Use Of Sacrificial Embankments To Minimize Bridge Damage From Scour During Extreme Flow Events

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USE OF SACRIFICIAL EMBANKMENTS TO MINIMIZE BRIDGE DAMAGE FROM SCOUR DURING EXTREME FLOW EVENTS

A Thesis Presented

by

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ABSTRACT

The leading cause of bridge failure has been identified as scour, which is generally defined as the erosion or removal of streambed and/or bank material around bridge piers and abutment foundations due to flowing water. Scour critical bridges are particularly vulnerable during extreme flooding events and pose a major risk to human life, transportation infrastructure, and economic sustainability. Retrofitting the thousands of undersized and scour critical bridges to more rigorous standards is prohibitively expensive; and current countermeasures inadequately address the core problems associated with bridge scour. This research tested the efficacy of using approach embankments as intentional sacrificial "fuses" to protect the integrity of bridges with minimal damage during large flow events by allowing the streams to access their natural floodplain and reduce channel velocities. This work also estimates stream flow return periods using a Bayesian approach to better reflect the non-stationarity observed in the United States Geological Survey (USGS) stream discharge records resulting from climate change in the Northeastern United States. The concept of using a fuse as a bridge scour mitigation technique was evaluated by developing models of three representative bridges on two river reaches using the Hydrologic Engineering Center's River Analysis System (HEC-RAS). The results show that (1) a Bayesian estimation of streamflow return periods can be a useful tool in designing hydraulic infrastructure to account for the non-stationarity observed in long-term stream-flow records, and (2) sacrificial embankments provide an economical mitigation strategy for reducing scour damage to bridges, while also reducing the flood velocities and stage upstream of the bridge sites.

CITATIONS

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CHAPTER 1

INTRODUCTION

1.1 Motivation

Scour is the primary cause of bridge failures in the United States (Kattell and Eriksson, 1998). The Federal Highway Administration (FHWA) Bridge Scour Evaluation Program reports that as of 2011, the U.S. has over 23,000 (4.7%) scour critical bridges, and over 40,000 (8.3%) bridges with an unknown foundation (Arneson et al., 2012). The Hydrologic Engineering Circular 18 (HEC 18) (Arneson et al., 2012) provides numerous examples of scour related bridge damage and failure. Between 1969 and 1991, more than 1,000 bridges in the United States failed; 60% of those failures were due to scour (Briaud et al., 1999). During the 1987 spring floods, 17 bridges in New York and New England were damaged or destroyed by scour. Failure of the I-90 Bridge over the Schoharie Creek near Amsterdam, NY resulted in the loss of ten lives and millions of dollars in bridge repair and replacement costs (FHWA, 2015). In 1985, flooding destroyed 73 bridges throughout Pennsylvania, Virginia and West Virginia. A 1973 national FHWA study of 383 bridge failures caused by catastrophic floods showed that 25 percent involved pier damage and 75 percent involved abutment damage. The 1993 flood in the upper Mississippi basin caused damage to 2,400 bridge crossings (FHWA, 2015) including 23 bridge failures (Arneson et al., 2012). The analysis of over 300 Vermont bridges damaged in 2011 Tropical Storm Irene indicated that about 61% of the damaged bridges had scour damage, 27% had channel flanking, and the remaining 12% had superstructure and debris damage (Anderson et al., in-review).

During the Third National Climate Assessment, Walsh et al. (2014) concluded that the United States is experiencing an increase in the frequency and intensity of heavy downpours and hurricane-level storms. The northeast has seen the largest increases in heavy precipitation with a 71 percent increase in the amount of precipitation during heavy storm events (Karl et al. 2012; Guilbert et al, 2015). Further compounding the problem is that storm events in the Northeast US are persisting longer than in the past, further increasing flooding risk through persistent wetness and lack of ground surface infiltration capacity during long periods of rainfall (Guilbert et al., 2015). This leads to more devastating and frequent extreme flooding events, further straining our infrastructure network and increasing the need for innovative scour-mitigation solutions. Current countermeasures for existing bridges listed in HEC-18 consist of constructing relief bridges, guide banks, river channel work, and using riprap. Retrofitting the thousands of undersized and scour critical bridges throughout the country to the current standards is prohibitively expensive; and current countermeasures inadequately address the core problems associated with bridge scour. Climate change is causing some regions to experience non-stationary streamflow return periods, i.e., the return periods used for most infrastructure designs are changing. This results in greater uncertainly because practitioners are experiencing difficulty adapting our current infrastructure to the new streamflow return periods. Bayesian statistics can help improve the quantification of uncertainty because, compared to the more standard (frequentist) approach, the method provides a distribution of parameter estimates to a distribution, rather than a single parameter estimate. This distribution helps quantify the uncertainty associated with a calculated streamflow return period, allowing designers and policy makers to make more informed decisions about infrastructure development. In addition, this approach accounts for the non-stationarity in measured streamflow because the Bayesian estimator constantly updates its estimates of the dataset parameters.

A frequentist approach to the flood frequency discharge attempts to fit a model with certain parameters to a histogram of the data. Common models include the log-normal, Extreme Value, and Log-Pearson Type III distributions. These models contain two to three parameters, which are best fit to the select distribution and used to make inferences about future flooding events by interpolating or extrapolating upon the calculated distribution. Significant issues can arise with this approach; for instance when data are sparse (generally defined as less than 20 years), the model estimates may vary significantly from future estimates when more data are available. In addition, this approach fails to account for the inherent uncertainty in both the parameter estimates and the model itself. Point estimates are difficult to work with because they often give an inflated sense of confidence in streamflow return period estimates and may lead policy makers and designers to overestimate or underestimate the infrastructure needs of an area. A distribution helps a designer better understand and accommodate the uncertainty involved in such estimates and subsequent designs. The consequences of ignoring this uncertainty can be very dire. For instance, researchers believe that a contributing factor of the current drought in the Western United States was the underestimation of streamflow in the Colorado River due to a lack of adequate stream gauge data (Woodhouse and Lukas, 2006). Similarly, uncertainty in parameters describing northeastern flow distributions can lead to erroneous estimates of design flows for infrastructure design.

1.2 Potential of Fuse-Plugs as Scour Remediation Devices

The need to develop transportation infrastructure often conflicts with protecting the natural environment. In many areas, roads and bridges are placed near or across rivers and streams, cutting them off from their natural floodplains. Lack of floodplain access often increases stream velocities, worsening bank erosion and increasing bridges' vulnerability to scour. Developing smart mitigation strategies that reduce stream velocities and bridge scour during large storm events is critical for long-term sustainability. A fuse-plug embankment design (as depicted in Figure 1.1) allows streams to access their floodplain during extreme storm events, reducing channel velocities, and correspondingly, bank erosion and bridge scour. This approach reduces the destructive potential of a high flow event. The idea of designing a component which is part of a larger engineered structure to fail intentionally is utilized in bridges and buildings for earthquake mitigation (Bozorgzadeh et al., 2006), and in the design of dams, where a sacrificial member is used to prevent damage to the greater system (Schmocker et al., 2013). However, the concept of using fuses in mitigating bridge scour has not been explored prior to this research.

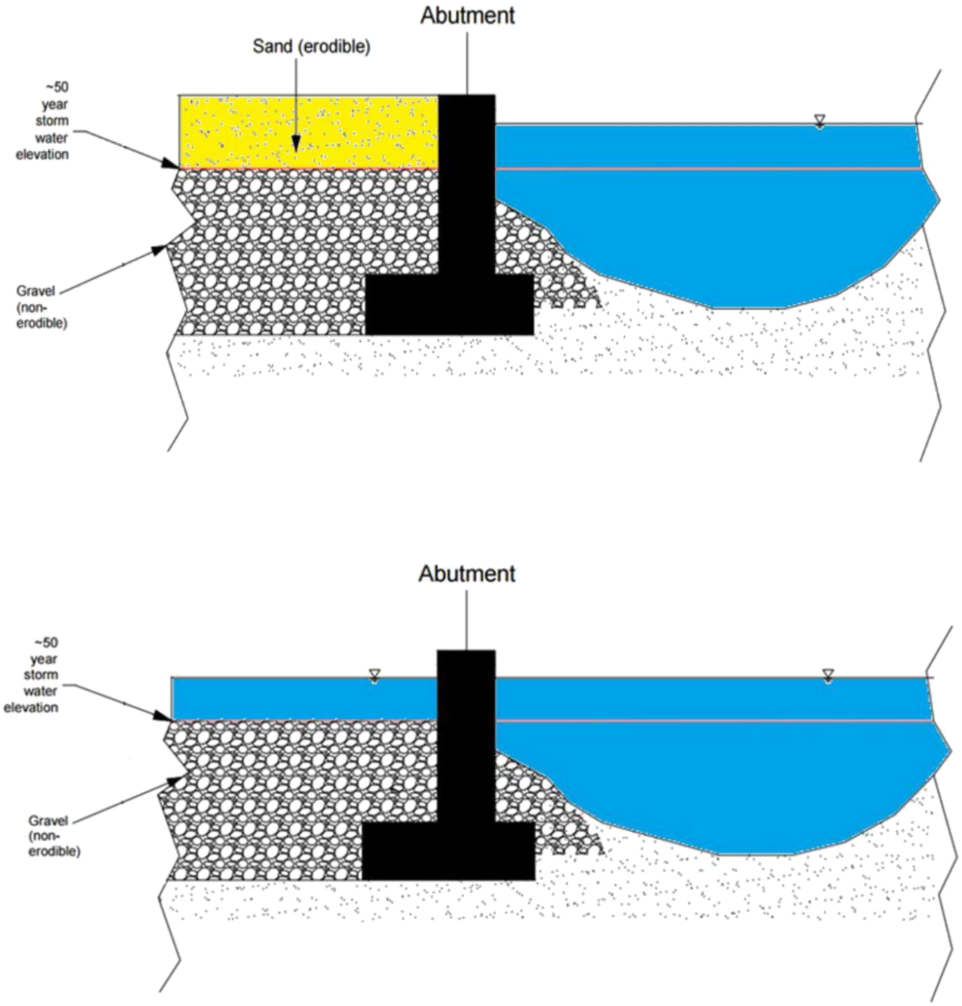


Figure 1.1: Proposed embankment design with anticipated outcome

1.2 Research Objectives

The main objectives of this research are as follows:

1) Develop a statistical Bayesian-based methodology to account for non-stationarity observed in streamflow return period estimates;
2) Demonstrate potential effectiveness of employing sacrificial bridge embankments as a technique to reduce bridge scour under extreme flow events;
3) Assess any secondary benefits of sacrificial embankments in reducing stage and channel velocities; and
4) Demonstrate the cost effectiveness of sacrificial embankment installation as a bridge scour mitigation technique.

1.3 Organization of the Thesis

This thesis is organized as follows. This introduction chapter provides the motivation for this research and the overall research objective. Chapter 2 presents a literature review. The third chapter contains a manuscript submitted to the Journal of Natural Hazards. Chapter 4 presents overall conclusions and recommendations for future work, followed by a comprehensive bibliography.

CHAPTER 2

LITERATURE REVIEW

2.1 “Fuse-Plug” Design and History

It is becoming an acceptable design methodology to incorporate fuses in buildings for earthquake retrofits and during flood mitigation strategies of dams and levees. This research first explored whether fuse-plugs could be used for bridge scour mitigation under extreme flow events. In the traditional hydraulic engineering field, “fuse-plugs” are generally designed to work as passive emergency spillways in dams when a design water height is reached. The author was unable to find research on fuse-plugs being used in hydraulic bridge design; however, there is a significant body of work on using fuse-plugs for earthen and rockfill dams.

