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By

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Abstract

Long-term climate change due to global warming is expected to produce increased frequency of storms and precipitation in the northeastern United States. Consequently, there may be an increase in peak streamflows and thus an increase in the scour of bridge foundations. A case study of possible impacts was performed in eastern Massachusetts for an important highway bridge with two concrete piers on reinforced concrete spread footings. The bridge selected for this study was classified as close to scour critical by Federal Highway Administration(FHWA)/Massachusetts Highway Department(MHD) criteria under present climate conditions. We evaluated the possible effects due to 10 to 30 percent increases in the 100 year flood discharge caused by climate change and then possible footing remediation and bridge replacement strategies. We found that riprap was the most cost effective footing protection method. If the superstructure of the bridge was in poor condition, a single span superstructure was found to be preferred because it was least expensive compared to multiple span alternatives and scour protection was needed only at the abutments.

Introduction

In the future, climate change is expected to occur because of global warming. In the New England region of the United States, extreme values of storm precipitation may increase leading to higher flood discharges and velocities in rivers and channels (New England Regional Assessment Team, 2001). Bridge scour is directly associated with flooding conditions. Scour will start at the rising stage of the stream when the stream velocities approach the critical range and mobilize the streambed material. This process will continue as long as the flooding continues. Scour will reverse as the flood recedes by depositing sediment on the scoured bed. Once, however, the scour depth drops below the

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bottom of the bridge foundation, the foundation will become unstable and unsafe for travel.

The tragedy at Schoharie Creek in April 1987 when ten people died during the catastrophic failure of the bridge on the New York State Thruway during a near-record flood highlighted the national problem of bridge scour. Stream instability, long-term streambed aggradation or degradation, general scour, local scour, and lateral scour cause 60 percent of all U.S. highway bridge failures (Lagasse, 1995). In addition to their human toll, such failures cost millions of dollars each year in direct costs for replacement and restoration as well as in indirect costs related to disruption of transportation facilities.

Here we examine the possible effects of climate change on bridge scour through a bridge case study. First, the relationship between flow and scour depth was determined. Next, we investigated the effects of increased scour depths on the safety of the case study bridge. Finally, after an in-depth scour analysis, possible solutions were suggested to remedy any potential damage due to scour. This work was conducted as part of a senior capstone design project at Tufts University. Details of the analyses are in Bettencourt et al. (2001).

Case Study Description

The bridge chosen for analysis carries Interstate Route 95 (I-95) over the Neponset River in eastern Massachusetts as shown in Figure 1. The criteria for selection of the case study included location of the bridge within metropolitan Boston , an FHWA/MHD scour rating of 4 or higher (acceptable scour), the availability of recent flood and inspection reports, and a bridge that has already been analyzed with the Hydrologic Engineering Center River Analysis System (HEC-RAS, HEC, 2002) hydraulic modeling software. The availability of the HEC-RAS data set resulted in much of the hydrologic and hydraulic data being already collected, allowing more time for the actual scour analysis.

The Neponset River has its headwaters in Foxboro, Massachusetts and flows northeast into Dorchester Bay. In the Canton, Massachusetts area, which is where our bridge is located, the river is characterized by extensive swamplands and extremely sluggish flow. The bridge that we selected is of major importance because the roadway serves as a critical artery for the City of Boston and all of northern New England. Interstate 95 is classified as an Urban Interstate road and the conveyed daily traffic was reported in May 2000 to be 151,000 vehicles per day, 11% of which is estimated to be truck traffic (MHD,2000).

The bridge actually is two different structures. MHD Bridge C02026 carries I-95 northbound traffic, while Bridge C02027 carries I-95 southbound traffic. The existing structures were constructed in 1955. The northbound roadway was expanded in 1964 to make room for an on-ramp, but the expansion is currently not in use.

