Managing Network-Level Scour Risks for Iowa Bridges

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16. Abstract

In recent years, risk-based management of infrastructure assets has gained predominance in infrastructure asset management. The Moving Ahead for Progress in the 21st Century Act (MAP–21), in alignment with this, has required state transportation agencies to incorporate risk-based management into their planning for systematic preventative maintenance, replacement, or rehabilitation for their bridge networks. However, states currently vary in what type of methodology they choose or how they define risk. At present, state agencies are challenged at the network level to identify and quantify these risks and therefore to develop procedures to address these risks. There is an immediate need for research on effective methodologies that will allow state transportation agencies to develop a risk-based approach in managing their bridge networks.

For Iowa bridges, scour risk has been the primary risk to manage, due to increasingly frequent and heavier floods in recent years. Based on scour management history and experience in Iowa, three major modifications to the HYRISK software's prediction of scour risk and estimate of scour risk costs for the Iowa DOT bridge network are proposed in this study. First, since there have been limited state-owned bridge failures in Iowa, HYRISK's estimation of bridge failure and user costs was replaced by estimation of the cost of installing scour countermeasures. Second, based on previous studies, soil erodibility was incorporated into HYRISK's foundation type risk adjustment factor, in addition to a newly developed risk adjustment factor accounting for the presence of scour protections at bridges. Finally, HYRISK's flow depth distributions were calibrated by using Iowa-specific flood estimation models that resulted in a decreased probability of failure.

The resulting modified HYRISK was then used to estimate Iowa's annual as well as flood-event-specific cost of scour risk, and this produced arguably more accurate assessment of the Iowa DOT's scour risk protection needs as well as cost in terms of match to current Iowa DOT scour-related expenditures. This project thus demonstrates HYRISK modifications that can enable improvement for both network- and project-level management of scour risk.

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MANAGING NETWORK-LEVEL SCOUR RISKS FOR IOWA BRIDGES

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INTRODUCTION

The erosive action of flowing water can remove sediments around bridge abutments and piers, which leads to the formation of holes called scour holes. If the potential for scour holes is not considered in the design of the footings and piles of a bridge, in some cases scour holes can undermine the footings, reducing the integrity of the bridge and eventually causing structural failure.

Abutment-Related Erosion

Every bridge has two abutments that have downward slopes called “berms.” One of the most common types of scour issues in Iowa is berm erosion, where this slope gets washed away due to shear stress from the flow of water in a waterway. As a result, the abutment piles and foundations will be undermined and, if not treated, can cause bridge instability and even failure. However, the presence of long piles in abutment foundations substantially increases their stability.

Another concern with bridge abutments is the erosion of approach materials. In this case, the water continues washing materials from beneath the approaches, making them vulnerable. The bridge itself might remain stable; however, the approaches will be at risk and, if they fail, the bridge will no longer be usable and must be closed to traffic.

Figure 1 shows an example of abutment scour where approach materials are washed out and there is high risk of approach failure. However, unlike the example in Figure 1, scour holes below approaches are not always visible, which makes them more difficult for inspectors to identify.

U.S. Geological Survey

Figure 1. Abutment scour at a bridge approach

Pier-Related Scour

In addition to abutments, multispan bridges also have piers that are usually more exposed to flowing water. The shear stress resulting from this flow forms a hole around the piers, and the higher the stress, the deeper and wider scour holes are. In order to evaluate a bridge for scour, the expected depth of the scour holes should first be assessed and then the structural stability of the bridge should be evaluated based on that. A rule of thumb from the Iowa DOT is that when the unbraced length of a pier is more than 20 feet or when the exposed length of a pile is more than 50 percent of its total length, the bridge may be vulnerable and should be assessed in more detail.

In general, pier scour is more pronounced when piles are short or with bridges that do not have piles. Fortunately, the Iowa DOT has been designing and implementing relatively long piles since the early 1930s and, therefore, there are few Iowa bridges that do not have deep piles, except the ones that have shallow foundations located on near-ground bedrock. Longer piles can withstand deeper scour holes and therefore there is mostly no need in Iowa for implementing countermeasures to reduce the scour risk at piers. As a result, according to Iowa DOT staff, most of Iowa's bridge scour issues are at abutments or approaches while pier scour is not as critical of a concern.

History of Scour Evaluation in the US

Based on a review of more than 500 bridge failures between 1989 and 2000, scour and flooding account for about 50 percent of all the bridge failures in the United States (Wardhana and Hadipriono 2003). Also, scour is more pronounced during flood events, when the speed and depth of flowing water are at their maximum. For example, the 1993 flood in the upper Mississippi basin caused 23 bridge failures and $15 million of damage. Also, the total damage to

Georgia bridges from Tropical Storm Alberto in 1994 was estimated to be $130 million (Arneson et al. 2012).

Until 1988, bridges were not necessarily designed to withstand the scouring effect of floods. After the failure of the Schoharie Creek Bridge in New York, however, Federal Highway Administration (FHWA) published the Technical Advisory (TA) T5140.20, establishing a national scour evaluation program that provides guidelines and recommendations for assessment of bridge scour risk (FHWA 1988). In 1991, the Technical Advisory T5140.23, "Evaluating Scour at Bridges," superseded the previous TA (FHWA 1991).

To facilitate implementation of the recommendations of T5140.23, in 1991 FHWA also published Hydraulic Engineering Circular No. 18 (HEC-18) containing the required models and equations for estimating scour depth to be used in designing new bridges (Richardson et al. 1991). HEC-18 also provided guidelines for assessing existing bridges for scour vulnerability. Since 1991, FHWA has published four editions of HEC-18 to reflect the advances made in estimating the impact of scour on bridges. Among the major changes across the different versions of HEC-18, increased accuracy in the equations and more conservative design floods are primary. As an example, in the earlier versions of HEC-18, depending on the size and importance of the bridge, the largest design flood was only as large as a 100-year flood event. However, in the fifth edition, the largest design flood is as large as a 200-year flood.

Also, the Moving Ahead for Progress in the 21st Century Act (MAP-21) has mandated that state DOTs develop and utilize a risk-based decision-making framework in their transportation asset management programs (FHWA 2012). Consequently, MAP-21 has been another motivation for developing new scour analysis tools to help DOTs and decision-makers better assess the scour risk for existing bridges.

History of Scour Prevention in Iowa

Bridge failures have catastrophic consequences; therefore, identifying bridges in their network that are more vulnerable is crucial for transportation agencies. In general, scour vulnerability assessment for individual structures has higher accuracy and is less costly compared to network-level assessment. Also, there are many project-level tools and methodologies available to help agency managers have a better understanding of the current condition of their bridges and make more informed decisions. However, there is great need for an accurate, comprehensive tool that can be applied to an entire bridge network without requiring expensive data collection.

LITERATURE REVIEW

Scour risk is a function of the probability of scour failure and its associated cost (Stein et al. 1999). FHWA in 1994 developed a methodology for estimating the relative scour risk of bridges by using the National Bridge Inventory (NBI) database (Elias 1994). To help implement this methodology, in 1999, FHWA had HYRISK coded as a network-level scour analysis tool for prioritizing bridges in a network based on their expected scour risk. For estimating the Probability of Failure (POF), HYRISK uses 6 items from the NBI database:

- Item 26: Functional classification of inventory route
- Item 43: Structure type
- Item 60: Substructure condition rating
- Item 61: Channel and channel protection condition rating
- Item 71: Waterway adequacy
- Item 113: Scour-critical bridges

HYRISK is intended to be used to help decision-makers allocate available budget amounts in a more efficient way. The HYRISK procedure for estimating scour risk consists of two components, the probability of failure and potential cost associated with failure. Details of these two components are summarized in the following sections obtained from the users' manual for the HYRISK software.

