge failures recorded in the NYSDOT database are hydraulic, collision, overload, deterioration,

geotechnical, nature, and other. Based on the triggering cause, specific information should be gathered related to each event type. Each of the above causes is discussed in detail below:

- Hydraulic. Hydraulic caused bridge collapses are due to any form of water influence. The most common triggering cause is hydraulic (Wardhana and Hadipriono, 2003 and Chapter III). Current data is insufficient to distinguish the exact cause of collapse, often due to the lack of a forensic analysis of the bridge collapse.
 - Scour. Scour is the water induced erosion of the streambed or bank. The natural process of stream movement is dynamic and location specific. Scour has been identified as the leading mechanism to result in bridge collapse (AASHTO, 2010 and Arneson et al., 2013). Identification of the scour types can assist designer's future specification development and ultimately bridge performance. Tracking scour determines the scour events instigated by flood, storm, tidal effects, low stream migration exacerbated by a flood event, etc. Again, enabling and triggering causes are in a relationship and are to be indicated in reporting. NHI had identified four main causes of scour (2004). The four types of scour are:
 - General Scour. General scour or streambed degradation occurs through the natural process of sedimentary movement, lowering the entire streambed elevation. General scour can initiate pier damage as well as bank/abutment stability.

- **Contraction Scour.** Contraction scour is the result of a narrowing waterway under a bridge. In order to maintain constant flow through a narrowing waterway velocity must increase, accelerating erosion.
 - **Local Scour.** Local scour is the localized lowering of the streambed adjacent to a waterway obstruction, such as piers. Obstructions have been known to induce turbulent flows and vortices, which result in increased streambed movement.
 - **Lateral Stream Migration.** Lateral stream migration is a shift in the flow path due to changes in the embankments.
- **Lateral and Drag Forces or Drift.** Lateral and drag forces or drift acting on superstructure or substructure resulting in damage of bridge elements.
 - **Soil Type and Stream Velocity.** If the stream velocity can be determined or estimated from a flow monitoring station, the soil type rate of erosion is potentially useful information (Shatanawi et al., 2008).
 - **Buoyancy and Uplift.** Buoyancy and uplift is a known external force that has resulted in bridge collapses (Padgett et al., 2008).
 - **Return Period of Flood Event.** Ascertaining the probability of an event captures the level of design effort required to avoid failure.
 - **Restricted waterway opening.** “A restricted waterway opening is the blockage in the channel that reduced the hydraulic opening of the bridge” (NHI, 2004). The restricted flow has been known to occur through:
 - **Aggradation.** This is the rise in the entire streambed elevation.

- Vegetation growth.
 - Debris build-up.
 - Sediment deposits.
- Storm or Hurricane. Flooding can be the result of a severe storm that causes bridge collapses.
- Collision. The triggering causes of collision for bridge collapses are due to items striking the structure and marring it to the extent of meeting a definition of collapse. Knowing the article striking the bridge (airplane, ship, train, semi-tractor trailer, oversized load, etc.) will enable analysis of the probability of being struck. Three common subsets of collision are unsecured loads striking bridges, collision induced fires or explosions, and marine vessel collisions.
 - Unsecured loads. This is retractable equipment attached to, or parts of the vehicle improperly secured have resulted in considerable bridge damage.
 - Fire and explosions. When volatile materials are involved with bridge collisions fires and explosions have historically escalated bridge damage to result in collapsed bridges.
 - Marine vessel collision. This is already included in AASHTO Bridge Design Specifications (2010).
- Overload. Overload is the triggering cause when a load crossing the bridge results in collapse. Overload can be, but is not necessarily, a combination of deterioration and overload. Records should therefore indicate whether the bridge was intended to be load restricted, whether it was physically posted, whether the

vehicle exceeded the legal/posted limit, and if the posted limit was correct, based on the known level of deterioration.