The first hydraulically-scaled model of fuse-plugs appears to have been performed by the U.S. Bureau of Reclamation to determine their usefulness for flood control for dams in the 1980’s. The report concluded that a properly designed fuse-plug embankment would predictably wash out when a large flood needs to pass through a reservoir. The Bureau notes, however, that while passive fuse-plug embankments have been installed in full-scale applications, they have never had to be used in the field (Pugh, 1985).

Detailed hydraulic analysis of fuse-plug designs performed for a canal in Switzerland found that fuse-plugs are also useful in smaller applications, such as along a river or canal (Schmocker et al., 2013). Two fuse-plug designs, i.e., a large inclined clay core and a sandy fill with a small clay core, were scaled and tested in a flume. Schematics of the two designs are shown in Figure 2.1.

Both designs performed as expected and eroded away in a quick and controlled manner. The authors recommended the sandy fill fuse-plug design because of its ease of construction and performance compared to the inclined clay core fuse-plug.

In May of 2011 at the New Madrid Floodway on the Mississippi River near Cairo, Illinois a fuse-plug was activated when the US Army Corps of Engineers detonated a forward levee to allow the Mississippi River to access a large floodplain during a storm to reduce the stage of the flood upstream of the breach. A map showing the location of Cairo is shown in Figure 2.2 and the fuse-plug breach locations are shown in Figure 2.3.

Researchers studied the impacts of detonation after the storm and determined that the fuse-plug reduced the flood stage by 0.8 meters and was a significant factor in minimizing damage to Cairo (Luke et al., 2015). The authors state that future hydraulic modeling studies on breach geometries and floodplain activation techniques would be useful to the New Madrid Floodway and others with similar geometries. In addition, other researchers have proposed similar mechanisms for reducing flooding stage and velocities by purposefully breaching key levees during floods as a flood mitigation technique (Jaffe and Sanders, 2001). Translating the design concepts of fuse-plugs from a levee situation to a bridge embankment situation is reasonable as levees and bridge embankments share many of the same design characteristics.

“Flanking” damage is very similar to the type of damage that a bridge with a fuse-plug embankment would experience. The differences between scour and “flanking” damage are shown in Figure 3.3. A cost analysis performed by Anderson et al. (2014) of the effects of August 2011 Tropical Storm Irene on Vermont’s bridges showed that damage due to flanking had an estimated average repair cost of about $70,000, while damage due to scour was estimated at about $239,000 on average to repair. Complete bridge replacement can cost hundreds of thousands of dollars and take months to years to complete, whereas washed-out approaches require a simple backfill and leveling, and can be reopened hours or days after the storm subsides. Therefore, this research focuses on treating flanking damage as an analogous substitute for a fuse-plug in a bridge sacrificial embankment.

The author conducted a proof-of-concept bridge scour test in 2014 using the re-circulating flume located in the UVM hydraulics laboratory as part of an undergraduate research internship supported by the UVM Transportation Research Center. A set of preliminary demonstrative spread footing abutment models were hydraulically scaled using similitude analysis and tested with erodible and non-erodible bridge approaches. When contraction and flood flows were induced, greater foundation scour occurred in the scaled model with a less erodible stone fill approach (**Figure 2.4**a). The model with an erodible approach (**Figure 2.4**b) showed a significant decrease in the amount of scour at the bridge foundation compared to the non-erodible approach. The experiment mimicked the observations on bridge damage from Tropical Storm Irene, where flanking resulted in less damage.

These results were considered a proof-of-concept and provided motivation for further work into sacrificial embankments. The author also noticed that during testing, the sacrificial embankments allowed for a wide margin of error in flow estimates because they provided a continuous increase in cross-sectional area as the storm became more intense. Sacrificial embankments are an uncertainty-compliant mitigation strategy for bridge scour because they account for the wide error margins associated with bridge scour and streamflow calculations.

2.2 Bridge scour causes and effects

One of the earliest papers on bridge scour by Laursen and Toch (1956) developed predictive scour models based on physical model studies conducted in laboratory flumes. Though their study was a seminal contribution, the authors concluded that both empirical and analytical approaches to predicting scour are extremely difficult due to the huge variety of confounding variables and geometries of bridges and streams.

Standard practice for evaluating scour comes from the Hydrologic Engineering Circular 18 (HEC-18) from the Federal Highway Administration (FHWA) that uses empirical correlations to estimate scour based on a one-dimensional flow velocity (Arneson et al., 2012). Most of the empirical correlations were developed using laboratory flume studies that have difficultly predicting bridge scour in the field due to scaling issues. Landers and Mueller (1996) compared numerous pier scour equations using 139 measurements and found that “none of the selected equations accurately predict the depth of scour for all the measured conditions.”

Scour equations are known to be overly conservative, and frequently overestimate scour depth. For example, Sheppard et al. (2014) performed a comprehensive review of nearly all scour equations and found that the HEC-18 method underestimated scour depth only 0.3% of the time; but its normalized standard error in predicting scour depths is 21%. The paper concludes that all of the equilibrium scour equations overpredict the field-measured depths. This is especially true for larger structures, for which the current scour equations are not accurate enough to account for the design flow event, resulting in scour depths that are unreasonable for design (Sheppard et al., 2014). The variability of scour and streamflow estimates highlights the need for a different approach to both estimating streamflow and scour-remediation techniques.

2.3 Bayesian Statistics and Estimation of Extreme Storm Events and Modeling

The earliest paper on using Bayesian statistics to develop better streamflow return period estimates was from Wood and Rodriguez-Itrube in 1975. The paper proposed the idea of using a Bayesian versus a frequentist statistical approach to develop flood frequency discharges. The Bayesian approach estimates the distribution of streamflow parameters compared to a point estimate. The paper notes several issues with using frequentist models; for instance, they do not account for uncertainty in model parameters or the chosen model itself. While Bayesian statistics has proved popular with academics, it has been slow to be implemented in practice. Some reasons for this include difficulties in explaining uncertainty analysis to the general public, subjectivity in analysis, and the belief that a Bayesian statistical approach is difficult to perform (Pappenberger and Beven, 2005).

However, the benefits of using uncertainty analysis are too important to ignore and have been explored by many academics (O’Connel, 2005, Botto et al., 2013).

Botto et al. (2013) recently designed a Bayesian framework for decision making in hydrologic studies and developed a model that predicts the least costly design flood while properly accounting for the estimated uncertainty. This approach can be extremely useful for bridge planning and scour design as more researchers note the difficultly in developing accurate point estimates of streamflow in a non-stationary, changing climate.

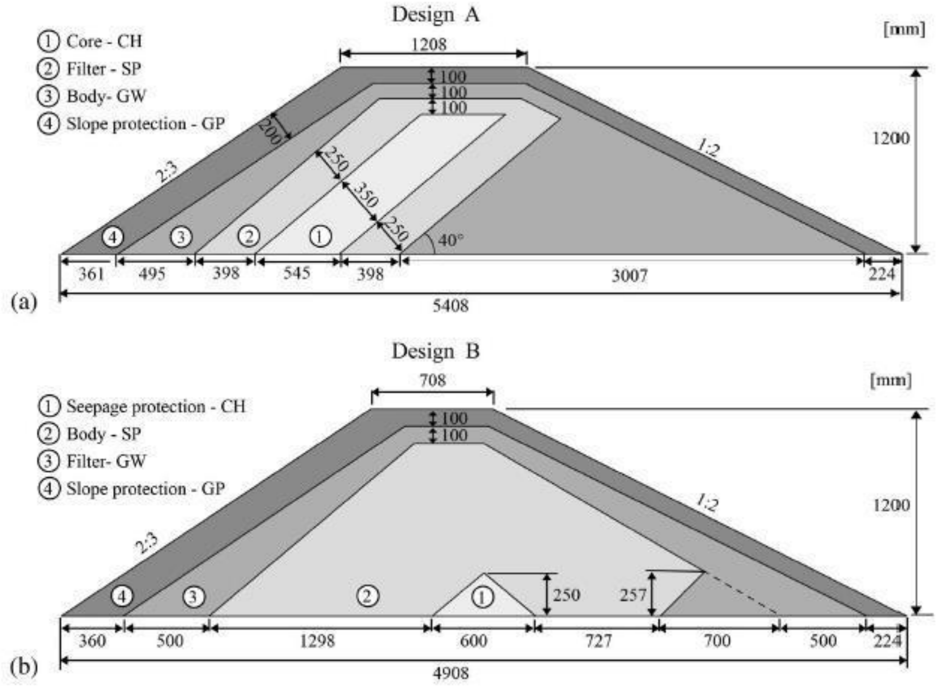


Figure 2.1: Schematic of “fuse-plug” designs with a clay core (top) and sandy core (bottom) tested for a canal in Switzerland (Schmocker et al., 2013)

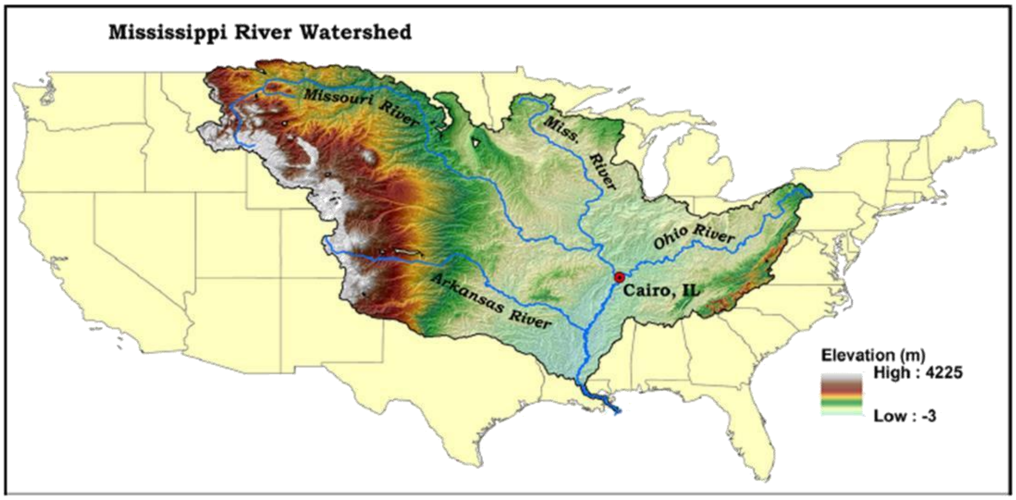


Figure 2.2: Location of Cairo, Illinois in the Mississippi River Watershed (Luke et al., 2015)

