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Resiliency planning: prioritizing the vulnerability of coastal bridges to flooding and scour

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Abstract

Bridge owners are faced with the daunting task of maintaining or replacing aging infrastructure over the next century. Added to this challenge are climate change projections such as rising sea levels. A major concern to bridge owners is the need to strengthen the resiliency of their bridges while utilizing a limited amount of financial resources. This paper will offer a methodology for prioritizing the vulnerability to flooding and scour for a state department of transportation's bridge inventory. Through the use of geographic information system (GIS) software, data is mined from the National Bridge Inventory (NBI) - making this methodology applicable to any state agency in the country. The New York City metropolitan region will be presented as a case study.

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Keywords: resiliency; vulnerability; prioritization; sea level rise; flooding; scour; bridges; geographic information systems; national bridge inventory; finance; policy; risk management; data mining

1. Introduction

According to the American Society of Civil Engineers (ASCE), one in nine bridges are rated as structurally deficient in the United States (ASCE, 2013). The Federal Highway Administration (FHWA) estimates that $20.5 billion will need to be invested annually to address these deficiencies. This is a challenge for federal, state and local bridge owners since only $12.8 billion is currently being spent, leaving a shortfall of $8 billion.

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Now added to this challenge is the reality of climate change projections. The Intergovernmental Panel on Climate Change (IPCC), a leader in collaborative climate change research, issued its fifth assessment report in 2014. Many governments, including New York City, are comparing the IPCC's latest global scale climate projection models to their local scale models in order to make decisions on how to best mitigate and become resilient to climate change impacts. In response, the New York City Panel on Climate Change (NPCC) released their 2015 report, Building the Knowledge Base for Climate Resiliency. This report focuses the need to increase the resiliency of many systems, including infrastructure, around New York City and the larger metropolitan region. It also includes local climate projections through 2100. Key findings include sea level rise projections. Sea level rise in New York City is projected to continue to "exceed the global average" and could possibly "reach as high as 6 feet by 2100" (NPCC, 2015). This alone would increase the frequency of the current 100-year flood by the 2080s. The 100-year flood is defined as a flooding event with a 1% probably of occurrence each year. This is of particular concern to civil engineers as the 100-year flood is used as a benchmark when designing bridges for flooding and scour. Scour is the erosive action of water on soil which may undermine the foundation of a bridge.

The objective of this research was to develop a methodology for prioritizing the vulnerability to flooding and scour for a state department of transportation's bridge inventory. The National Bridge Inventory (NBI) database was the source from which the prioritization criteria were developed. It is the author's hope that this criteria could be used as a decision making tool to assist bridge owners in determining which bridges are likely to be the most vulnerable to climate change projections. These bridges can then be given the highest priority towards a more thorough risk assessment and resiliency planning. By focusing on the highest priority bridges first, funding could be spent more efficiently.

The New York coastal area was chosen as the case study because of the region's sensitivity to changes in sea level (see Fig. 1). The criteria developed using the NBI database was customized for the New York coastal geographic region, and this could be done for any coastal area. The methodology and results of the prioritization criteria are presented and discussed in this paper specifically for the New York coastal area.

Fig. 1. New York coastal region study area.

2. Utilization of available data

In order to encourage bridge owners and decision makers to consider the impacts of climate change projections, it is recommended that existing and readily available data be utilized. This will speed up the prioritization process and reduce cost by not having the need to acquire additional data. The Code of Federal Regulations, Part 650, Subpart C contains the National Bridge Inspection Standards (NBIS) which set the bar for the proper safety inspection of all highway bridges in the United States. The NBIS requires that all routine inspections occur at intervals not to exceed twenty-four (24) months. Each state or federal agency must prepare and maintain an inventory of all bridges subject to the NBIS. Certain Structure Inventory and Appraisal data must be collected and retained by the agency and is collected by the Federal Highway Administration (FHWA). Data is collected using FHWA established procedures as outlined in the "Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges" (FHWA, 1995). Data items considered for the development of the prioritization criteria are shown in Table 1.