Factors Impacting a Bridge's Probability of Failure

Determining a bridge's probability of failure (POF) requires estimating its overtopping frequency as well as the flow discharge and water depth distribution of its waterway.

Overtopping Frequency

The first step toward estimating a bridge's probability of failure is estimating its overtopping frequency. Overtopping occurs when the stream opening at a bridge location is full of water and the water elevation reaches the bridge superstructure. The importance of overtopping is that the probability of scour has a direct relationship with the depth and speed of water and is at its maximum when overtopping occurs.

The definitions of various overtopping frequencies are shown in Table 1 and are obtained from description for NBI item 71.

Table 1. Overtopping frequency ranges

Overtopping Frequency	Return Period	Annual Probability
N (None)	Never	Never
R (Remote)	> 100	0.01
S (Slight)	11 to 100	0.02
O (Occasional)	3 to 10	0.2
F (Frequent)	< 3	0.5

By definition, each overtopping frequency has a range for its return period; however, the HYRISK software models return periods at 100, 50, 5, and 2 years for the remote, slight, occasional, and frequent frequencies, respectively.

Overtopping frequency can be extracted from the NBI database by using NBI item 71, Waterway Adequacy, and item 26, Functional Classification. As shown in Table 2, the higher the functional classification of a road, the less frequent the probability of overtopping is likely to be, since bridges in higher functional classes are generally larger and designed to accommodate more severe flood events compared to the ones in lower functional classes.

Table 2. Overtopping frequency by NBI items 26 and 71*

NBI Item 26: Functional Classification	NBI Item 71: Waterway Adequacy								
	2	3	4	5	6	7	8	9	N
Principals and interstates (1, 11)	O	O	O	O	S	S	S	R	0
Freeways or expressways (12)	F	O	O	O	S	S	S	R	0
Other principal arterials (2, 14)	F	O	O	O	S	S	S	R	0
Major arterials (6, 16)	F	O	O	O	S	S	S	R	0
Major collectors (7, 17)	F	O	O	O	S	S	S	R	0
Minor collectors (8)	F	F	O	O	O	S	S	R	0
Locals (9, 19)	F	F	O	O	O	S	S	R	0

*Overtopping frequencies are none (N), remote (R), slight (S), occasional (O), and frequent (F).

Water surface elevation depends on the intensity of flood events. When a flood occurs that causes the water surface elevation to reach a bridge deck, the overtopped bridge might be closed to traffic for several days. Therefore, assessment of the economic cost of overtopping requires determining the flood intensity necessary to cause bridge overtopping. However, the most severe flood considered in HYRISK is a 100-year flood and on-waterway bridges are usually built high enough to accommodate 100-year or more severe floods. Therefore, due to this limitation of the HYRISK software, bridge overtopping frequency was not assessed in this study. (It should be mentioned that although overtopping frequency can be obtained from the NBI database, it was found that the NBI data are less accurate compared with that of Iowa DOT bridge design documents.)

Flow Discharge

Once the expected frequency of an overtopping flood event has been determined, it is possible to estimate flood discharges as well as other discharges associated with lower water levels. To estimate flood discharges, the HYRISK software utilizes regression equations developed by FHWA that are applicable to any small rural basin in the United States (Fletcher et al. 1977).

HYRISK assumes that the cross section of streams is a triangle and, therefore, the hydraulic radius of the stream is the same as its flow depth. Thus, the following equation, which is based on Manning's equation, can be used for estimating water discharge when the water surface elevation is lower than the stream's full depth.

$$\frac{\mathrm{Q}}{\mathrm{Q_f}} = \left(\frac{\mathrm{D}}{\mathrm{D_f}}\right)^{1.66} \text{ or } \frac{\mathrm{D}}{\mathrm{D_f}} = \left(\frac{\mathrm{Q}}{\mathrm{Q_f}}\right)^{0.6} \quad \textbf{(1)}$$

where *Q* is the flow discharge, *D* is the depth of the water, and *f* represents the condition where the stream is full of water. Using Equation 1 and the expected overtopping frequency, the stream discharge when the water level is lower than the full depth of the waterway can be calculated. As an example, if the overtopping discharge is assumed to be 5000 ft^3/sec, the discharge when the stream is at half of its full depth would be:

$$\frac{\mathrm{D}}{\mathrm{D_f}} = \left(\frac{\mathrm{Q}}{\mathrm{Q_f}}\right)^{0.6} \rightarrow \frac{0.5\mathrm{D_f}}{\mathrm{D_f}} = \left(\frac{\mathrm{Q}}{5000}\right)^{0.6} \rightarrow \mathrm{Q} = 1{,}582\ \frac{\mathrm{ft}^3}{\mathrm{sec}} \quad \textbf{(2)}$$

Discharges for water levels at 25 and 75 percent of the full depth can be similarly calculated.

Water Depth Ratio

The next step in assessing a bridge's probability of failure is determining the associated annual probability of the resulting discharges by using flood estimation models. Once the annual probabilities have been determined, the probability of the water level being at different depth ratios can be calculated. For example, if it is assumed that a bridge has an overtopping frequency of 2 percent (i.e., a “slight” overtopping frequency) and the annual probabilities of the water level being at 25, 50, and 75 percent of the full depth are 78, 45, and 10 percent respectively, the probability of the water level being within each of the depth ratio ranges can be calculated based on equations 3–7:

$$\mathrm{P(Overtopping)} = 0.02 \quad \textbf{(3)}$$

$$\mathrm{P(0.75\ to\ 1.0)} = \mathrm{P(0.75)} - \mathrm{P(Overtopping)} = 0.10 - 0.02 = 0.08 = 8\% \quad \textbf{(4)}$$

$$\mathrm{P(0.50\ to\ 0.75)} = \mathrm{P(0.50)} - \mathrm{P(0.75)} = 0.45 - 0.10 = 0.35 = 35\% \quad \textbf{(5)}$$

$$\mathrm{P(0.25\ to\ 0.50)} = \mathrm{P(0.25)} - \mathrm{P(0.50)} = 0.78 - 0.45 = 0.33 = 33\% \quad \textbf{(6)}$$

$$\mathrm{P(0\ to\ 0.25)} = 1 - \mathrm{P(0.25)} = 1 - 0.78 = 0.22 = 22\% \quad \textbf{(7)}$$

Hence, the water level in that specific stream would have a 22 percent probability of being lower than $0.25D_f$, a 33 percent probability of being between $0.25D_f$ and $0.5D_f$, a 35 percent probability of being between $0.5D_f$ and $0.75D_f$, an 8 percent probability of being between $0.75D_f$ and D_f , and a 2 percent probability of being higher than D_f.

While each bridge has its own flood discharge and unique depth distribution, for easier application HYRISK calculations are based on the average probability for bridges with the same overtopping frequency. Table 3 shows these average depth distributions, and as can be seen, the more frequent overtopping is, the higher the expected water levels are.