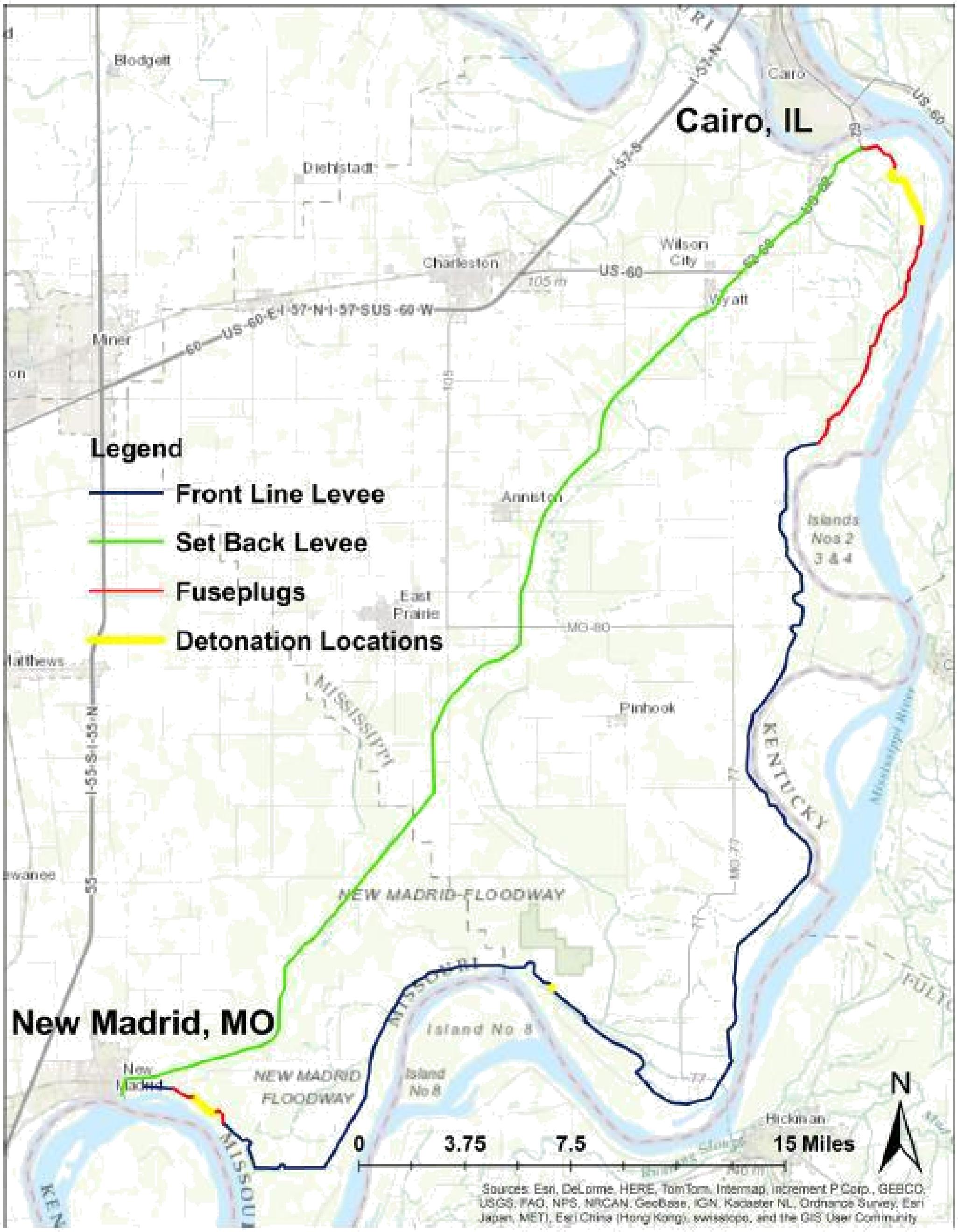
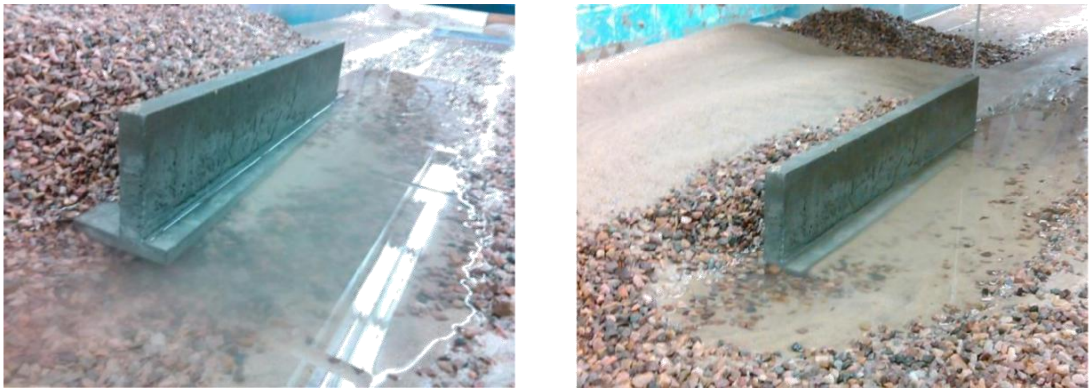


Figure 2.3: Location of New Madrid Floodway with levee's and fuse-plug detonation locations (Luke et al., 2015).



(a) Abutment with non-erodible approach

(b) Abutment with erodible approach

Figure 2.4: Scale model flume experiments on spread footing abutments

CHAPTER 3

JOURNAL ARTICLE 1

TO BE SUBMITTED TO: NATURAL HAZARDS

3.1 Abstract

The leading cause of bridge failure has often been identified as bridge scour, which is generally defined as the erosion or removal of streambed and/or bank material around bridge foundations due to flowing water. These scour critical bridges are particularly vulnerable during extreme flood events, and pose a major risk to human life, transportation infrastructure, and economic sustainability. Climate change is increasing the intensity and persistence of large flow events throughout the world, further straining bridge infrastructure. Retrofitting the thousands of undersized and scour critical bridges to more rigorous standards is prohibitively expensive, and current countermeasures inadequately address the core problems related to bridge scour. This research tested the efficacy of using approach embankments as intentional sacrificial "fuses" to protect the integrity of bridges with minimal damage during large flow events by allowing the streams to access their natural floodplain and reduce channel velocities. The concept was evaluated using the Hydrologic Engineering Center's River Analysis System (HEC-RAS) models. Steady flow models were developed for three specific bridges on two river reaches. Bayesian streamflow return period estimators were developed for both river reaches using available United States Geological Survey (USGS) stream gauge data to evaluate sacrificial

embankments under non-stationary climatic conditions. Fuse placement was determined to be a cost effective scour mitigation strategy for bridges with suboptimal hydraulic capacity and unknown or shallow foundations. Additional benefits of fuses include reductions in upstream flood stage and velocity.

3.2 Introduction

2 Introduction

Scour is the primary cause of bridge failures in the United States (Kattell and Eriksson 1998) and other parts of the world. Melville and Coleman (1973) report 31 case studies of scour damage to bridges in New Zealand, of which 13, 8, 4 and 6 cases were primarily attributed to pier failure, erosion of the approach or abutment, general degradation, and debris flow or aggradation, respectively. The Federal Highway Administration (FHWA) Bridge Scour Evaluation Program reports that as of 2011, the United States has over 23,000 (4.7%) scour critical bridges, and over 40,000 (8.3%) bridges with an unknown foundation (Hydraulic Engineering Circular 18 (HEC-18) by Arneson et al. 2012). Between 1969 and 1991, more than 1,000 bridges failed; 60% of those failures were due to scour (Briaud et al., 1999). Wardhana and Hadipriono (2003) analyzed 503 cases of bridge failure in the United States from 1989 to 2000 and found that the leading causes of bridge failure relate to flooding and scour. HEC 18 provides several examples of scour related bridge damage and failure in the United States. For example, during the 1987 spring floods, 17 bridges in New York and New England were damaged or destroyed by scour. Failure of the I-90

Bridge over the Schoharie Creek near Amsterdam, NY resulted in the loss of 10 lives and millions of dollars in bridge repair and replacement costs (FHWA 2015). In 1985, flooding in Pennsylvania, Virginia and West Virginia destroyed 73 bridges. A 1973 national study (FHWA 1973) of 383 bridge failures caused by catastrophic floods showed that 25 percent involved pier damage and 75 percent involved abutment damage. A second more extensive study in 1978 indicated local scour at bridge piers to be a problem about equal to abutment scour problems (FHWA 1978; Arneson et al. 2012). The 1993 flood in the upper Mississippi basin caused damage to 2,400 bridge crossings (FHWA 2015) including 23 bridge failures (Arneson et al. 2012). The analysis of over 300 Vermont bridges damaged in 2011 Tropical Storm Irene indicated that about 56% of the damaged bridges had scour damage, 30% had channel flanking, and the remaining 14% had superstructure and debris damage (Anderson et al. in review).

As part of the Third National Climate Assessment, Walsh et al. (2014) concluded that some regions of the United States are experiencing an increase in the frequency and intensity of heavy downpours and hurricane-level storms due non-stationary weather conditions. The Northeast has seen the largest increases in heavy precipitation with a 71 percent increase in precipitation during heavy storm events (Karl et al. 2012). In the Northeast United States, this problem is compounded by the fact that storm events are persisting longer than in the past, further increasing flooding hazard through persistent wetness and lack of ground surface infiltration capacity during long periods of rainfall (Guilbert et al. 2015). The recent increase in extreme rainfall events and persistence leads to non-stationary streamflow return period estimates. Non-stationarity of streamflow return periods is defined as when watershed streamflow parameters such as mean or variance are proven to be changing with time. This can lead to infrastructure not meeting necessary design criteria throughout time. The Northeast United States is not alone in experiencing this phenomenon; numerous studies have shown that flooding risk is increasing throughout the world in places such as China (Fu et al. 2013), England (Fowler et al. 2005), India (Rajeevan et al. 2008), and Switzerland (Schmocker-Fackel and Naef 2010). This leads to more devastating and frequent flooding events, further straining infrastructure and increasing the need for cost-effective scour-mitigation solutions for bridges. Retrofitting the thousands of existing undersized and scour critical bridges to the current standards is prohibitively expensive; and typically countermeasures do not adequately address the core problems related to bridge scour.

Adding complexity to the linkages between bridge scour and damage is the fact that roads and bridges often encroach rivers and streams floodplains, which restricts the natural stream flow during high-flow events. Lack of floodplain access often increases stream velocities, worsening in-stream incision and bank erosion, and in turn, increasing bridges' vulnerability to scour. Developing smart mitigation strategies that reduce stream velocities and bridge scour during large flow events helps to balance the tradeoffs between human infrastructure needs and protection of the natural environment for long-term sustainability.

This research studies the efficacy of using approach embankments that intentionally act as sacrificial fuses to protect the bridge, while minimizing economic damage during large storm events. A sacrificial approach embankment design allows streams to access their floodplain during high-flow events, reducing channel velocities, and correspondingly, the potential destruction associated with bank erosion and bridge scour. This concept can prove effective for both existing and new bridges as a scour-mitigation technique.

A very limited amount of research was found on the use of sacrificial embankments in hydraulic bridge design; however, there is a significant body of work on fuse-plugs for earth- and rock-filled dams. A fuse-plug spillway, as defined by the United States Bureau of Reclamation (USBR), is a form of auxiliary spillway consisting of a low embankment specifically designed to be overtopped and washed away during an exceptionally large flood. The first physical hydraulic model study of fuse-plugs was performed by the USBR to determine their usefulness for flood control dams in 1980s. The report (Pugh, 1985) concluded that a properly designed fuse-plug embankment would predictably wash out when a large flood needs to pass through the reservoir.