- **Deterioration.** The enabling cause deterioration is when insufficient information is known on the condition or accelerated deterioration results in meeting a definition for collapse. Records should indicate the last Pontis/NBI condition prior to collapse and the role condition played in collapse, and the principle material(s) to have failed.
- **Geotechnical.** When the triggering cause is due to events such as erosion, slope stability, consolidation, sinkhole, soil compaction, subsidence, etc. geotechnical causes should be stated.
- **Nature.** When the triggering cause is due to events such as wind, tornado, earthquake, volcanic eruption, avalanche, insect attack, and tree fall the causes should be stated.
- **Other.** A cause not previously covered is an “other” cause. This allows a writable data field for any additional entry.

Consequence Data Field Collection

The amount of information that can be supplied to the consequences section will be highly dependent on the adverse effects of a bridge collapse. Consequences are diverse, naming a few: life loss, injury, critical or emergency routes, economic loss, environmental concerns, and historical significance. When considering decision management alternatives, a hierarchy is sure to exist on the potential outcomes if a bridge or portfolio of bridges were to experience extreme loadings. Ethical issues arise with comparison of consequence categories but are applicable within a judgment of a

hierarchy. Each category has both direct and indirect effects. The recommended hierarchy of consequences is as follows:

- **Life Loss.** Life loss is when a fatality results from a bridge collapse. Life loss is a data field already included in the NYSDOT database, but requires being restated as a point of consistency.
- **Injuries.** Injuries are when an injury results from a bridge collapse.
- **Life Critical Route.** Life critical routes are those that serve evacuation routes and routes for medical facilities. Life critical routes are an important discussion in catastrophes of a regional nature, where multiple bridges, and therefore, lives are at risk of severe consequences.
- **At Risk Population.** An at risk population is in reference to all individuals that are on the structure, or would be, prior to collapse. The at risk population differentiates between fatalities, and injuries, out of all possible individuals.
- **Economic Loss.** The economic loss is a monetary loss that results from a bridge collapse. Economic losses can have direct cost through litigation and expedited bridge replacement and indirect costs through stifled economic development and high user cost. Direct consequences are often simpler to measure and records exist of this nature. On the other hand, indirect consequences are inclined to be onerous to collect and more complex. As such, records should be more thorough as the adverse effects increase.
 - **Expedited construction.** This is the cost to return the bridge to the same level of service with year.

- User cost per day. This is the daily cost to users resulting from the incapacitated structure.
- Litigation and settlement costs. This is the legal costs and damages paid to harmed individuals and entities.
- Stifled economic development. This is the resulting stunted economic growth estimation or ranking.
- Detour Length. The detour length is the additional travel distance required to complete the path. If detour length is unclear in NBI, detour length is in the NBI, clarification is needed for alternate routes longer than 99 km compared with no feasible alternate route.
- Criticality of Bridge. The criticality of bridge is in reference to identifying critical links in bridge roadway network systems that pose severe service disruption if collapsed.
- Societal Routes. A societal route is referring to bridges that carry utilities and communication facilities which, if disrupted, result in substandard living conditions.
- Environmental Concerns. Environmental concerns are regarding pollutants and impacts on the environment. Bridge materials and materials on the structure at the time of collapse have potential to pollute air and water.
- Historical Significance. Historical significance is referring to the historical value of a structure.

Conclusions

The primary recommendation on improved collection of bridge collapse data is the collection itself. The fundamental need is the development of a national repository for bridge collapse data. This investigation recommends certain types of analysis and data collection fields to facilitate MAP-21 goals. Failure rate analysis is the selected alternative with possible advancements into lifetime data. Statistical analysis of existing collapse data showed a relationship between age and structural deficiency, structural deficiency and bridge collapses, but age and only various cause types of collapse are related. Data fields of interest are stated based on analysis of existing collapse data; observations of existing data are as follows:

- Of the collapsed bridges 53% were classified as structurally deficient prior to collapse. The failure rate for bridge collapse, given the bridge is structurally deficient, is 1/1,100 annually.
- Hydraulic and collision caused collapsed bridges had an average age of 47.9 years which compared with average age of 45.5 years for the entire state inventory. Overload and deterioration collapsed bridges had an average age of 61.3 years which compared with average age of 64.5 years for the structurally deficient bridges in the state.
- Collision caused bridge collapses appear to be contingent on the vertical clearance roughly 90% had a vertical clearance between 4.26m (14 ft-0 in.) and 4.49m (14 ft-9 in.) when over a roadway and fracture critical bridges are susceptible to collision induced collapse.

- Overload cause bridge collapses have a relationship with being load restricted.

The overload caused failure rate for a bridge that is load restricted is determined to be 1/2,800 annually.

CHAPTER VI

CONCLUSIONS

This dissertation was divided into three investigation where the failure rate of bridge collapses was assessed, the failure rate by triggering causes were determined, consequences were coupled with causes by the rates of collapse, and trends were found from pre-collapse conditions of the bridges.

The first investigation used a database of bridge collapses to determine the collapse rate of bridges within one DOT and the causes. The frequency of bridge collapses for a sample population was modeled with a geometric distribution and a 95% confidence interval was determined. Six other state bridge collapse rates were evaluated from different DOTs in the United States. Results show the failure rates of the other states to be within the 95% confidence interval determined from the sample population. The expected United States collapse rate is estimated with a 95% confidence range. The dominant cause of collapse is hydraulic in nature.

The second investigation assesses bridge collapse rates by causes and coupled the rates with consequences. The consequence of bridge collapses were evaluated with subsets of the collapse database and correlation with national bridge inventory data. Life loss was quantitatively assessed from historical data, selected case studies, and tolerability based on a benchmark set by United States Army Corps of Engineers interim guideline for dam safety. Average daily traffic was also quantitatively evaluated for collapsed bridges and found bridge collapse to be random compared with average daily traffic.

The third investigation examined collapse bridge data correlation with pre-collapse national bridge inventory data to show specific trends among the collapsed bridges and recommendations were considered for certain types of improved analysis and data collection fields to facilitate MAP-21 goals. Most notably, statistical analysis of existing collapse data showed a relationship between age and structural deficiency, structural deficiency and bridge collapses, but age and only various cause types of collapse are related. Therefore, the best predictor of collapse is structural deficiency. Failure rate analysis is the selected probabilistic analysis alternative with possible advancements into lifetime data. Data fields of interest are stated based on analysis of existing collapse data; observations. The primary recommendation on improved collection of bridge collapse data is the collection itself.

The MAP-21 goals of ‘risk based data-driven’ asset management for State DOT infrastructure has opened numerous research and funding opportunities at the state and federal levels. Future investigations that can build upon this current body of research includes deterioration modeling of bridge condition ratings and the likelihood of extreme event accelerated deterioration, fault tree analysis of critical bridges in networks, and last would be the creation of a national repository of bridge collapses. A national repository of collapses would be highly contingent on federal regulations and is therefore a long term goal.

A bulleted summary is provided below for the results obtained from analysis of the three investigations:

1. Bridge Failure Rate

- a) A geometric distribution was used to model the expected number of annual roadway bridge failures. The expected bridge failure rate is 1 out of 4,700 annually. The sample population bridge failure rate had a 95% confidence interval of 1/6,900 and 1/2,700 annually. Six additional state datasets were studied and the failure rate of each is within 1/6,900 and 1/2,700 annually. As a result from the DOTs investigated, the United States projected average failure rate is between 87 to 222 bridges annually with an expected value of 128.
- b) The causes of the 92 bridge failures (excluding pedestrian and railroad bridges) in the dataset were 52% hydraulic, 20% collision, 12% overload, and 7% deterioration.