Each bridge is a three span, simply supported steel stringer bridge with an 8-inch reinforced concrete deck and a bituminous concrete wearing surface. The center spans are 57 feet long, and the two end spans are 35 feet long center to center of bearings. The bridge piers have a 20-degree skew to the roadway. The existing substructure consists of two reinforced concrete stub abutments with U-back wing-walls, and two reinforced concrete bent type piers on reinforced concrete spread footings. The piers are not protected against scour. The abutments are dry at normal flow conditions, and are armored with 2-foot diameter granite block riprap. The spread footings are bearing on medium dense fine to coarse sand, with traces of inorganic silt. The riverbed material consists of a thin layer of sand and gravel overlying a thick layer of medium dense fine to coarse sand, and a deeper layer of clayey silt. The existing riverbed surface is at elevation 33 feet above sea level (see Figure 2). The bottom of the footing is at elevation 26 feet; thus 7 feet deep is the critical scour depth.

An August 1998 inspection report describes the condition of the superstructure as poor to satisfactory. The reinforced cast-in-place concrete deck is in poor condition. A local deck failure on the bridge that occurred in January 2001 produced a three-foot by four-foot hole breaking completely through the deck (Raphael, 2001). There is heavy map cracking with efflorescence and water staining under the entire bridge and many minor to moderate spalls in the deck with some exposed rebar and rust stains. Some of the minor spalls have been covered by gunite. The existing structural steel stringers have up to 40% section loss due to corrosion, including holes in the web, and there is heavy rusting including lamination at several bearings.

The substructure is rated satisfactory with minor deterioration, but the existing bridge piers do not meet current seismic criteria. The bridge foundations were inspected in February 1999 and were determined to be stable for calculated scour conditions.

Methodology

Three types of scour affect bridges: progressive degradation, general scour, and local scour (Meadowcroft, 1993). Progressive degradation is the general removal of sediment from the river bottom by the flow of the river. This sediment removal and resultant lowering of the river bottom is a natural process, but may remove large amounts of sediment over time. Because progressive degradation may be independent of the presence of the bridge, this type of scour is not classified as bridge scour and was not considered here.

General scour, also called contraction scour, is the removal of sediment from the bottom and sides of the river due to an obstruction in the river channel. General scour is caused by an increase in the speed of the water as it moves through a bridge opening that is narrower than the natural river channel. Because flow velocities increase in the constricted reach, erosion in the river channel is increased.

Local scour is the removal of sediment from around bridge piers or abutments. Local scour is due to the complex, turbulent flow patterns which arise at an obstruction. These flow patterns cause scour holes to form adjacent to the structures.

The case study bridge has abutments which are dry for most storm flows and are already protected by riprap. Therefore the scour at the abutments was ignored in the analysis and only scour in the middle of the channel was analyzed.

Velocities, water surface and energy grade line elevations, and Froude Number conditions for the scour analysis under the present climate were taken from the existing HEC-RAS data and analysis done for the bridge (HNTB, 1999). HEC-RAS was re-run with modified discharge and boundary conditions data to determine hydraulic conditions under climate change.

HEC-RAS solves the equations that describe one-dimensional, steady state, non uniform flow in open channels. The data required for HEC-RAS includes the connectivity of the river system, cross section data, reach lengths, Manning's coefficients, energy loss coefficients, stream junction information, flow regime, boundary conditions, and peak discharge. For the climate change analysis, only two variables were modified: the flow and boundary conditions. The present 10, 50, 100 and 500 year discharges were increased by 10, 20, and 30 percent to simulate a climate change with increased precipitation. New boundary conditions corresponding to the new flows were based on a relationship between upstream flows and downstream boundary conditions from an exponential fitting of the relationship between present 10, 50, 100 and 500 year discharges and their downstream boundary conditions. The R-squared of the fit was 0.9948.

The scour calculations also require a value for the D_{50} grain size diameter. Based upon sieve analysis of bottom sediments, a value of 3 millimeters was estimated.