Table 3. Depth distributions by overtopping frequency and water depth ratio

Overtopping	**Water Depth Ratio**				
Frequency	**0–0.25**	**0.25–0.50**	**0.50–0.75**	**0.75–1.0**	**>1.0**
Remote	0.12	0.48	0.31	0.08	0.01
Slight	0.12	0.34	0.43	0.09	0.02
Occasional	0.07	0.13	0.25	0.35	0.20
Frequent	0.04	0.08	0.15	0.23	0.50

Once the water depth distribution has been determined, the final probability of failure for a bridge can be calculated by estimating the probability of failure for each range included in the distribution.

HYRISK's Estimation of the Probability of Bridge Failure

HYRISK uses a set of scour failure probabilities that have been developed based on water level ratio and bridge scour criticality (NBI Item 113), as shown in Table 4.

Table 4. Bridge scour failure distribution by NBI item 113 rating and water depth ratio

	Water Depth Ratio				
NBI 113	**0–0.25**	**0.25–0.5**	**0.5–0.75**	**0.75–1**	**> 1**
0	1	1	1	1	1
1	1	1	1	1	1
2	0.25	0.4	0.55	0.7	0.88
3	0.14	0.2	0.3	0.45	0.65
4	0.06	0.1	0.15	0.26	0.41
5	0.002	0.002	0.002	0.03	0.1
6	0.1	0.15	0.225	0.355	0.53
7	0.1	0.15	0.225	0.355	0.53
8	0.002	0.002	0.002	0.01	0.05
9	0.002	0.002	0.002	0.002	0.01
N	0.002	0.002	0.002	0.002	0.002

The last step in determining the final probability of failure (POF) of a bridge due to scour is calculating the product of the failure probability for each depth category (Table 4) and the associated water depth distribution probability (Table 3). Below is an example for calculating the

POF for a bridge rated 4 on NBI item 113 that is expected to have a “slight” overtopping frequency.

$$\mathrm{POF} = (0.06\times0.12) + (0.1\times0.34) + (0.15\times0.43) + (0.26\times0.09) + (0.41\times0.02) = 0.1373 \quad \textbf{(8)}$$

Similarly, POF can be calculated for all NBI item 113 ratings and overtopping frequencies. The results of this calculation are provided in Table 5.

Table 5. Probability of failure by NBI item 113 rating and overtopping frequency

NBI 113	Overtopping Frequency			
Rating	Remote	Slight	Occasional	Frequent
0	1	1	1	1
1	1	1	1	1
2	0.4573	0.4831	0.628	0.7255
3	0.2483	0.2673	0.3983	0.49510
4	0.1266	0.1373	0.2277	0.2977
5	0.00522	0.00648	0.0314	0.05744
6	0.18745	0.2023	0.313	0.3964
7	0.18745	0.2023	0.313	0.3964
8	0.00312	0.00368	0.0144	0.02784
9	0.00208	0.00216	0.0036	0.006
N	0.002	0.002	0.002	0.002

HYRISK’s Risk Adjustment Factors

Based on available information, for some bridges it might be reasonable to reduce their estimated POF. There are two risk adjustment factors used in HYRISK, K_1 and K_2, and the product of these is the final risk adjustment factor.

K_1 is based on bridge type and structural continuity and is obtained from NBI item 43. K_2 accounts for foundation design and type and should be calculated separately for piers and abutments, with the larger value ultimately used. The recommended K_2 values range from 0.2 for bridges built on rock to 1.0 for bridges with unknown foundations. It should be noted that the required information for determining the K_2 risk adjustment factor is not stored in the NBI, so other information sources must be used for this calculation.

HYRISK’s Scour Cost Estimates

The expected cost of scour for bridges, as represented in Equation 3, is the product of the probability of failure (POF), adjustment factor (K), and failure cost.

$$Annual\ Risk\ Cost = POF \times K \times [Rebuild\ Cost + Running\ Cost +\ Time\ Cost] \quad \textbf{(9)}$$

where *Rebuild Cost* is the money required for reconstruction while *Running Cost* and *Time Cost*, respectively, are the costs to bridge users associated with additional vehicle operation and the value of their lost time resulting from bridge failure. HYRISK estimates risk cost on an annual basis; however, it should be noted that its estimates do not represent real costs and should only be used for comparing the relative risk for various bridges.

HYRISK's Limitations

The HYRISK software, in spite of its goal of being comprehensive, has had limitations that have hindered its use by state agencies. Three limitations of HYRISK are addressed in this study.

The first and most important limitation of HYRISK is its overestimation of bridge failures. In 2005, all 356,378 bridges in the US were analyzed via HYRISK, resulting in an estimated 60,511 bridge failures each year—in other words, approximately 1 bridge failure out of every 6 bridges. However, based on interviewing done with 25 states (Stein and Sedmera 2007), the actual number of annual bridge failures due to scour is only about 1 in 5,000 bridges. Therefore, HYRISK's currently estimated POF is not realistic and should be calibrated or modified.

A second limitation of HYRISK is its overestimation of failure costs. Although half of the total bridge failures in the US are due to floods and scour, the damage from scour does not necessarily cause bridge failure. Especially in Iowa, there have been only a very limited number of state-owned bridge failures due to scour in recent years. Therefore, in this study, the cost of scour protection installation for piers and abutments was considered as the outcome of scour damage rather than bridge failure and reconstruction being considered as its consequence.

A final shortcoming of HYRISK has been not incorporating soil erodibility based on the specific soils bridges are built on. The shear strength of the soil supporting a given bridge plays an important role in assessment of the bridge's scour vulnerability. The expected depth of scour holes is less in soils with higher shear strength, such as clays, compared to weaker soils (Arneson et al. 2012). However, HYRISK reduces the POF only for foundations that are built on rock, with no reduction considered for other soil types. Therefore, a risk adjustment factor based on the erodibility of the soil supporting a bridge has been needed to improve HYRISK predictions of the costs associated with scour risk.

Past Improvements to HYRISK: Adding a Soil Erodibility Risk Adjustment Factor

As mentioned above, different soils scour at different rates. Specifically, scour holes form rapidly in loose soils while cohesive soils are more resistant. Therefore, given the same final scour depth for different types of bed materials, the time needed for reaching this maximum scour depth will be greatest for soil with the highest shear resistance (i.e., more serious flood events must occur for such soil to reach a given final scour depth). Therefore, in scour analysis, there should be differentiation between bridges having piers and abutments built on more resistant soil layers compared to ones constructed on looser and more granular materials.

Originally, HYRISK did not consider the soil that a bridge was constructed on as a contributing factor. To address this, the Georgia DOT with the cooperation of the Georgia Institute of Technology, has improved the original HYRISK methodology by incorporating soil properties into it.

Similar to previous studies (e.g., Thoman and Niezgoda 2008), Bones et al. (2017) used data collected from 68 soil samples at various bridge locations to develop five categories for soil erodibility ranging from "Very Erodible" to "Very Resistant." However, determining soil shear strength and erodibility for the abutments and piers of all bridges in a network is extremely expensive and time-consuming. Therefore, Bones et al. (2017) associated their erodibility categories with soil classifications from the Unified Soil Classification System (USCS), since a bridge's soil classification is usually easily accessible in bridge documents and boring logs. This use of USCS soil classification enables adjustment of estimated POF to be more realistic for bridges with more resistant soils. Bones et al. (2017) have therefore modified HYRISK's estimated POF according to their previously defined categories by developing a downward adjustment factor ranging from 0.2 to 1.