2. Failure by Causes and Consequences

- a) Based on proportions the annual collapse rate multiple causes were determined. The annual probability of failure by overload is $2.40E-5$, and for deterioration is $1.88E-5$ both values are illustrations of the causes of failure probabilities established.
- b) The dominant causes of failure are due to the feature under or what travels under the structure, as such; a conditional probability was determined to account for features under. The condition probability of failure calculated the most likely cause of failure is hydraulic in nature ($1.52E-4$), adjusting for the fact the most bridges in the United States are over water.
- c) Historically, life loss occurred on about 4% of bridge failures. A benchmark set by United States Army Corps of Engineers interim

guideline for dam safety and Federal Energy Regulatory Commission show bridge failures rate and life loss are in a tolerable range compared to the benchmark.

- d) Analysis and simulation of ADT of historically failed bridges shows bridges fail randomly and in turn, high consequence bridge failures are expected. From simulation at least one bridge fails annually with an ADT of 70,000 or greater.

3. Bridge Collapses Trends and Improved Collection Efforts

- a) Overload cause bridge collapses have a relationship with being load restricted. The overload caused failure rate for a bridge that is load restricted is determined to be 1/2,800 annually.
- b) Of the collapsed bridges 53% were classified as structurally deficient prior to collapse. The failure rate for bridge collapse, given the bridge is structurally deficient, is 1/1,100 annually.
- c) The sample population hydraulic and collision caused collapsed bridges had an average age of 47.9 years which compared with average age of 45.5 years for the entire state inventory. Overload and deterioration collapsed bridges had an average age of 61.3 years which compared with average age of 64.5 years for the structurally deficient bridges in the state.
- d) The sample population collision caused bridge collapses appear to be contingent on the vertical clearance roughly 90% had a vertical clearance between 4.26m (14 ft-0 in.) and 4.49m (14 ft-9 in.) when over a roadway and fracture critical bridges are susceptible to collision induced collapse.

- e) The fundamental need for improved data collection is the development of a national repository for bridge collapse data.

REFERENCES

- American Association of State Highway and Transportation Officials (AASHTO). (2010). "LRFD Bridge Design Specifications." 5th Ed., Washington, DC.
- "AASHTOWare." (2013). <<http://aashtoware.camsys.com>> (Jan. 6, 2014).
- Akgul, F., and D. M. Frangopol. (2003). "Rating and reliability of existing bridges in a network." *J. Bridge Engrg.*, ASCE, 8(6), 383-393.
- Arneson, L. A., L. W. Zevenbergen, P. F. Lagasse, and P. E. Clopper. (2012). "Evaluating Scour at Bridges." *FHWA-HIF-12-003, HEC-18. 5th Ed.*, Washington, DC.
- Bowles, D. S. (2007). "Tolerable risk for dams: How safe is safe enough?" *Proc. Dams Annual Conf., US Dam Society*, Philadelphia, 1-24.
- Brown, D. A., J. P. Turner, and R. J. Castelli. (2010). "Drilled shafts: Construction procedures and LRFD design methods." *GEC No. 10, FHWA-NHI-10-016*, Washington, DC.
- Bulleit, W. M. (2008). "Uncertainty in structural engineering." *Practical Periodical on Struct. Design and Constr.*, 13(1), 24-30.
- Chang, F. E. M. (1973). "A statistical summary of the cause and cost of bridge failures." *Pub. FHWA-RD-75-87*, Washington, DC.
- Duckett, W. (2005). "Risk analysis and the acceptable probability of failure." *Struct. Engrg.*, 83(15), 25-26.
- Dunker, K. F., and B. G. Rabbat. (1990). "Highway bridge type and performance patterns." *J. Perform. Constr. Facil.*, ASCE, 4(3), 161-173.
- Elms, D. G. (1999). "Achieving structural safety: Theoretical considerations." *Struct. Safety*, 21(4), 311-333.
- Federal Highway Administration (FHWA). (1995). "Recording and coding for the structure inventory and appraisal of the nation's bridges." *Pub. FHWA-PD-96-001*, Washington, DC.
- FHWA. (2012). "National bridge inventory."
<<http://www.fhwa.dot.gov/bridge/nbi/ascii.cfm>> (May 11, 2012).
- FHWA. (2013). "MAP-21." <<http://www.fhwa.dot.gov>> (Jan. 6, 2014).