Table 1. Sample NBIS data item codes.

NBIS item code	Description
19	Detour length
27	Year built
34	Bridge skew
39	Navigational vertical clearance
44	Structure type
45	Number of spans
48	Length of maximum span
51	Bridge roadway width
61	Channel protection
62	Culverts
71	Waterway adequacy
113	Scour critical rating

3. Application of geographical information systems

The major benefit of the NBIS database is that nearly all of the data are numerical. Most of the data is in the form of a rating system with lower numbers indicating poorer quality and higher numbers indicating good condition or health. This numerical format can be easily queried for specific criteria. In addition, each bridge structure is given a latitude and longitude location. The combination of coding for geographical location and comprehensive numerical rating data are a natural fit for the application of geographical information systems (GIS) software to be used as an efficient tool for prioritization. Results queried from a GIS, as opposed to tabular results, allow the additional benefit viewing the prioritized bridges geographically. If there are clusters of high priority bridges, bridge owners may consider a different strategy for protecting the structures as opposed to an isolated high priority bridge. Additional layers can be overlain in the GIS to view the relationship between high vulnerability bridges and other elements, such as floodplains or evacuation routes. This will enable bridge owners to make better decisions by being able to see multiple elements at once.

4. Criteria selection methodology

The NBIS data were divided into three main categories which directly or indirectly affect the prioritization for hydraulic vulnerability of a bridge. The three main categories in which the criteria categorized are: a) hydrologic & hydraulic, b) structural & geotechnical and c) social importance (Figure 2). The hydrologic and hydraulic factors most directly affect the hydraulic vulnerability of a bridge because these factors have a direct influence on the amount of flooding or scour potential. Structural and geotechnical factors indirectly affect the hydraulic vulnerability because a deficiency in the structure may make it more susceptible to failure by hydraulic forces. Social importance factors are characteristics that stakeholders (bridge owners, tax payers, commuters, residents, etc.) may feel that a bridge should receive special attention to ensure that it remains in service.

4.1. Hydrologic and hydraulic factors

Hydraulic and hydrologic characteristics are those that deal with the mechanical properties of water. The hydraulic factors considered in this research are channel and bridge geometries that effect water pressure, flow and velocity. The number of spans is a good indicator of whether a bridge constricts the flow of the waterway in the immediate area. Multiple, short spans indicate that there are multiple piers in the water. This reduces the cross sectional flow area under the bridge. A reduced cross sectional area increases the flow velocity which, in turn, increases erosion potential (scouring) of the streambed. During a flood event such as the 100-year storm, scouring may occur rapidly and the bridge may be compromised within a short period of time. The NBIS Item 45 records the number of spans for each bridge.

The reduced area also makes the bridge more prone to flooding and overtopping of the roadway. If the roadway is flooded, motorists will not be able to use the bridge. Bridges are currently rated by the NBIS Item 71 for their ability to pass the 100-year storm (or less) under the bridge. Bridges rated 0-2 experience frequent overtopping while bridges rated with a 9 seldom experience flooding. However, this is based on historic or observed flood events, not projected flooding events due to climate change.

Waterway embankment with evidence of slumping, erosion, or local failures are an indication that the channel is vulnerable to failure, particularly during a flood event. Embankments with well-established vegetation or man-made protection such as steel sheeting or riprap are less vulnerable. NBIS Item 61 rates channel condition and protection measured from a poor condition (0-2) to a satisfactory condition (8-9).

Many of the waterways that bridges cross are under navigation control by the United States Coast Guard. These waterways are important because ships, boats, ferries and barges utilize the waterway to transport goods and passengers. If the waterway is blocked or the vertical clearance under the bridge reduced, marine traffic would be affected. The vertical clearance is the minimum distance between the lowest part of a bridge's substructure and the free water surface. The NBIS Item 39 records the vertical clearance in meters. It is expected that vertical clearance will be reduced throughout the study region as sea levels are projected to continue to rise. Bridges with already minimal vertical clearance (e.g. < 3m) would be affected most.