METHODOLOGY

The main goal of this study is improving HYRISK scour risk predictions by addressing some of the shortcomings of this software and also applying required modifications based on Iowa DOT experiences and policies regarding bridge scour management.

Figure 2 shows the general procedure of the original HYRISK for estimating scour risk as it was elaborated earlier. Because, in general, HYRISK overestimates both the probability and consequences of failure, this study proposes modifications based on identified limitations and available Iowa DOT resources, in order to increase the accuracy and applicability of the original HYRISK methodology. The green boxes in Figure 2 represent the steps that were modified in this study and the red box is recommended to be completely excluded.

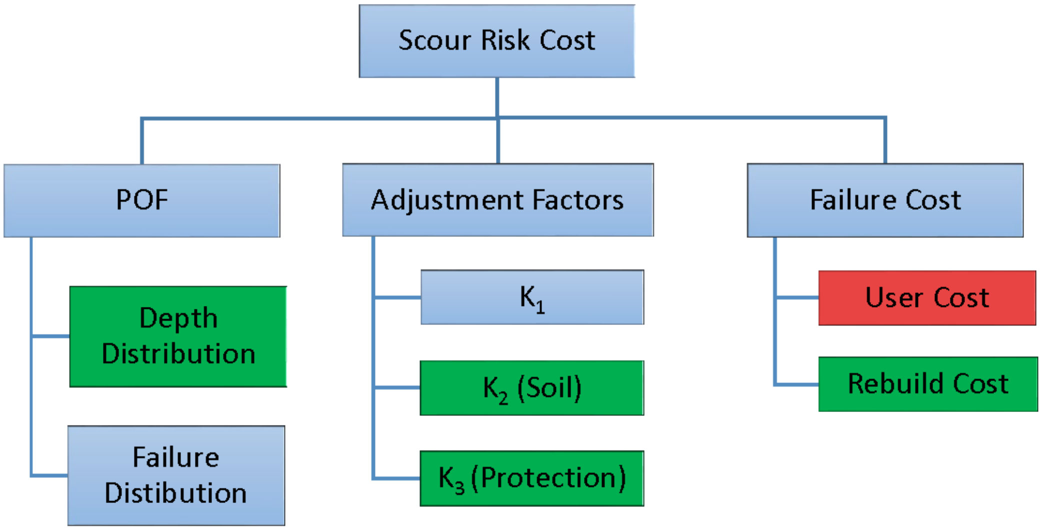

Figure 2. Original vs. modified HYRISK procedure for estimating scour risk

These proposed modifications to HYRISK are as follows:

- Calibrate HYRISK’s water depth distribution for Iowa
- Modify HYRISK’s risk adjustment factors to account for soil erodibility and scour countermeasures
- Modify HYRISK’s failure cost estimates to reflect the cost of scour countermeasures vs. bridge reconstruction

The shortcomings of HYRISK are discussed in the following section in relation to each proposed modification, along with any relevant data collection procedures.

Calibrating HYRISK's Water Depth Distribution for Iowa

The original depth distributions of HYRISK were developed using 1977 flood estimation equations that were applied to all bridges in the US. Today, custom equations, enabled by advanced technology and improved flood estimation tools, can be developed and used, leading to enhanced accuracy.

The latest flood estimation equations for Iowa were obtained from a U.S. Geological Survey (USGS) report also used by the Iowa DOT for bridge design (Eash et al., 2013). For flood estimation, an online tool developed by the USGS named StreamStats was used that calculates basin characteristics and flood discharges for any user-specified point along streams. Eight flood events with return periods of 2, 5, 10, 25, 50, 100, 200, and 500 years respectively were calculated by StreamStats for each Iowa bridge. In addition, to further calibrate these water depth distributions, the overtopping frequency from Table 2 was used to estimate the return period of other flood events associated with lower water levels. Specifically, estimates of the probability of the water depth being less than 25, 50, and 75 percent of the full depth of the streams was estimated by using Equation 1 along with flood events data available from StreamStats. Linear interpolation was done between the two most relevant available flood discharges.

Water depth distributions are unique for each bridge, since bridges have different basin characteristics and, therefore different estimated flood discharges. However, to summarize the results of the above calculations, the average of all depth distributions for Iowa bridges is provided in Table 6.

Table 6. Iowa-calibrated depth distribution by overtopping frequency and average water depth ratio

Overtopping	**Average Water Depth Ratio**				
Frequency	**0–0.25**	**0.25–0.5**	**0.5–0.75**	**0.75–1**	**> 1**
Remote	0.35	0.39	0.21	0.05	0.01
Slight	0.34	0.37	0.21	0.06	0.02
Occasional	0.18	0.23	0.24	0.15	0.20
Frequent	0.09	0.15	0.14	0.12	0.50

By comparing Table 6 with Table 3, it will be noticed that the original expected depth distribution values are higher than the calibrated ones. Originally, the categories of 0.25–0.5 and 0.5–0.75 had the highest probable depth distribution values. However, after the calibration, the peak shifted to the 0–0.25 and 0.25–0.5 categories.

It can be seen from Table 4 that higher depths are associated with higher probabilities of failure (POF). Therefore, the calibrated values result in a smaller estimated POF and the reduction in POF for bridges with higher values on NBI item 113 is less pronounced. Table 7 shows this reduction in POF based on NBI Item 113 and overtopping frequency after the depth distribution used in this study was calibrated for Iowa in particular.

Table 7. Probability of failure using an Iowa-calibrated water depth distribution

	Overtopping Frequency			
NBI 113	**Remote**	**Slight**	**Occasional**	**Frequent**
0	0	0	0	0
1	0	0	0	0
2	0.0434	0.0689	0.0728	0.0426
3	0.0219	0.0388	0.0534	0.0320
4	0.0132	0.0222	0.0342	0.0205
5	0.0003	0.0006	0.0051	0.0032
6	0.0176	0.0305	0.0438	0.0262
7	0.0176	0.0305	0.0438	0.0262
8	0.0001	0.0002	0.0015	0.0009
9	0	0	0	0
N	0	0	0	0

Modifying HYRISK's Risk Adjustment Factors

The original HYRISK included the two risk adjustment factors of structural continuity and foundation type. However, as explained earlier, the type of soil underneath a bridge has a significant effect on the vulnerability of bridges to scour. As a result, a modified version of the foundation type risk adjustment factor was previously developed for the Georgia DOT in order to account for soil erodibility (Garrow et al. 2016). In the current study, it was assumed that the same key properties (i.e., critical shear stress and median grain size) define the vulnerability of soil in Iowa to scour as in Georgia, so the same adjustment factors based on soil classification have been used to reduce HYRISK's calculation of risk.

Unfortunately, neither the NBI nor any other national database has soil characteristics available for every bridge. However, in general, state DOTs maintain databases for storing original design and as-built documents that are the best available sources of soil data. Over the last decades, the organization of design documents and the details they cover have changed and improved. Nevertheless, manual review of bridge documents was the only way of collecting comprehensive soil data. Databases from the Iowa DOT that were used in this study are the Structure Inventory and Inspection Management System (SIIMS) and the Electronic Record Management System (ERMS). SIIMS is used by the Iowa DOT for storage and review of bridge information and contains details about the latest inspection, documents about the last reconstruction and original construction, and details of any major maintenance action done on bridges. ERMS stores documents associated with different projects of the Iowa DOT, including bridge maintenance and construction.