- Foster, M., R. Fell, and M. Spannagle. (2000). "The statistics of embankment dam failures and accidents." *Canadian Geotech. J.*, 37(5), 1000-1024.
- "Google Maps." (2014). <<http://www.maps.google.com>> (Jan. 6, 2014).
- Harik, I. E., A. M. Shaaban, H. Gesund, G. Y. S. Valli, and S. T. Wang. (1990). United States bridge failures, 1951-1988." *J. Perform. Constr. Facil.*, ASCE, 4(4), 272-277.
- Hao, S. (2010). "I-35W Bridge Collapse." *J. of Bridge Engrg.*, ASCE, 15(5), 608-614.
- Henley, E., and H. Kumamoto. (1981). "Reliability engineering and risk assessment." *Prentice Hall, Inc.*, Englewood Cliffs, NJ.
- Housner, G. W., and P. C. Jennings. (1972). "The San Fernando California earthquake." *EQ. Engrg. Struct. Dynam.*, Calif. Inst. of Tech., Pasadena, 5-31.
- Housner, G. W., and C. C. Thiel. (1990). "Competing against time: Report of the governor's board of inquiry on the 1989 Loma Prieta earthquake." *EQ. Spectra*, 6(4), 681-711.
- International Commission on Large Dams (ICOLD). (2005). "Risk assessment in dam safety management: A reconnaissance of benefits, methods and current applications." *Bulletin*. 1-130.
- Kamojjala, S., N. P. Gattu, A. C. Parola, and D. J. Hagerty. (1994). "Analysis of 1993 upper Mississippi flood highway infrastructure." Proc. 1st Intern. Conf., Water Resources Engrg., San Antonio, 1061-1065.
- Larson, O. D. (1993). "Ship collision with bridges-The interaction between vessel traffic and bridge structures." *IABSE Struct. Engrg. Doc. 4, IABSE-AIPC-IVBH*, Zurich, Switzerland. 1-131.
- LeBeau, K. H., and S. J. Wadia-Fascetti. (2007). "Fault tree analysis of Schoharie Creek bridge collapse." *J. Perform. Constr. Facil.*, ASCE, 21(4), 320-326.
- Lee, G. C., and E. A. Sternberg. (2008). "New system for preventing bridge collapse." *J. Issues Sci. Tech.*, 24(3), 31-36.
- Lichtenstein, A. G. (1993). "The silver bridge collapse recounted." *J. Perform. Constr. Facil.*, ASCE, 7(4), 249-261.
- Liu, M., and D. M. Frangopol. (2006). "Probability-based bridge network performance evaluation." *J. of Bridge Engrg.*, ASCE, 11(5), 633-641.