Bridges that have observed or calculated scour conditions are considered to be scour critical. These have the highest vulnerability because scour has occurred or is expected to occur in the future due to a storm event or long-term degradation of the channel.

Bridges with multiple piers in the waterway as well as abutments projecting (thus constricting flow) are important factors when determining hydraulic vulnerability since they tend to constrict flow. NBIS items 48 and 49, length of maximum span and overall structure length, respectively, were considered. NBIS Item 46, number of approach spans, was also seen as an indicator of constriction of flow.

4.2. Structural and geotechnical factors

The type of structure is an important factor. If the main structure of the bridge is continuous, this is more structurally redundant than a simply supported bridge. A redundant structure has alternate paths for the loads to travel which can allow for more time to remove motorists from the bridge. The NBIS Item 43 gives a general classification to the main superstructure of the bridge. Simply supported concrete slabs or steel floor systems are classified from 1 through 7. Truss, arch, suspension, and moveable bridges are classified from 8 through 19.

The year the bridge was built is an indicator of its vulnerability. Bridges built prior to 1940, (NBIS Item 27) particularly along the south shore of the study region tend to be characterized by simply supported spans, short span lengths and piers comprised of multiple, short timber piles. Short span lengths may mean that multiple piers are in the waterway which increases obstruction to flow. The use of timber piles in the early 20th century was common, but the timber piles are often not embedded enough to resist scour or the depth of embedment is unknown. All of these factors make a bridge more vulnerable to failure. In addition, many bridges in the New York City coastal region were built in the early 1900's. Many bridges are likely to be at the end of their service lives and will require extensive reconstruction or complete replacement. The impact of climate change projections should be incorporated into the design.

NBIS Item 67, indicates the overall rating of the superstructure, (deck, roadway, truss members, etc.) and substructure (piers, piles and abutments) of the bridge. Bridges in excellent condition will be expected to perform as designed while bridges in poor condition are more likely to be vulnerable to flooding and scour.

4.3. Social importance factors

The purpose of the social importance criteria - for the purpose of prioritization - is to give an indication of the impact a bridge would have on the population if it were to fail, be taken out of service completely or have a reduced level of service (e.g. less travel lanes available due to repair work). Not all bridges are created equal, so to speak. Roads are categorized as highways (interstate, state and county), streets and roads (NBIS Item 5). Interstate highways are typically hundreds of miles long with multiple lanes while roads can be just a single lane and less than a mile long. As a result, bridges carrying interstate highway traffic are typically of higher importance than a local road.

Another means of identifying the importance of a bridge is the average daily traffic (ADT). The ADT is a record of the average number of vehicles that traverse the bridge each day (NBIS Item 29). Bridges that serve a large number of motorists are likely of greater importance than bridges serving a small number of motorists.

The social importance of a bridge is also reflected in the bypass or detour length a motorist would have to travel should the bridge become out of service. Detour length (NBIS Item 19) is defined as the amount of additional kilometres that a motorist would have to travel in order to reach his or her destination. The greater the detour length, the greater the travel time and economic cost (e.g. gasoline) the motorist will experience. Since the average commuter in the New York City Region experiences a commute of 30 minutes, a detour of 30 km would essentially double the commute time.

The preservation of a bridge with historical significance (NBIS Item 37) is often important to a community. The historical significance of a bridge may involve a variety of characteristics. The bridge may be a unique example of the history of engineering, architecture or art. The crossing itself might be significant because it is associated with a significant event or circumstance. Within the United States, bridges may be designated as historic by the National Register of Historic Places.

5. Selecting prioritization criteria for the New York coastal region

Using the factors identified the prioritization criteria were developed specifically for the New York coastal region. Bridges within the New York coastal area were initially categorized into high, medium and low priority for the historic climate condition. After a hydraulic and scour analysis was performed, the bridges were re-prioritized for the projected climate condition. The NBIS Items selected for the prioritization process are discussed in the following sections.