To filter out documents of interest, various bridge identifiers can be used in SIIMS and ERMS. However, one of the easiest ways of finding desired design documents is using a bridge's FHWA number in the SIIMS database. Information about the thickness of different soil layers as well as types of soil and their erodibility classification are generally included in design documents, usually under "Situation Plan" or other sections related to geotechnical design. However, it should be noted that not all the design documents available through SIIMS have soil data and, therefore, for such designs the project number, which can usually be found in design documents, needed to be identified and then used for querying ERMS. Nevertheless, there were bridges for which soil data was not available through either SIIMS or ERMS, so the soil type for these bridges was coded as "Unknown" and a foundation type risk adjustment factor of 1.0 was assigned to them.

A third risk adjustment factor has been introduced in this study to account for the presence of scour countermeasures. When HYRISK was originally developed, bridges rarely included scour protections, so it was not necessary to consider them as a contributing factor for scour risk assessment. However, since the 1990s, many state DOTs have begun to evaluate and retrofit their bridges against scour based on HEC-18 procedures (Richardson et al. 1991).

In order to determine the likelihood of Iowa bridges having specific types of scour damage, the FHWA number (NBI item 8: Structure number) was used to query each bridge in the SIIMS database and the bridge's original design and reconstruction plans were downloaded for review purposes along with any documents related to scour. (If scour protections had already been installed by the Iowa DOT, a document explaining the type, design specifications, and date of implementation of the treatments was available in SIIMS.) Also, if the bridge had been identified as a scour-critical bridge, any Plan of Action (POA) developed was available and downloaded to be reviewed.

Scour-related issues for bridges include abutment-related erosion, pier-related scour, and bridge overtopping. The review of bridge design documents for scour-related information requires one to be familiar with how various soil types at different water depth distributions affect scour outcomes. In the review process for bridge design documents in this study, information about the weakest identified soil layer, as well as the presence and type of scour countermeasures, was collected.

Documents for Iowa bridges built after the 1990s contain the estimated scour depth at piers and abutments. The estimated scour depth defines the depth of soil that should be reviewed for pier-related scour. For abutment-related scour, the limits of the abutment footing or area around the berm should be evaluated in order to find weakest soil layer. As an example, Figure 3 illustrates a three-span bridge for which the bottom of the scour hole is estimated to be at elevation 977 feet.

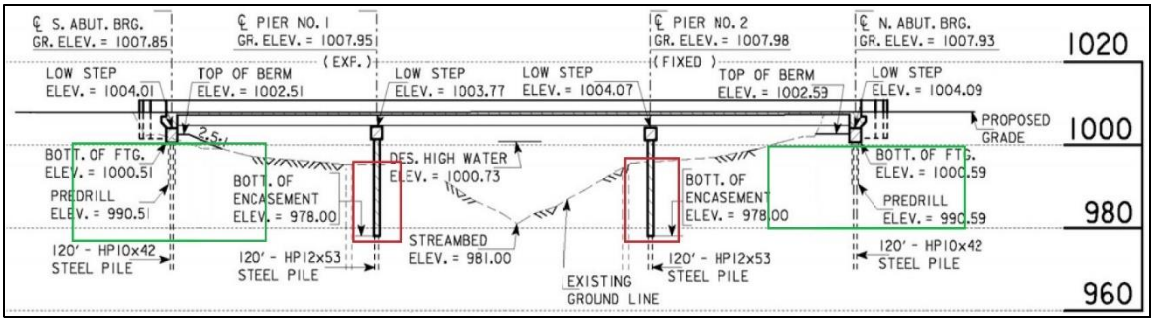

Figure 3. Longitudinal section of a bridge with a known scour depth

Therefore, the red areas including the soil from the surface of the ground down to the estimated scour hole should be evaluated for pier scour. For abutments, the green areas should be evaluated since they are approximately the areas that, if washed away, could cause serious threat to either the bridge itself or its approaches. It can also be seen in this figure that the bridge is not protected by any scour countermeasures around its piers or abutments.

Bridges that were built before 1990 do not have scour depth calculated for them. In these cases, the minimum depth of scour hole required for bridges to be considered scour-critical was estimated using the general rules explained in the pier-related erosion section, namely the longest of either 20 feet of unbraced pile length or exposure of at least 50 percent of the piles.

Figure 4 is an example of a bridge that does not have an estimated scour depth.

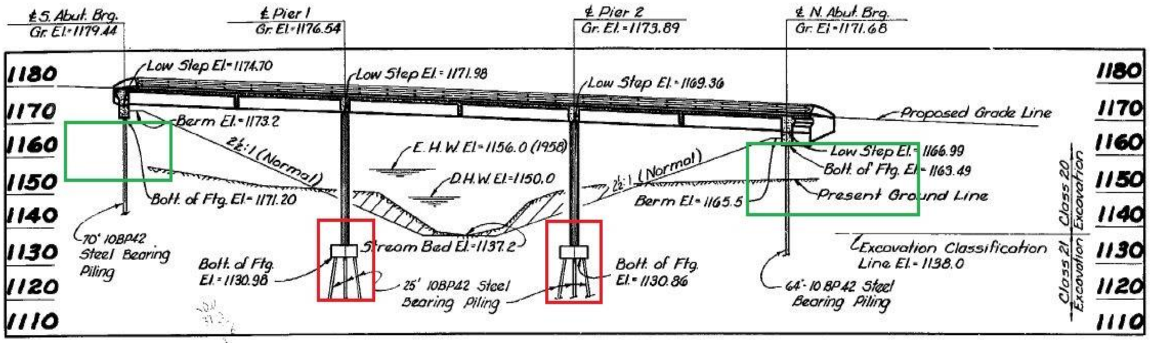

Figure 4. Longitudinal section of a bridge with an unknown scour depth

For the abutments, similarly to the previous example, the green areas near the abutment piers and under the approaches should be evaluated. Also, for the piers, the soil near the pile cap down to 50 percent of the piles should be assessed, which in this case would be around the elevation of 1118 feet.

In this study, once the area of interest was determined, the soil layers were reviewed and, in order to be conservative, the weakest layer was identified and assigned to the bridge. Table 8 was used as a guide for comparing the erodibility of different soil types based on the Unified Soil Classification System (USCS).

Table 8. Soil erodibility risk adjustment factors based on the Unified Soil Classification System

	Soil type	Adjustment factor	Erodibility
Coarse-grained soils (sand and gravel)	SW & SP	1	Very Erodible
	SM & SC	0.8	Erodible
	GW &	0.6	Moderately Resistant
	GP	0.6	Moderately Resistant
	GM &	0.4	Resistant
	GC	0.4	Resistant
	Rock	0.2	Very Resistant
Fine-grained soils (silt and clay)	CL	1	Erodible
	CL-ML	0.8	Erodible
	ML	0.6	Moderately Resistant
	MH	0.4	Resistant
	CH	0.4	Resistant

Source: Adapted from Garrow et al. (2016)

As a demonstration, the weakest soil layer corresponding to the piers of the bridge depicted in Figure 4 is identified. As indicated before, the area that should be evaluated is from the surface of the ground around the piers down to an elevation of 1,118 feet. As can be seen in Figure 5, pier 2 has sand and coarse sand in that vicinity which are the weakest soil types (Table 8), so the corresponding foundation type risk adjustment factor corrected for soil erodibility is 1.0, which means no reduction in scour risk.