A detailed hydraulic analysis of fuse-plug designs performed for a canal in Switzerland by Schmocker et al. (2013) found that fuse-plugs are also useful in smaller applications, such as along a river or canal. They tested two scaled fuse-plug designs in a flume, one with a large inclined clay core and a second having sandy fill with a small clay core. Both designs performed as expected and eroded away in a quick and controlled manner. The authors recommended the sandy fill fuse-plug design over the inclined clay core because of its comparative ease of construction and equivalent performance.

In May of 2011 at the New Madrid Floodway on the Mississippi River near Cairo, Illinois, a fuse-plug along the Mississippi River was activated when the United States Army Corps of Engineers detonated a forward levee to allow the Mississippi access to a large floodplain during a storm and reduce the stage of the flood upstream of the breach. Luke et al. (2015) studied the impacts of detonation after the storm and determined that the fuse-plug reduced the flood stage by 0.8 m and was a significant factor in minimizing damage to Cairo. Luke et al. (2015) suggest that future hydraulic modeling studies on breach geometries and floodplain activation techniques would be useful to the New Madrid Floodway and others with similar geometries. In addition, other researchers have proposed similar mechanisms to reduce flooding stage and velocities by purposefully breaching key levees as a flood mitigation technique (Jaffe and Sanders 2001). Translating fuse-plug designs from a levee situation to a sacrificial embankment situation is feasible because levee and bridge embankments share many of the same design characteristics.

The research presented here has two main objectives. We first demonstrate the functional and economical effectiveness of sacrificial approach embankments in significantly reducing bridge scour. The second objective illustrates the benefits of reconnecting a stream to its floodplain during large flow events with sacrificial embankment installation by reducing the stream stage and velocity. To incorporate non-stationarity a Bayesian approach to better estimate streamflow return periods was adopted for the streams studied.

3.3 Methods

To analyze the effectiveness of the sacrificial embankments in reducing bridge scour, we made some reasonable assumptions to simplify the hydraulic model. First, we assumed that when a flood wave hits a bridge, a well-designed sacrificial embankment erodes away immediately. In addition, we assumed the United States Geological Survey (USGS) stream gauge information to be accurate. Using the stream gauge data, we developed a Bayesian estimator to generate a distribution of possible streamflow return periods to test the efficacy of incorporating a sacrificial embankment fuse under non-stationary climatic conditions. We evaluated three existing bridges that cover a broad range of structural and hydraulic characteristics and analytically tested the effectiveness of sacrificial embankments to reduce scour at these bridges. The study is designed as a “proof of concept” and is not meant to make specific recommendations for the select bridges at each study site. Although the study used data from the Northeastern United States, specifically the state of Vermont and the 2011 extreme flood event Tropical Storm Irene, the methodology presented here is applicable to other settings.

3.3.1 Stream Flow Estimates Using a Bayesian Approach

Bayesian statistics, first proposed in a hydrologic context by Wood and Rodriguez-Iturbe (1975), has become increasingly popular. The Bayesian estimation of streamflow return periods allows uncertainty to be incorporated into designs because it provides a range of possible values for design parameters compared to single estimates (Botto et al. 2014). In addition, Bayesian estimation allows a designer to update estimates of streamflow return periods based on monitoring data as they become available.

According to Bayes theorem, the probability of A given B is equal to the product of the probability of B given A with the probability of A, divided by the probability of B and is shown in Equation 3.1.

$$(|) = \frac{(|) \, ( )}{( )} \qquad [3.1]$$

For this paper, A is defined as one of the log-normal distribution parameters, μ or σ associated with the measured maximum annual streamflow measured over a period of n years; and B is defined as the maximum streamflow in a given year, x. Using measured annual stream flow maxima, we may estimate the log-normal distribution parameters, μ and σ. We utilized an analytical solution to the Bayesian estimation of the log-normal distribution parameters, μ and σ, to develop our Bayesian return period estimates. The data passed the Shapiro-Wilk W Goodness of Fit test for normality using JMP Pro Version 12.

For the purposes of this paper, an example dataset was tested using streamflow information from the USGS National Water Information System (NWIS). These data are openly available and often have instantaneous, daily statistics, monthly statistics, and annual statistics. The NWIS annual maximum streamflow data were the primary data used for the Bayesian return period estimator. We used the maximum recorded streamflow in a given water year (October 1st to September 30th) for 100 years measured from the USGS Montpelier stream gauge on the Winooski River (Site Number 04286000) and the Lamoille River (Site Number 04292000).

The estimator was then run for the length of the dataset (77 and 89 years for the Winooski and Lamoille Rivers, respectively). The estimated Bayesian outputs contained distributions of μ and σ for each year. Distribution estimates of maximum likelihood, σ, for the last year of streamflow for the Winooski and Lamoille River are shown in Figure 3.1, and are used to illustrate the process of estimating different Bayesian 100-year flow events. Using Figure 3.1, one finds standard deviations of the distribution of σ. The standard deviations are then used as multiples of the maximum likelihood value of σ (approximately 0.31 and 0.33 for the Winooski and Lamoille Rivers, respectively) to develop possible values for σ based on the distribution. Values chosen for both the Lamoille and Winooski River analyses were 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 standard deviations away from the maximum likelihood of σ. The selected σ multipliers were then used to best fit the log-normal distribution for the observed streamflow data and develop the return periods. Figure 3.2 shows the streamflow associated with the 100-year return period for each multiple of σ, with the USGS 100-year streamflow estimates for comparison. It is important to note that this methodology may be used to analyze any bridge that spans a stream given a reasonable amount of available streamflow data.

3.2.2 Estimation of Scour Depths for Sacrificial and Non-Sacrificial Embankments

A review of inspection photographs of Vermont bridges damaged in Tropical Storm Irene revealed that a noteworthy number of bridges experienced erosion of the soil behind the bridge abutments (flanking), and did not show significant signs of traditional scour (around and under pier and/or abutment foundation). Two photographs highlighting the differences between scour damage and flanking damage are provided in Figure 3.3. Flanking damage is very similar to the type of damage that a bridge with a sacrificial embankment might experience. The primary difference between flanking and scour damage is that flanking primarily occurs around a bridge abutment and tends to destroy the road and embankment, but does not threaten the structural integrity of the bridge. Scour damage results from undermining of the bridge abutment and/or pier and can threaten the integrity of the entire bridge.

Scour depths at the studied bridges were calculated using the most current methods recommended in HEC-18 (Arneson et al. 2012). For the embankment without a fuse, we used both methods (NCHRP and Froehlich) without any modifications.

For the sacrificial embankment, we used the National Cooperative Highway Research Program (NCHRP) method (Arneson et al. 2012) for the situation when a bridge embankment is flanked, which is analogous to a sacrificial embankment scenario. In addition, we assumed that when the embankment is removed, the abutment could be treated as a pier and accordingly used the relevant pier scour equations (CSU equation) as a way of verifying the NCHRP method.

3.2.3 Scour Repair Cost Estimates

Anderson et al. (in review) reported that 328 bridges were damaged in Tropical Storm Irene, which deposited between 127 mm and 254 mm of rain and had an estimated return period in excess of 100 years in most areas of Vermont and in excess of 500 years in some areas. Of these 328 bridges, 313 bridges had span lengths longer than 6 m. Anderson et al. (in review) had access to cost estimates for repair/replacement for a total of 103 bridges, and clustered the observed damage into four categories – slight, moderate, extensive, and complete (Figure 3.4). The descriptions of damage in these categories are summarized in Table 3.1. The horizontal line and asterisk in each box plot represent the median and mean, respectively; the edges of the box are the 25th and 75th percentiles, and the whiskers extend to the most extreme data points not considered outliers. Outliers are plotted individually. We fit curves through the means and upper and lower quartiles of each damage category. These curves, presented in Figure 3.5, provide reasonable estimates of the mean, upper bound, and lower bound of repair costs per deck area for typical Vermont bridges for each of the four damage categories. For the purpose of this study, we redefined the level of damage in terms of the estimated scour depth compared to the depth of foundation, as reflected in the horizontal axis of Figure 3.5 so we could relate calculated scour depth to remediation cost estimates. The mean repair costs along with the upper and lower quartile costs for each category are fit using curves (Figure 3.5) and used to estimate corresponding sour damage repair costs for the example bridges considered in this work.

A cost analysis study of the effects of 2011 Tropical Storm Irene on Vermont's bridges performed by Anderson et al. (2014) showed that damage due to flanking had an estimated average repair cost of $70,000, and the cost of flanking-induced repair per square meter of the deck area ranged between $101 and $182 per square meter. In comparison, damage due to scour was estimated to cost $239,000 on average to repair with an average repair cost of $398 per square meter of deck area. Complete bridge replacement can cost hundreds or thousands of dollars and take months to years to complete, whereas washed-out approaches require a simple backfill and leveling, and can be reopened hours or days after the flood subsides. This research treats flanking damage as an analogous substitute of a sacrificial embankment for the purposes of cost estimates. In this work, we assume the cost of constructing a sacrificial embankment to be similar to the estimated repair costs of flanking damage to bridges seen in Tropical Storm Irene. We estimate cost using the same methods described previously in this section and then add a cost for installation and replacement of the sacrificial embankment to the estimated scour costs. These additional installation and repair costs are estimated using the repair costs associated with bridges that experienced flanking damage during Tropical Storm Irene.

3.2.4 Study Sites and Hydraulic Modeling Techniques

We used three example bridge sites in Vermont for our analysis. The relevant characteristics of each bridge are summarized in Table 3.2. Note that the "Federal Sufficiency Rating" is based on the United States National Bridge Inventory inspection program, where bridges are given a score from 0 - 100 based on their condition. A score of 100 is considered to be in perfect condition; and a 0 represents a bridge that is unusable or entirely deficient. According to the FHWA, "any bridge with a sufficiency rating of 50.0 or less is eligible for replacement or rehabilitation, while bridges with a sufficiency rating of 80.0 or less are eligible for rehabilitation" (Burrows et al. 2015).

The first bridge, labeled "Bridge 1", was built in 1992 and is considered at lower risk of failure due to scour at the 100-year storm design because of its age, geometry, and foundation type and depth.

The second bridge (Bridge 2) was built in 1985 and is a general example of a bridge with a "moderate" risk of failure due to scour at the design storm. In addition, the Federal Inspection report noted that the stream has a slight chance of overtopping the roadway during the 100-year storm event.

The third bridge (Bridge 3) was built in 1928 with a steel pony truss and simple slab foundation at an unknown elevation below the original streambed surface. The foundation depth was assumed to be 1.8 m below the original streambed elevation as per standard Vermont Agency of Transportation practice (Wark et al. 2015). The bridge is considered functionally deficient by federal standards. Significant repairs are needed for both the superstructure and substructure. One abutment is cracked, rotated and in need of repairs; the other abutment is also cracked. This structure represents some of the worst-case bridge scenarios – those in need of repair and also having unknown foundations.

Hydraulic modeling was performed using the Hydrologic Engineering Centers River Analysis System Version 4.1.0 (HEC-RAS). HEC-RAS is a one-dimensional river modeling software package that takes streamflow, channel geometry, and estimates of Manning’s n values to solve the one-dimensional St. Venant’s equations to develop stage, discharge, and water velocity estimates. During the study period, HEC-RAS 5.0 was released, which uses a more sophisticated two-dimensional modeling technique compared to the one-dimensional HEC-RAS 4.1.0 model. However, because this study is a proof-of-concept and the one-dimensional version is still used extensively in practice, its use was considered acceptable. The original models were developed and calibrated by the USGS, and we modified them to incorporate nonstationary flows and sacrificial embankments. Storm modeling was performed using the 100-year streamflow and multiple maximum likelihood σ estimates from the Bayesian analysis for a steady state HEC-RAS model. The streamflow inputs from the corresponding σ multiples are shown in Figure 3.2 for the Winooski and Lamoille Rivers. Each HEC-RAS streamflow simulation was run for a bridge scenario with and without a fuse; and the appropriate model output (i.e., stage height, velocity, and bridge geometry) were extracted and subsequently used to estimate scour using the methods described earlier; the latter was performed using MATLAB (Version R2015b).