The following procedures from Hydrologic Engineering Center (HEC, 1993) were then used to determine the scour depth for each of the present and climate change discharge conditions. First, it was determined if the river demonstrated "live-bed flow" or "clear-water flow" conditions. Clear–water scour occurs when there is no transport of bed material upstream of the bridgecrossing . Live-bed scour, on the other hand, occurs when there is transport of bed material from the upstream reach into the crossing. This was done using Neill's Equation, given below.

$$Vc := 11.52(y_1)^{\frac{1}{6}}(D_{50})^{\frac{1}{3}}$$

V_c = critical velocity, ft/second
y_1 = depth of upstream flow, ft

D_{50} = median diameter of bed material, ft

When V_c is less than the upstream velocity, live-bed scour occurs. If V_c is greater than this, clear-water scour occurs. After determining whether the scour was live-bed or clear-water, contraction and local scour were calculated using the below equations.

Live-Bed Contraction Scour (Modified version of Laursen from HEC, 1993):

$$y_2 = y_1 \left[\frac{Q_2}{Q_1}\right]^{\frac{6}{7}} \cdot \left(\frac{W_1}{W_2}\right)^{K_1}$$

Y_1 = depth of upstream flow, ft
Y_2 = depth in contracted section, ft
W_1 = top width upstream, ft
W_2 = top width in contracted section (minus piers), ft
Q_1 = upstream flow, cubic feet per second (cfs)
Q_2 = flow in contracted section, cfs
k_1 = exponent from HEC(1993)

y_s = depth of average scour = y_2-y_1

Clear-Water Contraction Scour (Laursen Equation from HEC, 1993):

$$Y_2 := \left(\frac{Q_2^{\,2}}{120\, D_m^{\frac{2}{3}}\, W_2^{\,2}}\right)^{\frac{3}{7}}$$

Y_1 = depth of upstream flow, ft
Y_2 = depth in contracted section, ft.
W_2 = top width in contracted section (minus piers), ft
Q_2 = flow in contracted section, cfs
Dm = effective mean diameter of bed material ($D_m = 1.25D_{50}$), ft
y_s = depth of average scour = y_2-y_1

Local Scour at Piers (CSU equation from HEC, 1993):

$$y_s = y_1 \cdot 2.0 \cdot K_1 \cdot K_2 \cdot K_3 \cdot \left(\frac{a}{y_1}\right)^{0.65} \cdot (Fr_1)^{0.43}$$

y_1 = depth of upstream flow, ft
K_1 = correction factor for pier nose shape, from HEC(1993)
K_2 = correction factor for angle of attack flow, from HEC(1993)
K_3 = correction factor for bed condition, from HEC(1993)
a = pier width, ft
Fr_1 = Froude Number
y_s = depth of average scour= y_2-y_1

Results

Since the 100 year flood discharge is the design value, results are only reported for this discharge in Table 1. Based upon possible errors in measuring grain size and estimating the downstream boundary point elevation, the scour depths in Table 1 may vary by +/- 0.3 feet.

Table 1 shows that the bridge is in danger of becoming scour critical at the present 100-year flood. We calculated a present scour depth of 6.8 ft, which leaves only 0.2 ft. of soil above the base of the footing. This is not viewed as a “stable” structure and thus some type of rehabilitation or reconstruction is necessary. The table also shows that, as expected, the scour depth increased as the flow increased and that a 10 % increase in discharge will result in the critical scour depth of 7 feet or greater. A computed critical scour condition for this bridge would elevate it from an FHWA/MHD scour rating of 5 (stable) to an FHWA/MHD scour rating of 3 (scour critical) rating. Note also that these results must be considered within the context of a possible error of 0.3 ft as mentioned earlier.

Footing Protection

Once the scour analysis was complete the next step was to determine the costs of: 1) just protecting the footings from scour; and 2) total bridge reconstruction with improved scour protection. For footing protection, channel countermeasures and geotechnical rehabilitation techniques were evaluated to protect against scour. The channel countermeasures included riprap systems and modification of channel hydraulics. The geotechnical rehabilitation techniques included steel sheeting and micropiles. Economic analysis indicated that riprap was the most cost effective method for footing protection from scour.