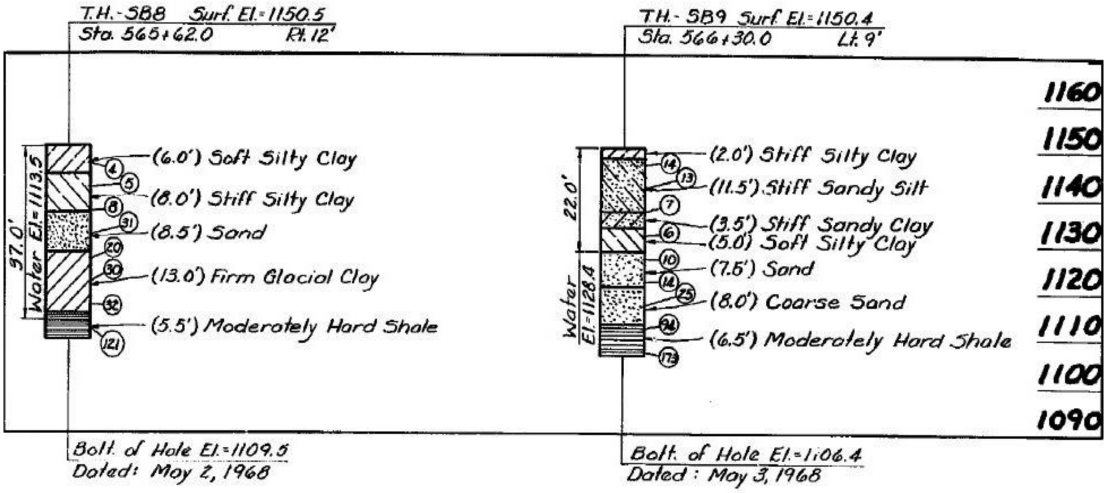

Figure 5. Soil layers beneath the piers of an example bridge

Iowa DOT experience indicates that the presence of scour protections for a bridge significantly improves its stability, leading to their recommendation of a 75 percent decrease in estimated scour risk in the presence of scour countermeasures. On this basis, a new risk adjustment factor of 0.25 has been developed in this study for bridges that have scour protections, with this factor calculated separately for piers and abutments. For application of this proposed risk adjustment factor, the following equation has been developed.

$$Risk\ Cost = POF \times [(CMC_{Pier} \times P_{Pier} \times K_{Pier}) + (CMC_{Abut} \times P_{Abut} \times K_{Abut})] \tag{10}$$

where CMC_{Pier} and CMC_{Abut} are the costs of countermeasure installation for piers and abutments, respectively; P_{Pier} and P_{Abut} are the probabilities of having pier or abutment scour damage, respectively; and K_{Pier} and K_{Abut} are the risk adjustment factors for the presence of pier or abutment protection, respectively.

Modifying HYRISK’s Failure Cost Estimation

HYRISK significantly overestimates the number of expected bridge failures and therefore also the actual costs of bridge failure (as evidenced by the relatively few state-owned bridge failures in the state of Iowa). When a bridge experiences scour, installing suitable scour countermeasures typically is sufficient for reducing its vulnerability. The cost of installing a countermeasure is, of course, much lower than the cost of bridge reconstruction and the associated user cost.

Therefore, considering the history of scour-related countermeasures in Iowa, the only consequence of scour damage considered for this study was the cost of implementing scour countermeasures. Scour protection costs depend on both bridge type and type of scour damage. For single-span and multispan bridges, the Iowa DOT estimates the cost of installing pier protection to be $50,000 and abutment protection to be $70,000 and $150,000, respectively.

RESULTS

The three proposed HYRISK modifications in this study are to calibrate HYRISK's water flow depth distribution, to make use of two new risk adjustment factors, and to modify HYRISK's method of estimating failure costs. This modified HYRISK can be used in two ways to estimate the expected cost of scour risk for Iowa's bridge network. The first recommended application of this study's modified HYRISK is estimating the annual expected cost of scour risk under normal rainfall and stream discharges. The second recommended application is estimating the cost of scour risk for a group of bridges that are affected by a severe flood. Calculation procedures for each of these two applications are described in the next two sections.

Annual Expected Cost of Scour Risk in Iowa

In order to calculate the annual expected cost of scour risk in Iowa, all state-owned bridges were assessed using this study's modified HYRISK approach.

First, all on-waterway bridges under Iowa DOT maintenance responsibility were reviewed and based on their weakest soil type, an adjustment factor was assigned to each bridge. The results of this analysis are summarized in Table 9.

Table 9. Soil types and soil erodibility risk adjustment factors for Iowa bridges

Soil Type	Name	Erodibility	Adjustment factor	# of Bridges	% of Bridges
SW & SP	Sand	Very erodible	1.0	983	52.0
U	Unknown	Very erodible	1.0	135	7.1
CL	Lean clay	Erodible	1.0	84	4.4
CL-ML	Silty clay	Erodible	0.8	322	17.0
SM & SC	Clayey/silty sand	Erodible	0.8	68	3.6
ML	Silt	Moderately resistant	0.6	24	1.3
GW & GP	Gravel	Moderately resistant	0.6	14	0.7
CH	Fat clay	Resistant	0.4	100	5.3
GM & GC	Clayey/silty gravel	Resistant	0.4	0	0
MH	Elastic silt	Resistant	0.4	0	0
R	Rock	Very Resistant	0.2	159	8.4

Because, to be conservative, adjustment factors were based on bridges' weakest soil layers, the majority of Iowa's bridges were coded as having sand or silty clay soil. This means that, on average, the adjustment factor assigned was 0.84, which means the risk estimated by HYRISK was reduced on average by 16 percent.

In addition, more than 600 Iowa bridges were found through the bridge document review process to have at least one kind of scour protection installed by the Iowa DOT. Table 10 summarizes the collected data and shows that pier-related scour damage is less common in Iowa than abutment-related scour damage—undoubtedly due to the fact that the Iowa DOT has been constructing bridges with long piles for several decades.

Table 10. Scour countermeasures installed by the Iowa DOT

	NBI Item 113 Rated as 7			All Bridges		
	Pier Protection	Abutment Protection	Total	Pier Protection	Abutment Protection	Total
# of bridges	92	112	119	320	592	626
% of bridges	77.3%	94.1%	100%	51.1%	94.6%	100%

In contrast, about 95 percent of Iowa's scour-protected bridges have experienced abutment damage.

More elaboration on calculation of the annual expected cost of scour risk for an example bridge with the characteristics indicated in Table 11 is provided as follows.