5.1. Critical priority

For the purpose of this study, a new category was added called "critical". The need for this prioritization category was identified, after a hydraulic and scour analysis was performed, for bridges that were found to be undermined or compromised for the projected climate condition of sea level rise. A bridge categorized as "critical" is one whose structure, safety or serviceability may be compromised due to an observed or calculated condition. Bridges classified as critical for the historic climate condition are either closed to vehicular traffic or are receiving immediate corrective action, such as reconstruction or countermeasures. Bridges currently closed to traffic have not been included in this study since the future of the structure was unknown. .

5.2. High priority

The rationale for the selection of "high priority" criteria was to identify factors that are the most direct indicators of hydraulic vulnerability. For the New York coastal region, a bridge is considered to be of "high vulnerability" if any of the following conditions exist. If Item 113, Scour Critical Bridges, is rated either a 2 or 3, the bridge has an observed or calculated scour condition. This means that scour has occurred in the area of the bridge and has been documented in inspection reports or an engineering analysis indicates that the bridge foundation would be unstable for calculated scour conditions. Bridges with an Item 61, Channel and Channel Protection, rating of 3 or less have experienced streambed degradation, movement or failure of bank protection. Bridges with these ratings indicate a high vulnerability to scour and potential stability problems. For Waterway Adequacy, NBIS Item 71, bridges with a rating of 3 or less experience occasional to frequent overtopping of the bridge decking during flooding events. Bridges with a vertical clearance (NBIS Item 39) of less than 3m were selected since they may not be able to pass the storm surge with the projected sea level rise of 1.4m by 2080. NBIS items 48 and 49, bridges with a maximum span to overall structure length ratio of 0.25 (25%) were considered high priority. Bridges with more with 10 or more piers in the waterway (NBIS Item 46) were identified as high priority. The selection for the number of piers was based on findings from the hydraulic and scour analysis performed on the case studies.

5.3. High priority

"Medium priority" criteria include indirect indicators of hydraulic vulnerability or other factors that are of importance to bridge owners and stakeholders. If Item 67, Structural Evaluation, is rated 3 or less, the bridge structure is basically intolerable and requires high priority for corrective action. Again, the average commuter in the New York City Region experiences a commute time of 30 minutes, a detour of 30 km would essentially double the commute time. Thus, bridges with a detour length (NBIS Item 19) rating of 30km or more are considered of "medium priority". Bridges with an ADT of 100,000 vehicles per day or more as per NBIS Item 29 were selected due to the impact they would have should they go out of service. A significant number of bridges were built prior to 1940 in the region. For this reason, all bridges built prior to 1910 as per NBIS Item 27 were placed in this group since they are now over 100 years of age and many have design characteristics that are not favourable hydraulically or are not structurally redundant. Lastly, bridges designated as historic or soon to be historic with an NBIS Item 37 rating of 2 or less are considered in this category due to their significance to the community.

5.4. Low priority

"Low priority" bridges are those bridges that do not meet any of the critical, high or medium vulnerability criteria. It is recommended that bridges with low prioritization do not require a full-risk assessment unless engineering judgment warrants it. Figure 2 shows the results of the prioritization criteria as processed and visualized using the GIS software. Each bridge is prioritized and given a color code on the map: red for high, orange for medium and green for low priority.

Fig. 2. Prioritized bridges for the New York costal region.

6. Conclusions

Of the 300+ coastal bridges in the New York City area, it was found that approximately 10% would be categorized as high priority. By identifying the bridges that are likely to be the most vulnerable to sea level rise impacts, there is the potential for bridge owners to save a significant amount of time and resources by avoiding an across-the-board analysis and assessment of their entire bridge inventory. In addition, since the NBI data is standardized, this methodology could be adapted by governments of other coastal regions in the United States.

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