Riprap has some distinct advantages over other scour prevention techniques including availability, economy, ease of installation, and flexibility. Rock riprap in sufficient size and quantity is readily available in eastern Massachusetts. It can be placed easily around a pier during new construction and with reasonable care during low water flows around existing structures. Once installed, riprap provides good scour protection as long as it remains in place. However, because riprap is generally obscured by flowing water, inspection and maintenance may be difficult.

According to the HEC (1993):

$$D_{50}=0.692(KV)^2 / (S_s-1)*(2g)$$

D_{50}= median stone diameter for riprap, ft
K= coefficient for pier shape (1.5 for round-nose pier, 1.7 for rectangular pier)
V= velocity on pier, ft/sec
S_s= specific gravity of riprap (normally taken as 2.65)
g= 32.2 ft^2/sec

Using an upstream velocities corresponding to the 100-year flow and K=1.7 for rectangular piers, the median stone diameter was computed to be 0.259 ft (3.1 inches) for the original flow, 0.263 ft (3.2 inches) for the 10% increased flow, 0.287 ft (3.4 inches) for the 20% increased flow, and 0.307 ft (3.7 inches) for the 30% increased flow.

After designing the riprap size, the following design guidelines were considered (Ruff, 1999):

-*Gradation*. A well-graded mixture of rock sizes should be used instead of one uniform size. The maximum size rock should be no greater than twice the D_{50} size.
-*Quality of stone*. Riprap must be durable so that freeze/thaw cycles do not decompose it in a short time – most igneous stones such as granite have suitable durability.
-*Riprap thickness*. The thickness of riprap layers should be 3 times the maximum stone diameter. The top of the riprap mat should be placed at the same elevation as the streambed. The deeper the riprap is placed into the streambed, the less likely it will be moved. Placing the bottom of the riprap mat on top of the streambed is discouraged.
-*Riprap mat width*. The width of the riprap mat should extend horizontally at least two times the pier width, measured from the pier face.
-*Filter material.* In some conditions, filter material is required between riprap and the underlying soil surface to prevent soil from moving through the riprap – a filter cloth material or a layer of gravel is usually used for the filter.

The total cost for riprap installation at our site came to approximately $12,000 for protection around two piers including stone, mobilization costs, and machinery to place the stone. The riprap at the site would have to be annually monitored and reinstalled as needed during the bridge's lifetime. It would also have to be inspected after each high flow event. If riprap was damaged, repairs would have to be made promptly to prevent a potential bridge failure. If repairs were needed repeatedly at one location, the site should be reevaluated to determine if the original design conditions have changed. Channel obstructions such as trees and sediment bars can change flow patterns and cause erosive forces that may damage riprap

Reconstruction

In addition to the scour problems of our selected bridge, the inspection report described in **Case Study Description** noted many structural problems. Load analysis indicated that the existing superstructure was substandard.

Various superstructure alternatives were considered using the MHD type study. The replacement bridge would have to meet statutory loading requirements of the American Association of State Highway and Transportation Officials. The superstructure alternatives included both three-span and single-span continuous and simply supported designs.

The reconstruction analysis also considered the cost of new foundations to allow the loads to be carried into deeper soil strata in order to avoid present and future scour problems. The deep foundation alternatives included drilled piers and pre-cast concrete and steel cast-in-place piles. Construction problems including site access, river construction issues, demolition of existing foundations, and environmental impacts.

The final reconstruction recommendation is a single span concrete bridge. The analyses showed that the single span alternative had a more expensive superstructure than the three-span alternatives. However, the savings in foundation cost of the single span alternative, regardless of which type of deep foundation was used, produced a more economical overall design. It also had the best protection against scour since the only scour concern would be the abutments, which are already protected.

Conclusion

It was found that even a 10 percent increase in the 100 year peak discharge under climate change could make the case study bridge susceptible to scour failure. If the existing superstructure of the bridge was in satisfactory condition, then riprap would be the most cost effective protection method for the existing footings. If the superstructure of the bridge was in poor condition and total reconstruction must be considered, then a single span superstructure was found to be the least expensive. It would have the added advantage that scour protection would only be needed at the abutments.