3.4 Results and Discussion

3.4.1 Stream Flows

Comparisons between the USGS streamflow and the Bayesian estimates for the 10, 25, 50 and 100-year return periods for the Winooski and Lamoille Rivers are presented in Figures 3.6a and 3.6b, respectively. For both rivers, the results for the calculated most likely return period are similar to USGS results; and therefore, help validate the modeled results. It is important to note that these are just point estimate predictions used to verify the relative accuracy of the Bayesian estimator. The Bayesian estimator also provided a range of possible streamflows for both rivers based on the σ multiples and are reported in Figure 3.2.

3.4.2 Hydraulic Model Results and Scour Predictions

Figure 3.7 shows a profile of the Winooski River under a 100-year flow with flood stage with and without sacrificial embankment. The x-axis represents the distance along the modeled section of the main channel (in meters), and the y-axis is the modeled elevation of the stage (in meters). There is a significant scale distortion of 500-unit horizontal to one-unit vertical. The streambed and location of Bridge 1 are labeled for clarity. The sacrificial embankment scenario water elevation for the USGS 100-year flow is the solid line, and the non-erodible embankment scenario is the solid line with triangles. Replacing the south embankment with a sacrificial embankment resulted in a stage reduction of 0.66 meters just upstream of the bridge with the stage significantly reduced for about 3.2 km upstream of the bridge. Bridges 2 and 3 showed similar results when installing a sacrificial embankment, with 0.87 m and 0.091 m reduction in stage at Bridges 2 and 3, respectively.

In addition to reducing the stage at a given location, a sacrificial embankment can significantly reduce channel velocities by allowing the bridge to access its floodplain during an extreme streamflow event. For Bridge 1, the main channel velocity for the given 100-year storm design reduced significantly, from 3.3 m/s to 2.18 m/s, a 33% reduction in velocity. For Bridge 2, the main channel velocity was reduced from 3.57 m/s to 1.04 m/s (71% reduction) and Bridge 3 had main channel velocity reduced from 3.25 m/s to 3.02 m/s (7.1% reduction).

3.4.3 Cost Estimates and Scour Predictions

Using the methods and theory described earlier, bridge scour and cost estimates were performed for Bridges 1, 2, and 3. The scour depths calculated for a 100-year flow and the equivalent Bayesian estimated flow (Figure 3.8a) show that scour depth was significantly reduced when a fuse was installed at Bridge 1. However, under current flow conditions, it is not likely that the bridge would collapse due to scour from a 100-year flow. Figure 3.8a compares the costs of the bridge with and without a sacrificial embankment under changing flows. The range of cost estimates is due to the variability in estimated scour depths and damage cost categories calculations. Figure 3.9a shows that Bridge 1 is not an ideal location for sacrificial embankment placement under the current design flow. Using current streamflow estimates, installing a sacrificial embankment for Bridge 1 is not economically rational because the mean cost of repairing the damage after a 100-year storm is lower than the cost of installing and replacing a sacrificial embankment after a 100-year storm. However, the location provides insight into how sacrificial embankments may become cost effective over time as the magnitude and frequency of extreme storm events may increase. There is a “cross-over” point at about 0.5σ when the cost of the sacrificial embankment system becomes less expensive than the repair costs associated with doing nothing. Based on these results, this stream would require careful re-evaluation of streamflow records to ensure that the statistical trends used to estimate the original 100-year return period are stationary. If the statistical trends drift over time to more extreme and/or frequent flow events, it may become worthwhile to install a sacrificial embankment at that location.

The results of the cost analyses for Bridges 2 and 3 (Figures 9b and 9c) are presented in similar format to Bridge 1 (Figure 3.9a). Once again, the calculated scour depth for Bridge 2 was significantly reduced when a sacrificial embankment was installed, and never exceeded the 50% threshold for any calculation method. Based on current streamflow estimates, the scour equations predict that Bridge 2 would suffer major damage or collapse during a 100-year flow event because the calculated scour depth exceeds the foundation depth (Figure 3.8b). Figure 3.9b shows it is cost effective to install a sacrificial embankment under the current and future estimates of extreme streamflow; costs are approximately $600,000 less than the cost of doing nothing. In addition, the removal of the bridge abutment reduces the stage at the bridge by about 0.87 m, which could noticeably lower upstream flooding damages not accounted for in this analysis.

The scour calculations in Figure 3.8c show that Bridge 3 has the greatest risk of failure due to scour, and that at the 100-year stage, failure due to scour is almost certain. However, the estimated sacrificial embankment scour depth is significantly lower; and it is more likely that the bridge would survive the 100-year storm event. Figure 3.9c shows that on average, it would cost about $95,000 to leave the bridge “as is” compared to installing a sacrificial embankment. A secondary benefit of sacrificial embankments is stage reduction; this was not incorporated into the cost analysis. Depending on the geography of the area, the stage reduction could significantly reduce the flooding potential on the town upstream of the bridge.

The above calculations suggest that sacrificial embankments are effective as a scour mitigation technique even if current climatic conditions are stationary for the general conditions presented in Bridges 2 and 3. Sacrificial embankments can be effective for the situation presented in Bridge 1, especially if precipitation and corresponding streamflows become more extreme. In addition, sacrificial embankments are effective in reducing stream stage and velocity during high flow events and may also help reduce flooding upstream of the bridge.

3.5 Concluding Remarks

This work has shown that:

(1) Bayesian estimation of streamflow return periods can be a useful tool in designing hydraulic infrastructure to account for non-stationarity;

(2) Sacrificial embankments can significantly reduce bridge scour;

(3) Sacrificial embankments provide the secondary benefits of reducing the flood velocities and stage upstream of the bridge site; and

(4) The approach adopted to compute costs based on available data from an earlier extreme event from the region is reasonable and prove to be an effective tool for policy makers and bridge designers in the decision-making process to account for streamflow return period uncertainty in designing mitigation strategies for bridges.

This proof-of-concept study revealed that sacrificial embankments could be an economical and innovative scour mitigation strategy. Additional research is needed before this solution could be implemented in practice. To guide the needs for future work, we interviewed eleven professional engineers from the states of Vermont and New Hampshire including some with experience in post-disaster recovery and interactions with the United States Federal Emergency Management Agency (FEMA).

In general, all engineers agreed sacrificial embankments are an innovative idea and to the best of their knowledge they were not aware of any bridges where a sacrificial embankment was intentionally designed. Most engineers expressed a willingness to consider using a sacrificial embankment in practice if further studies prove its safety and cost effectiveness. At the top of the list was the need for sufficient studies proving that the sacrificial embankment would only wash away during the design flow event, and not simply during a heavy rainstorm, traffic loadings, or normal high water event. The pavement over the sacrificial embankment would need to support traffic loads adequately, but also wash away with the embankment. Rural bridges, spanning smaller streams with low average daily traffic and unpaved approaches, may be good candidates for incorporating sacrificial embankments. For widespread consideration, it would be helpful if design manuals incorporated this as a viable mitigation/countermeasure strategy. The engineers strongly suggested that further work assuring the cost effectiveness of installing a fuse, particularly the life-cycle costs, is critical. All engineers interviewed suggested that pilot studies are needed, and that the best place to start may be rural bridges spanning smaller streams with low average daily traffic and unpaved approaches.

The following potential issues were identified: (1) a washed away embankment would contribute a large volume of sediment to the stream negatively affecting water quality; (2) right-of-way and archeological aspects may not allow this solution at some sites; and (3) public perception and safety. Each interviewed engineer emphasized the importance of item 3 – ensuring public safety. In this regard, outreach and education of practicing engineers and general public would be of paramount importance. In terms of safety, they suggested signage and warning system that alert drivers and pedestrians to not use the bridge when flows near critical are expected.

3.6 Acknowledgements

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3.7 Tables

Table 3.1: Description of damage categories used in analysis (Anderson et al., in review)

Damage Category	*Depth of Calculated Scour (%)*	*Description*
Slight	0-10	Channel erosion that does not affect the bridge foundation, superstructure and guardrail damage and debris accumulation without scour present.
Moderate	10-75	Scour that affects the foundation, but not to a crucial state, bank and approach erosion, heavy aggradation and damage to the superstructure, but not to a crucial state.
Extensive	75-100	Crucial scour, with some settlement to a single foundation, but not to the point of collapse, full flanking of both approaches, and superstructure damage that makes it structurally unsafe.
Complete	100-105	Bridge washed away, collapsed, or has significant foundation damage that requires replacement.

Table 3.2: List of bridges used in analysis with relevant characteristics

Bridge	*Year Built*	*Foundation Type*	*Foundation Depth (m)*	*Drainage Area (km^2)*	*Span (m)*	*Deck Area (m^2)*	*Federal Sufficiency Rating*
1	1992	H-Pile	6.9	1,740	41.5	1,226	96.4
2	1985	H-Pile	12.2-13.4	331	30.5	1,486	83.8
3	1928	Slab Footing	Unknown (assumed 6 feet)	385	30.5	209.7	50.9

3.8 Figures

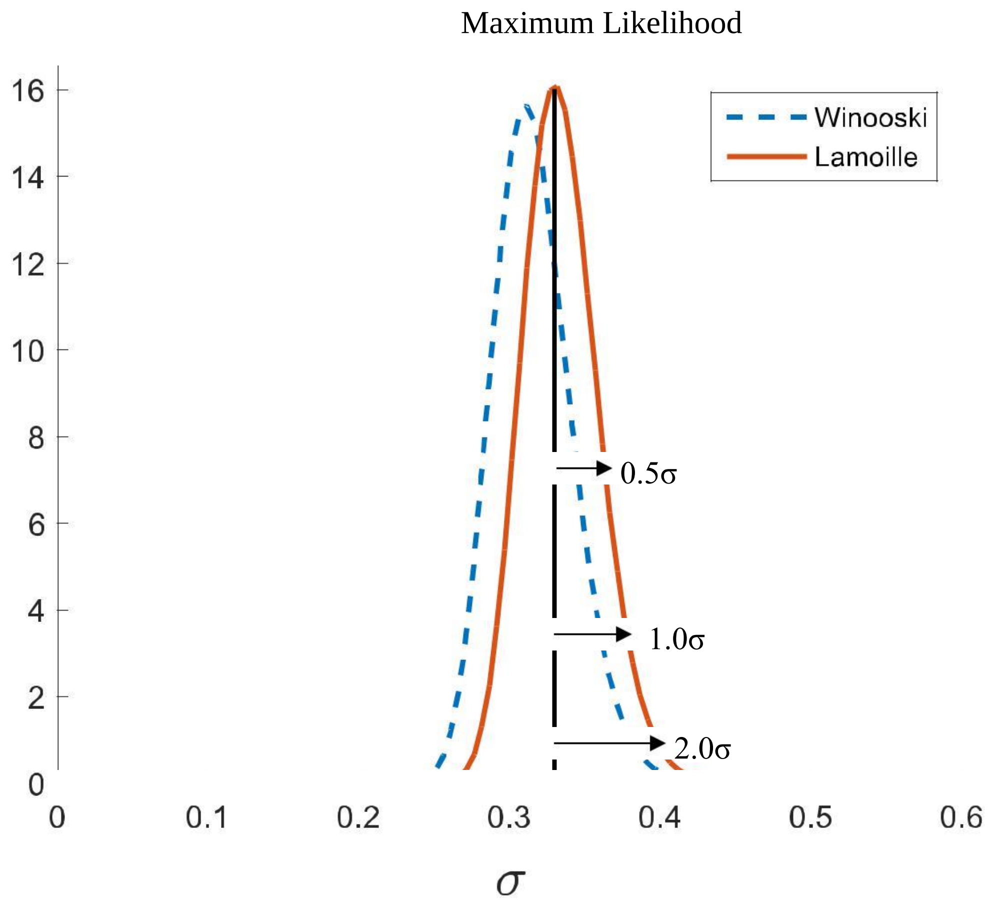


Figure 3.1: Distribution of σ estimate for Winooski and Lamoille Rivers streamgauge for final year