- MacDiarmid, P. R., and J. J. Bart. (1995). "Reliability toolkit: Commercial practices edition." *Reliability Analysis C. Rome Lab.*, Rome, NY.
- Menzies, J. B. (1996). "Bridge failures, hazards and societal risk." *Proc. Intern. Symp. safety of bridges*, ICE/HA, London. 36-41.
- Munger, D. F., D. S. Bowles, D. D. Boyer, D. W. Davis, D. A. Margo, D. A. Moser, P. J. Regan, and N. Snorteland. (2009). "Interim tolerable risk guidelines for US Army Corps of engineers dams." *Proc. Dams Annual Conf., US Dam Society*, Nashville, 1-17.
- National Highway Institute (NHI). (2004). "Safety inspection of in-service bridges." *FHWA-NHI-03-004. FHWA*, Washington, DC.
- National Oceanic and Atmospheric Administration (NOAA). (2014). <<http://www.weather.gov>> (Feb. 3, 2014).
- New York State Department of Transportation (NYSDOT). (2004). "Bridge Safety Assurance: Hydraulic Vulnerability Manual." *NYSDOT*.
- Nowak, A. S., and K. R. Collins. (2013). "Reliability of Structures." *CRC Press*, 2nd Ed., Boca Raton, FL.
- Padgett, J., R. DesRoches, B. Nielson, M. Yashinsky, O. S. Kwon, N. Burdette, and E. Tavera. (2008). "Bridge damage and repair costs from Hurricane Katrina." *J. of Bridge Engrg.*, ASCE, 13(1), 6-14.
- Pate-Cornell, M. E. (1996). "Uncertainties in risk analysis: Six levels of treatment." *J. Reliability Engrg. Syst. Safety*, 54 (2-3), 95-111.
- Rasmussen, N. (1975). "Reactor Safety Study." *Report WASH-1400*. U.S. Nuclear Regulatory Commission.
- Richardson, E. V., L. J. Harrison, J. R. Richardson, and S. R. Davis. (1991). "Evaluating scour at bridges." *HEC No. 18, FHWA-IP-90-017*, 1st Ed., Washington, DC.
- Scheaffer, R. L., and J. T. McClave. (1995). "Probability and statistics for engineers." *Duxbury Press*, 4th Ed., Belmont, CA.
- Shatanawi, K. A., N. M. Aziz, and A. A. Khan. (2008). "Frequency of discharge causing abutment scour in South Carolina." *J. Hyd. Engrg.*, ASCE, 134(10), 1507-1512.
- Shirole, A. M. (1995). "Development and implementation of NYS comprehensive bridge safety assurance program." *Proc. 4th Intern. Bridge Engrg. Conf.*, San Francisco, 187-192.

- Smith, D. W. (1976). "Bridge failures." *Proc. Inst. Civil Engr., Part 1*, 60(8), 367-373.
- Sobanjo, J. O., P. D. Thompson, and R. Kerr. (2013). "Evaluating natural hazards and damage on Florida bridges." *Proc. TRB conf.*, Washington, DC.
- Stearns, M., and J. E. Padgett. (2011). "Impact of 2008 Hurricane Ike on bridge infrastructure in the 2 Houston/Galveston region." *J. Perform. Constr. Facil.*, ASCE, 26(4), 441-452.
- Sundararajan, C. R. (1995). "Probabilistic structural mechanics handbook: Theory and industrial applications." *Chapman and Hall*. New York.
- Thompson, P. D., J. O. Sobanjo, and R. Kerr. (2013). "Modeling the risk of advanced deterioration in bridge management systems." *Proc. TRB conf.*, Washington, DC.
- Valdes, M., and M. Baker. (2013). "I-5 Bridge Collapse Survivor: 'You hold on.'" *Associated Press*, in press. <<http://news.yahoo.com>> (May 28, 2013).
- Wardhana, K., and F. C. Hadipriono. (2003). "Analysis of recent bridge failures in the United States." *J. Perform. Constr. Facil.*, ASCE, 17(3), 144-150.
- Willett, T. O. (1991). "Evaluating scour at bridges." *Technical Advisory. FHWA-T5140.23*, Washington, DC.
- Wilson, J. (2003). "Allison involving the M/V Brownwater V and the Queen Isabella Causeway bridge." *US Coast Guard*, Washington, DC.
- Wuttrich, R., J. Wekezer, N. Yazdani, and C. Wilson. (2001). "Performance Evaluation of Existing Bridge Fenders for Ship Impact." *J. Perform. Constr. Facil.*, ASCE, 15(1), 17-23.

APPENDIX

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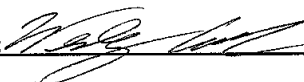
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Graduate Teaching Assistant, Utah State University, 2011-2012.

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