Table 11. Example bridge values for HYRISK calculation of probability of failure

Bridge Characteristic	Example Bridge Values
Bridge scour criticality (NBI item 113):	3 (unstable foundation)
Functional classification (NBI item 26):	1 (Interstate)
Waterway adequacy (NBI item 71):	8
Structure type (NBI item 43):	multispan, lengths <30m
Soil erodibility adjustment factor:	0.6
Scour protection:	Only abutment protection
Bridge age (from NBI item 27):	20 years

HYRISK calculates a bridge's probability of failure due to scour as described in Equation 11:

$$POF = [Failure\ Distribution] \times [Depth\ Distribution] \tag{11}$$

First, the failure distribution for the example bridge in Table 11 is obtained based on its bridge scour criticality rating of "3" (NBI item 113) as described in Table 4. Next, the bridge's depth distribution is obtained by determining its overtopping frequency based on its functional classification code of "1" (NBI item 26) and waterway adequacy rating of "8" (NBI item 71) as described in Table 2. This yields the overtopping frequency of "Slight," allowing identification of the corresponding calibrated water depth distribution in Table 6. Thus, the example bridge's POF is calculated as in Equation 12:

$$POF = [0.14 \quad 0.20 \quad 0.30 \quad 0.45 \quad 0.65] \times \begin{bmatrix} 0.34 \\ 0.37 \\ 0.21 \\ 0.06 \\ 0.02 \end{bmatrix} = 0.2246 \tag{12}$$

The next step is applying the appropriate risk adjustment factors in light of the example bridge's structural continuity (K_1) and soil erodibility (K_2). Based on HYRISK's recommended values, the example bridge's K_1 factor is 0.8 and K_2 factor is 0.6. Therefore, its adjusted POF is calculated as in Equation 13:

$$POF_{Adj} = POF \times K_1 \times K_2 = 0.2246 \times 0.8 \times 0.6 = 0.1078 \quad \textbf{(13)}$$

The original HYRISK estimated the annual cost of scour risk as in Equation 14:

$$Annual\ Risk\ Cost = POF \times K \times [Rebuild\ Cost + Running\ Cost +\ Time\ Cost] \quad \textbf{(14)}$$

However, as mentioned earlier, this results in a significant overestimate of expected bridge failures and therefore also of the actual costs of bridge failure. In light of Iowa's scour-related countermeasures, the estimate of the annual cost of scour risk was adjusted in this study to reflect countermeasure costs only, as in Equation 10 (repeated here as Equation 15):

$$Annual\ Risk\ Cost = POF \times [(CMC_{Pier} \times P_{Pier} \times K_{Pier}) + (CMC_{Abut} \times P_{Abut} \times K_{Abut})] \quad \textbf{(15)}$$

The values in parentheses are determined as follows. For the first term in parentheses, the Iowa DOT estimates the cost of installing pier protection for multispan bridges as $50,000, and, based on Table 10, the probability of the example bridge having pier damage is 51.1 percent. Given the case that the example bridge has no pier protection installed, no corresponding reduction in risk is applied. Similarly, for the second term in parentheses, the Iowa DOT estimates the cost of installing abutment protection for multispan bridges as $150,000 and, based on Table 10, the probability of the example bridge having abutment damage is 94.6 percent. Given the case that the example bridge has abutment protection installed, the Iowa DOT's recommended 75 percent risk reduction applies, so the risk adjustment factor of 0.25 is used.

Therefore, this study's modified HYRISK calculates the example bridge's annual expected cost of scour risk as in Equation 16:

$$Risk\ Cost = 0.1078 \times [(50{,}000 \times 0.511 \times 1) + (150{,}000 \times 0.946 \times 0.25)] = \$6{,}579 \quad \textbf{(16)}$$

Thus, this study's modified HYRISK was used to calculate the annual expected cost of scour risk for all bridges in Iowa and the Iowa DOT's total annual expected cost was estimated as $1,091,524, as shown in Table 12.

Table 12. Average expected scour risk cost to Iowa DOT bridges by NBI item 113 via the modified HYRISK, original HYRISK, and original HYRISK excluding user cost

Rating for NBI Item 113	# of Bridges	Average of Expected Risk Cost	Total Expected Risk Cost
Modified HYRISK			
3 (Scour-critical bridge)	13	$5,251	$68,268
5 (Scour within limits of foundation)	959	$540	$518,156
6 (Unassessed bridge)	3	$3,107	$9,320
7 (Scour countermeasure installed)	123	$1,566	$192,581
8 (Stable bridge foundation)	771	$328	$252,907
9 (Foundations on dry land)	20	$98	$1,963
Total	1889	$552	**$1,043,195**
Original HYRISK			
3 (Scour-critical bridge)	13	$3,262,011	$42,406,139
5 (Scour within limits of foundation)	959	$902,239	$865,247,006
6 (Unassessed bridge)	3	$4,905,933	$14,717,799
7 (Scour countermeasure installed)	123	$4,742,199	$583,290,509
8 (Stable bridge foundation)	771	$469,254	$361,795,095
9 (Foundations on dry land)	20	$322,855	$6,457,098
Total	1889	$992,014	**$1,873,913,645**
Original HYRISK (User Cost Excluded)			
3 (Scour-critical bridge)	13	$17,553	$228,183
5 (Scour within limits of foundation)	959	$6,784	$6,505,763
6 (Unassessed bridge)	3	$33,112	$99,335
7 (Scour countermeasure installed)	123	$15,131	$1,861,167
8 (Stable bridge foundation)	771	$4,768	$3,675,805
9 (Foundations on dry land)	20	$6,677	$133,547
Total	1889	$6,619	**$12,503,799**

Also, for better comparison of the expected risk cost from both the original and modified HYRISK methodologies in network-level scour management prioritization, a random sample of 30 Iowa DOT bridges was selected and the expected scour risk was calculated for each using both the modified and original HYRISK methods. The bridges were then ranked based on their estimated risk and the rankings for the modified vs. original HYRISK were compared.

As shown in Table 13, the bridges that already have scour protections or are built on stronger soils are located at the bottom of the list according to the modified HYRISK and generally are ranked lower than in the original HYRISK.

Table 13. Bridge rankings from the original vs. modified HYRISK

FHWA #	Erodibility Factor	Abutment Protection	Pier Protection	Modified HYRISK		Original HYRISK	
				Cost	Rank	Cost	Rank
025390	1	0	1	$3,565	1	$2,480,043	3
014480	1	1	0	$1,402	2	$4,823,339	1
604630	1	0	0	$1,096	3	$6,430	28
043840	1	0	0	$787	4	$767,382	8
034791	0.8	0	0	$746	5	$2,040,080	4
025011	1	0	0	$681	6	$546,984	9
039791	1	0	0	$598	7	$262,378	17
606500	1	0	0	$595	8	$2,280	29
018271	1	0	0	$587	9	$2,881,042	2
029101	1	0	0	$576	10	$418,964	12
031240	1	0	0	$569	11	$270,984	16
602320	0.8	0	0	$456	12	$149,213	21
032090	1	0	0	$424	13	$8,823	27
699240	0.4	0	0	$418	14	$2,100	30
031270	1	0	0	$376	15	$180,185	20
604020	0.8	0	0	$257	16	$79,569	26
607795	0.4	0	0	$232	17	$125,066	24
014841	0.8	1	0	$172	18	$453,569	11
609175	0.2	0	1	$153	19	$213,187	18
043231	1	1	1	$124	20	$277,631	15
051141	0.2	0	0	$122	21	$943,327	7
019290	0.2	0	0	$120	22	$190,720	19
052630	0.2	0	0	$119	23	$1,555,049	5
021071	0.2	0	0	$112	24	$1,077,155	6
028070	1	1	1	$108	25	$129,547	23
021310	1	1	1	$99	26	$520,916	10
027081	0.4	1	1	$96	27	$148,518	22
017951	0.8	1	1	$94	28	$352,451	14
019741	1	1	1	$94	29	$359,078	13
050781	0.2	0	0	$74	30	$100,920	25

The significant changes in Table 13's modified vs. original HYRISK rankings primarily result from the original HYRISK considering user cost as a component of failure cost (see Table 12) and not considering either soil erodibility or the presence of scour protections. (As mentioned earlier, this study excluded the user cost component from the total failure cost because, whereas the original HYRISK estimates the cost of bridge reconstruction that necessarily poses a significant cost to bridge users, this study's modified HYRISK estimates the cost of countermeasure installation that does not necessarily require bridge closure, allowing the original HYRISK calculation of user cost to be removed.