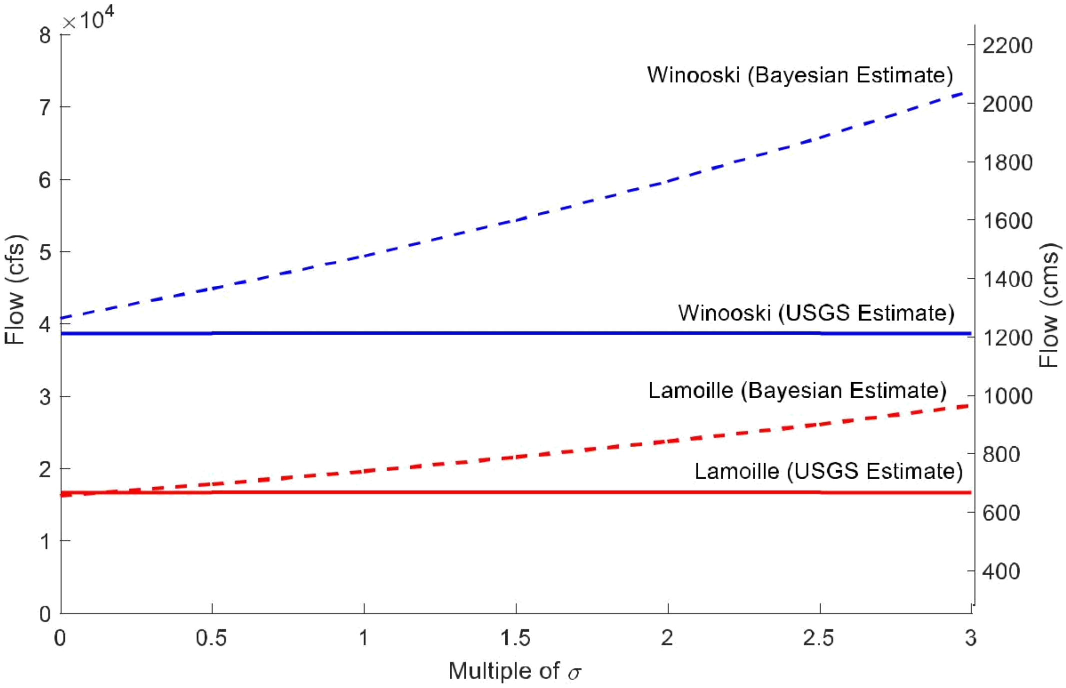


Figure 3.2 Comparison of Bayesian (dashed line) vs USGS streamflow (solid lines) for different σ multiples for the Winooski and Lamoille Rivers.

Figure 3.3: Example of flanking (a) and abutment scour (b) damage to bridge embankment and abutment due to Tropical Storm Irene (source: Vermont Agency of Transportation)

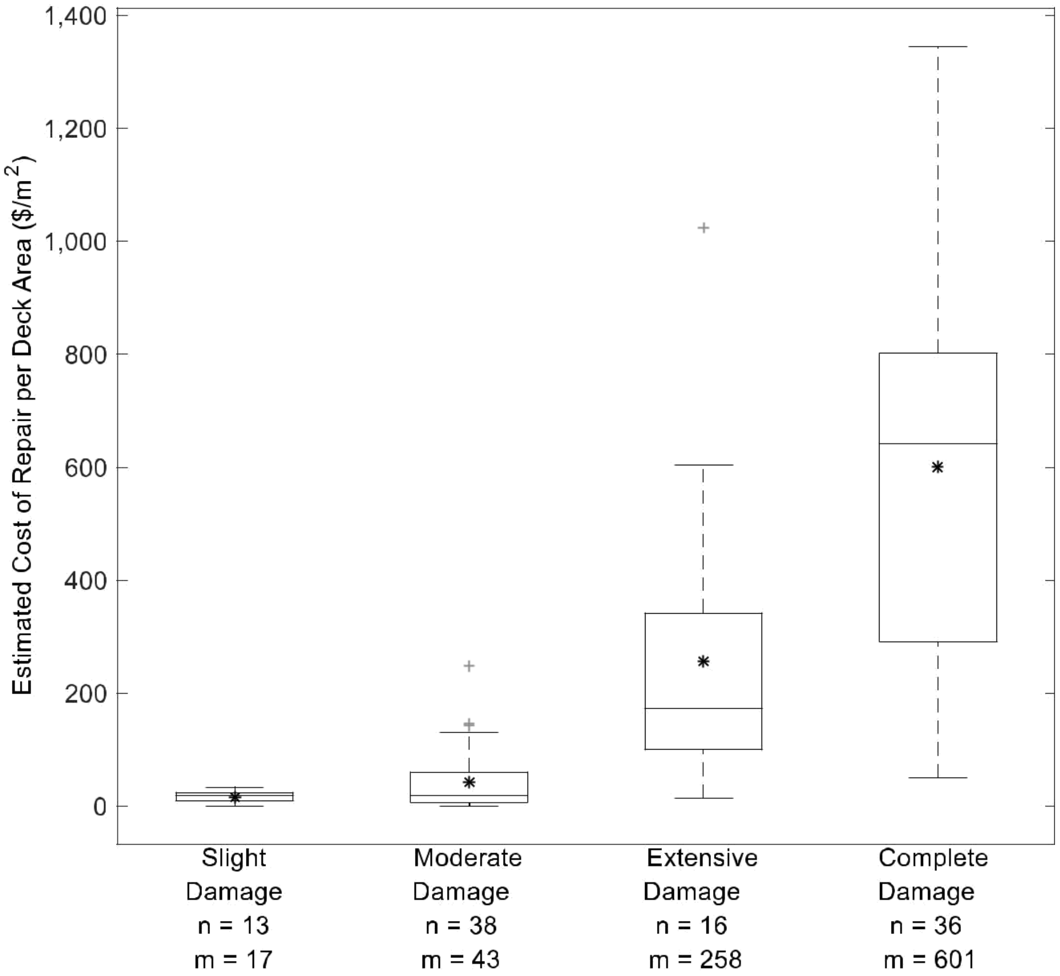


Figure 3.4: Estimated cost of repair for bridges damaged in Vermont during Tropical Storm Irene. The star represents the mean, bar the median, the box the 25th and 75th quantile, the whiskers the 95% confidence interval, and +'s are outliers (source: Anderson et al., in review).