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Table 1. Scour Results for 100-Year Flood

100-Year Flood	Scour Depth (ft)
Present	6.8
10%	7.0
20%	7.2
30%	7.5

Figure 1. Bridge Site (from Bettencourt et al., 2001)

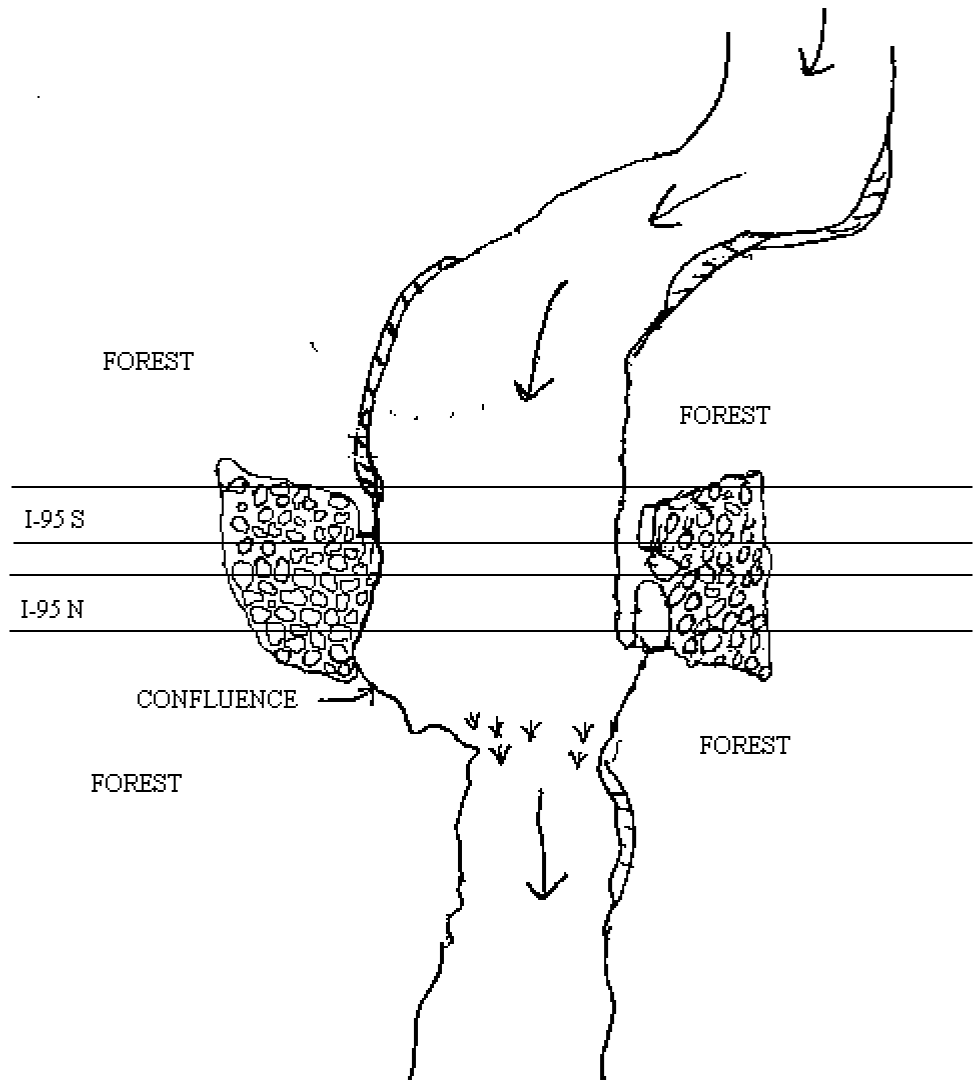

Figure 2. Bridge Footing and Calculated Scour Depths (from Bettencourt et al. 2001)