It will be noticed that because of the applied modifications, the magnitude of the estimated risks between the modified and original versions of HYRISK are significantly different. The main reasons for this difference are their different methods of calculating failure cost and the exclusion of the user cost in the modified HYRISK. In order to assess the effects of the other changes to the modified HYRISK, the user cost component was excluded from the original HYRISK analysis and the total annual expected cost of scour risk for Iowa bridges was again calculated. It was found that the majority of the difference in total expected risk costs from the two methodologies is due to the cost associated with users in the original HYRISK. However, there is still a significant gap between the estimates of the modified vs. original-HYRISK-without-user-cost that are the result of using this study's new adjustment factors as well as of targeting countermeasure installation rather than bridge reconstruction.

It should be noted that the risk costs provided in Table 12 do not represent real costs and they should only be used for comparison or for identifying groups of at-risk bridges. However, the results from the modified HYRISK are, in fact, closer to actual Iowa DOT expenditures on scour maintenance, which total around one million dollars annually. Also, with the exception of the NBI item 113 bridge scour criticality rating of "5" (due, as seen in Table 4, to the original HYRISK's relatively low estimation of bridge scour failure distribution values for this rating), Table 12 shows that as the value rated for NBI item 113 increases, the average expected scour risk cost estimated by the modified HYRISK decreases. However, this pattern cannot be seen in the original HYRISK results, since these depend on detour length for estimating the user cost and bridge size for estimating the reconstruction cost.

Flood-Event-Specific Cost of Scour Risk in Iowa

A second proposed application of the modified HYRISK is estimation of the cost of damage to the Iowa DOT from a single flood event of interest. Knowing the vulnerability of Iowa's bridges to different flood events can help decision-makers to have a better understanding of the resiliency of Iowa's bridge network. For this application, no restrictions need be made on the intensity of a given flood event and the expected damage from floods with any return period can be assessed. However, as previously mentioned, since HYRISK assumes that a 100-year flood would overtop all bridges, for this application, flood events larger than a 100-year flood would have the same estimated risk cost.

The process of risk cost calculation due to a flood event is very similar to the annual risk cost calculation, the only difference being the water depth distribution values. The annual expected cost of scour risk is based on the probability of the water level being at different depths under normal conditions. However, if a specific flood event is being considered, the associated water level is known, and the water depth distribution should be adjusted accordingly. Therefore, each overtopping frequency value in Table 6 would be zero except that into which the flood water elevation's actual depth category falls.

To determine the appropriate flood water elevation depth category, the Annual Exceedance Probability Discharges (AEPD) for the desired flood should be compared with the values in Table 6. The AEPD is the probability of the occurrence of a flood each year and it is the inverse of the flood's return period.

The resulting updated water depth distributions for a 10-year flood with an AEPD of 1 percent is shown in Table 14 and for a 100-year flood with an AEPD of 10 percent is shown in Table 15.

Table 14. Calibrated depth distribution for a 10-year flood by overtopping frequency and water depth ratio

Overtopping	Water Depth Ratio				
Frequency	**0–0.25**	**0.25–0.5**	**0.5–0.75**	**0.75–1**	**> 1**
Remote	0	0	1	0	0
Slight	0	0	1	0	0
Occasional	0	0	0	0	1
Frequent	0	0	0	0	1

Table 15. Calibrated depth distribution for a 100-year flood by overtopping frequency and water depth ratio

Overtopping	Water Depth Ratio				
Frequency	**0–0.25**	**0.25–0.5**	**0.5–0.75**	**0.75–1**	**> 1**
Remote	0	0	0	0	1
Slight	0	0	0	0	1
Occasional	0	0	0	0	1
Frequent	0	0	0	0	1

By comparing Tables 14 and 15, it will be noticed that both flood events have the same impact on bridges with an overtopping frequency of Occasional and Frequent, since these bridges would be overtopped by both floods. However, for bridges with a Slight or Remote overtopping frequency, the water surface level category for a 10-year flood is lower than for a 100-year flood and, consequently, its expected damage would be less.

Updated depth distributions similar to those in Tables 14 and 15 should be used for each flood event of interest. The other steps of estimating the cost of scour risk using the modified HYRISK are unchanged from how the annual expected cost of scour risk is calculated. However, it should be noted that only bridges affected by the specified flood should be assessed, not necessarily all bridges in the network.

For example, a major flood occurred in the upper Mississippi River basin in 2008 that affected the eastern part of Iowa as well as neighboring states. The Iowa DOT has estimated the damage resulting from this flood to the entirety of the highway network—including roadways, culverts, and bridges—to be around $15 million. As a case study, the modified HYRISK was used to estimate the expected damage from that flood. To accomplish this goal, the flooded area was determined, exported to ArcMap, and a total of 1,261 Iowa bridges were identified as having been flooded. Also, since the flood was severe, the values from Table 15 that are associated with a 100-year flood were used as the relevant depth distribution. This resulted in an estimated total bridge scour risk cost of $10,623,201, which is in line with the actual reported damage.

CONCLUSION

This study has improved scour risk prediction for the Iowa DOT bridge network by modifying FHWA’s network-level scour analysis software, HYRISK.

Based on Iowa’s scour management history and experiences, three major modifications to HYRISK were implemented in this study. First, HYRISK’s flow depth distributions were calibrated using Iowa-specific flood estimation models. Second, based on Garrow et al. (2016), soil erodibility was incorporated for each Iowa bridge into HYRISK’s foundation type risk adjustment factor. A newly developed risk adjustment factor accounting for the presence of scour protections at bridges was also included. Finally, because Iowa’s limited state-owned bridge failures have largely prevented user costs, HYRISK’s original calculation of bridge failure and user costs were adjusted to reflect the cost of installing scour countermeasures only.

The resulting modifications to the HYRISK software were then used to estimate the Iowa DOT bridge network’s annual expected cost of scour risk. Based on NBI data from 2016, this was estimated at $1,043,195, an amount close to the Iowa DOT’s actual annual scour management program expenditures of around $1 million. The modifications to the HYRISK software were also used to estimate the cost of scour risk due to a single flood event. As a case study, bridges that were affected by the 2008 flood in the Upper Mississippi River basin were analyzed. HYRISK’s estimated expected cost of the flood was around $10.6 million, while the actual damage to Iowa’s bridge and roadway networks combined was reported to be $15 million.

Finally, the HYRISK software was not only designed to enable estimation of network-level expected scour risk costs, but also to allow estimation of the number of piers and abutments expected to experience scour damage. Based on the original HYRISK estimations, around 15 Iowa bridges are expected to fail in the upcoming year. The modified HYRISK anticipates the Iowa DOT will need to implement only six abutment protections and five pier protections in the next year. This study’s modified HYRISK is expected to provide the Iowa DOT with a much more accurate estimate of the annual cost of scour risk to Iowa bridges as well as more accurate estimates of the cost of flood-event-specific scour risk.

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