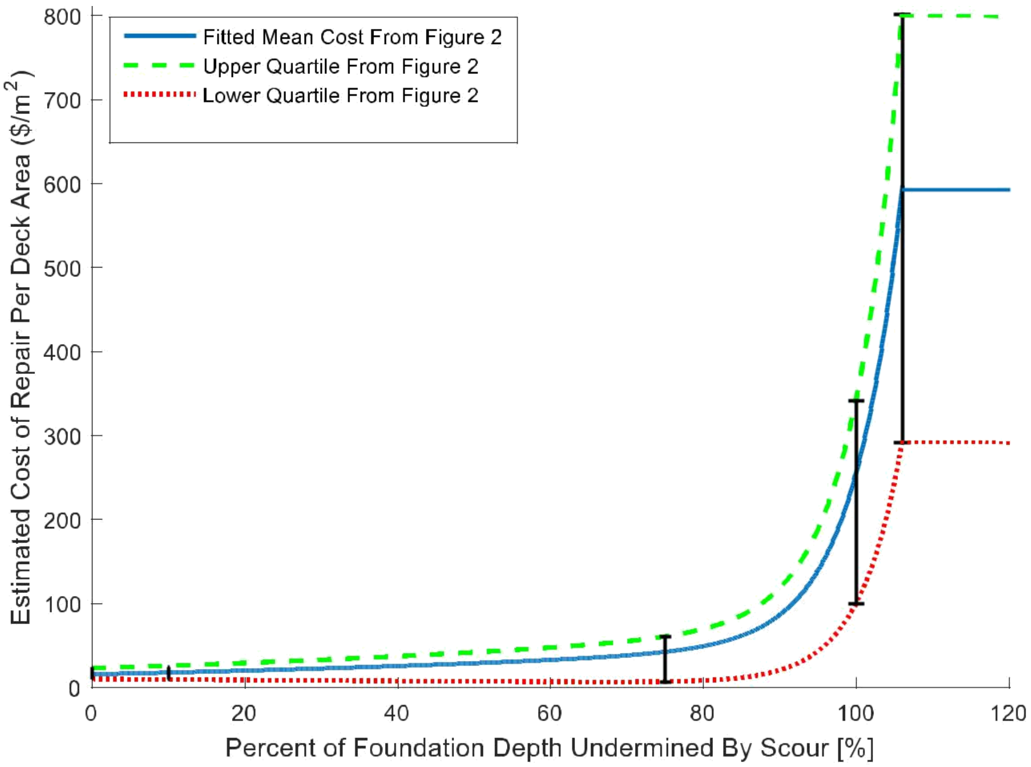


Figure 3.5: Smoothed curve estimate for cost of repair

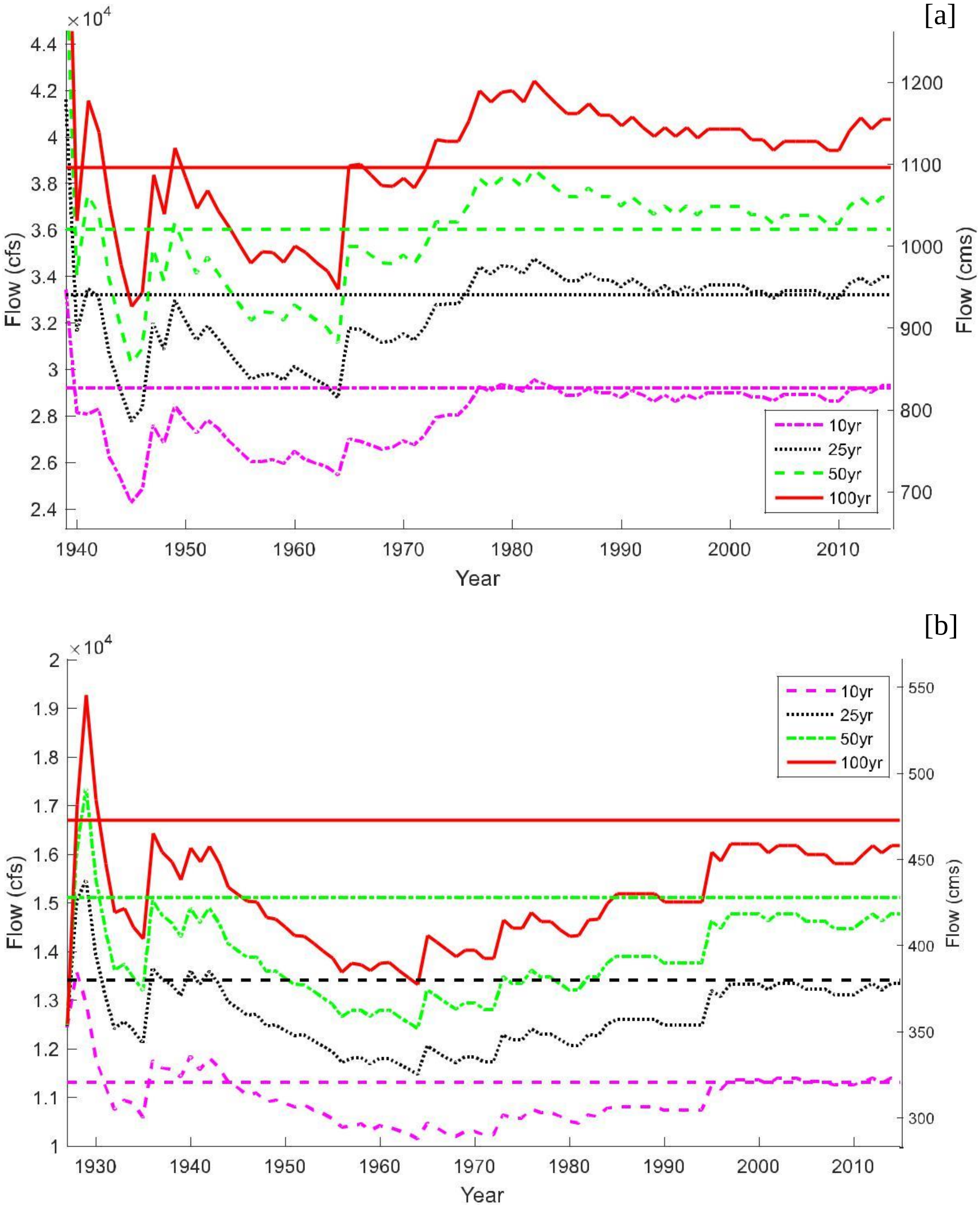


Figure 3.6: Streamflow return period estimates using a Bayesian Estimator (jagged line) vs. USGS estimates (straight line) for streamgauge on the Winooski River (a) and Lamoille River (b).

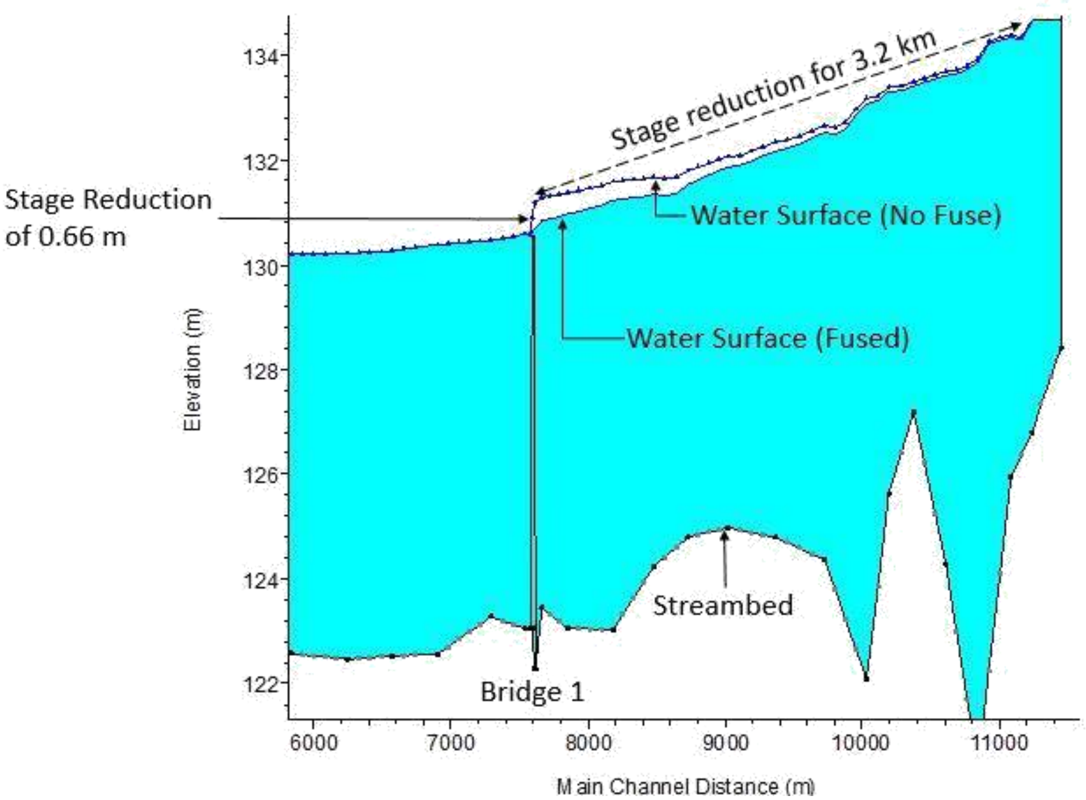
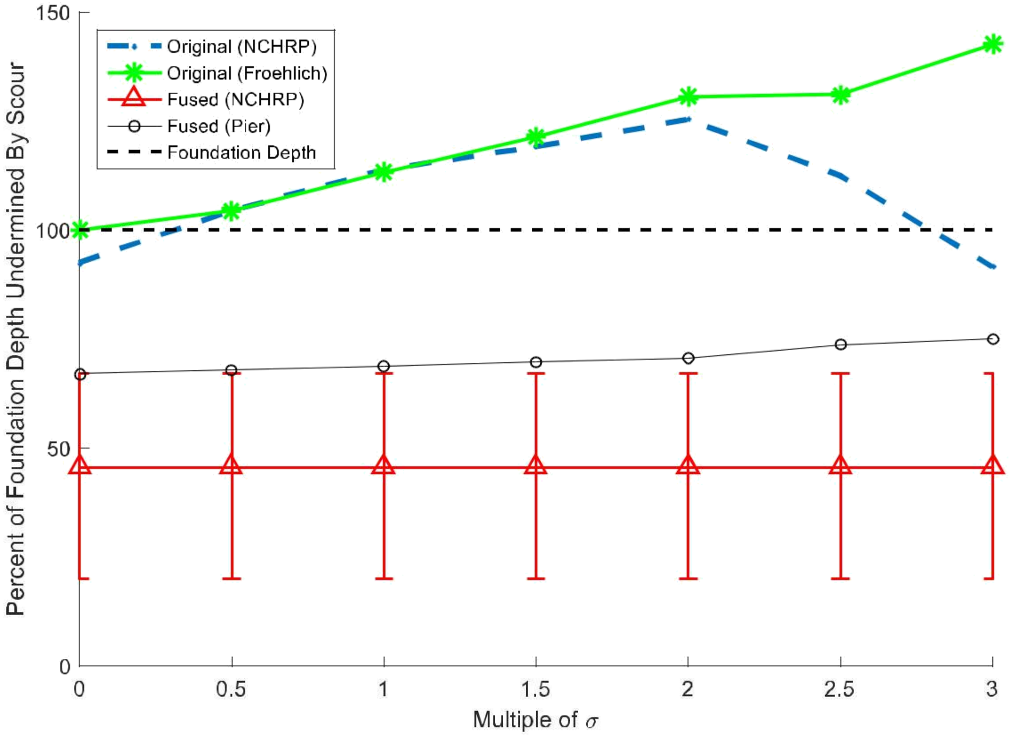


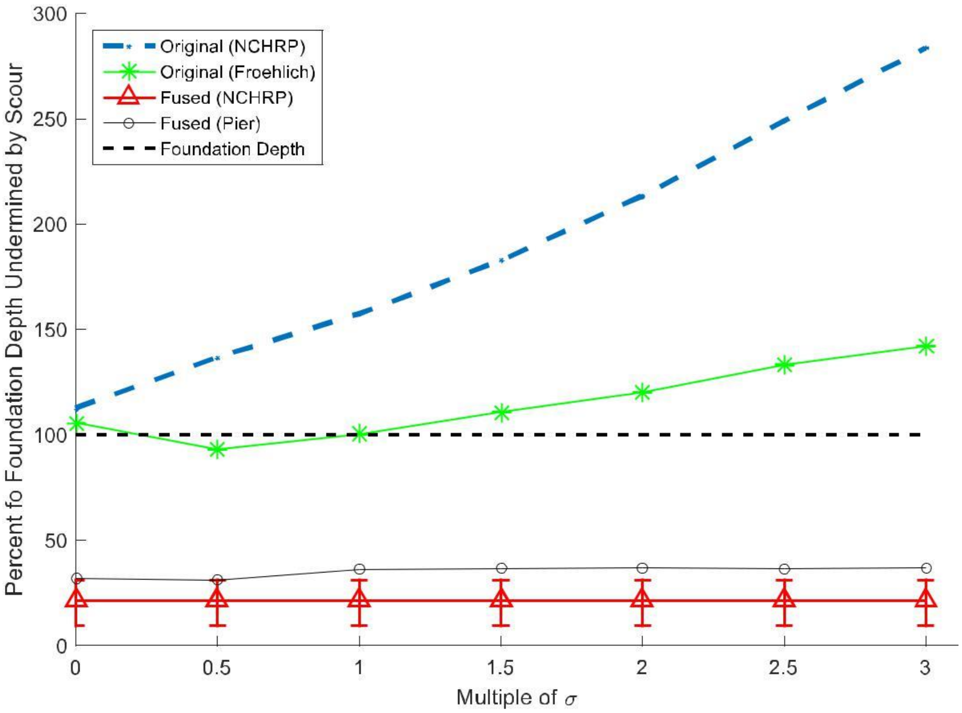
Figure 3.7: Profile view of river comparing fused vs non-fused embankment for "Bridge 1"

[a]



Original (NCHRP)
Original (Froehlich)
Fused (NCHRP)
Fused (Pier)
Foundation Depth
Percent of Foundation Depth Undermined By Scour
150
100
50
0
0
0.5
1
1.5
2
2.5
3
Multiple of σ

[b]


Original (NCHRP)
Original (Froehlich)
Fused (NCHRP)
Fused (Pier)
Foundation Depth
Percent fo Foundation Depth Undermined by Scour
Multiple of σ
300
250
200
150
100
50
0
0
0.5
1
1.5
2
2.5
3

[c]

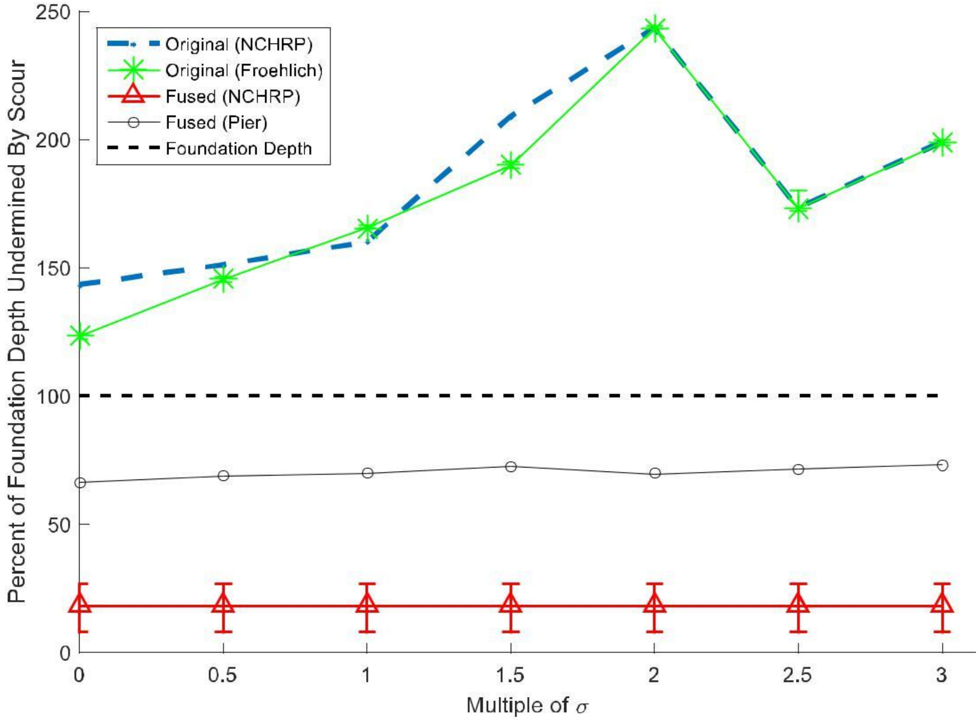
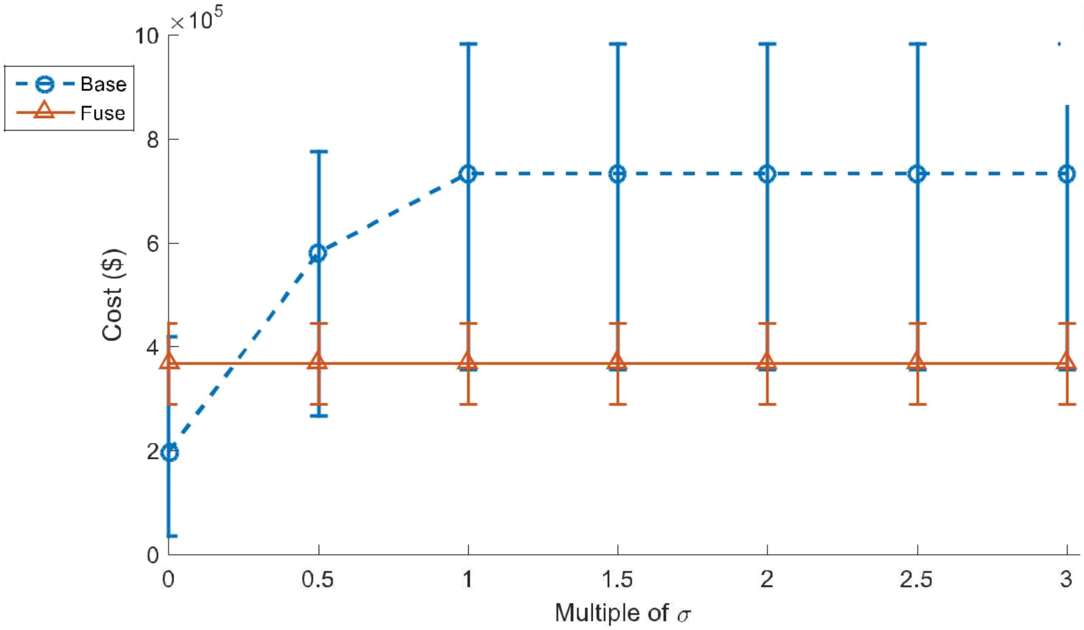
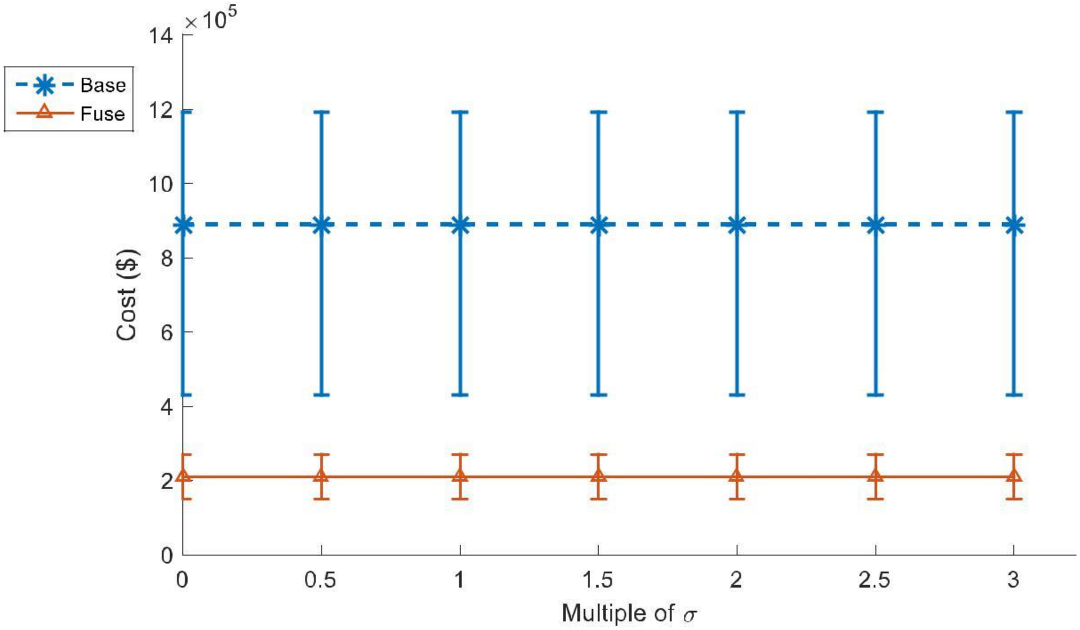


Figure 3.8: Calculated scour depth as a percentage of total foundation depth for various storm conditions

[a]



[b]



[c]

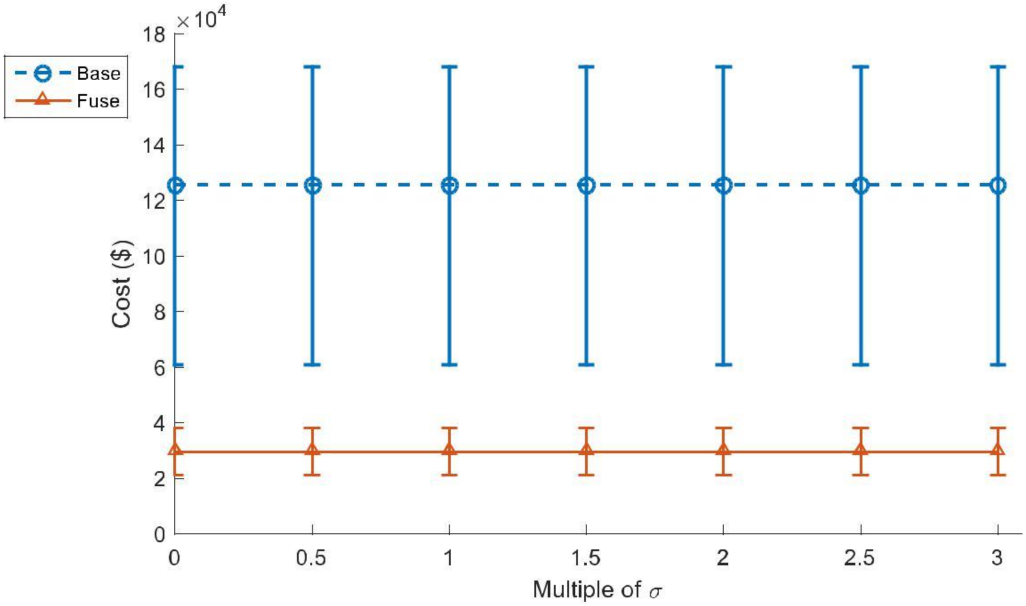


Figure 3.9: Cost curve estimate under different 100-year storm conditions for Bridges 1-3

3.9 References

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Chapter 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

This work indicates that sacrificial embankments can be an effective bridge scour mitigation technique when appropriately used under the assumptions made in this work. Properly designed fuses may provide the direct benefit of reducing scour depths and the corresponding risk of serious damage or collapse during extreme streamflow events. The sacrificial embankments are not only cost-effective, but they also provide the secondary benefits of reducing flood velocities and stage upstream and allow a stream to access its natural floodplain during high water events. This stage and velocity reduction may help reduce erosion and property damage resulting in significant savings, particularly in heavily populated areas.

The overall cost effectiveness of installing a fuse at a bridge depends on a wide variety of factors, including the site geometry, stream geomorphology, bridge foundation type and depth, and storm size. However, general rules can be extracted regarding the optimal site locations for fuses based on the results of the three bridges selected for this study. First, there should be an absence of important structures or utilities in or near the fuse location that could be washed away during a high flow event. Next, newer bridges, subject to higher standards, with deeper pile foundations and having more horizontal and vertical clearance to a stream (such as Bridge 1) generally have better chances of survival during large flow events, making the installation of a sacrificial embankment less economically viable. Older bridges with unknown foundations or slab footings with poor geometry situated on sandy or loose soil are good candidates for sacrificial embankments. The extent of scour depth in sacrificial embankment situations is almost entirely limited by the width of the wingwall or abutment, along with the angle of attack to flow, so abutments with small wingwalls or stubs that are well oriented to streamflow are also good candidates.

As we begin to see the effects of climate change on increasing magnitude and frequency of streamflow in the Northeastern United States and elsewhere, we need adaptive ways to remediate undersized bridges without the significantly increased cost required to widen them. Sacrificial embankments are not an all-encompassing solution, but intended as an economical alternative for policy makers and practitioners to consider in adapting to climate change and increasing resiliency of existing bridge infrastructure.

4.2 Recommendations for Future Work

Additional research is needed to further verify the efficacy of sacrificial embankments as a bridge scour mitigation technique with a specific focus on designs that ensure that the fuses will erode quickly and safely when a predetermined level of flow is exceeded. Specifically, special care should be taken to ensure sacrificial embankments only erode away during the desired storm event and not during normal flow events that could threaten the integrity of the bridge. This could be accomplished with more detailed flume studies in concert with real-world observation and study of bridges that experience flanking during high flow events. Finally, additional research on the geotechnical characteristics of sacrificial embankments is needed to ensure they support design traffic loads adequately.

Sacrificial embankments are not a solution for all types of bridge scour but rather provide an effective and innovative tool to help society adapt to climate change in an economically feasible manner, particularly in the northeastern United States where a large increase in magnitude of upper precipitation quantiles may cause pronounced nonstationarity. Sacrificial embankments allow rivers to behave more naturally during extreme storm events, reducing human's impact on our natural systems. With further research and investigation sacrificial embankments could become an important tool for designers and policy makers alike.

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