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Title: Case Studies of Bridge Failure due to Scour and Prevention of Future Failures

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Abstract

For US bridges over water, 70% are NOT designed to withstand scour, 21000 are currently "scour critical", and 80% of bridge failures are due to scour, often during floods and peak flow events which are becoming more common with climate change (Flint et al., 2017). Lin et al. (2013) examined 36 bridge failures due to scour in terms of structural, hydraulic, and geotechnical conditions. Local scour, channel migration scour, and contraction scour were responsible for 78% of failures. Sadly, many lives were lost during these failures.

ALL bridge scour failures are produced by large-scale scouring vortices formed at piers and abutments that bring high velocity water down to the river bed. Since the scouring forces on the bed material vary with the SQUARE of the local velocity, it is clear that the best scour countermeasure is to PREVENT THE SCOURING VORTICES.

The purpose of this paper is to show that scouring-vortex-preventing designs would have

prevented ALL of the bridge scour failures and will prevent future failures at all flow speeds. Designs for various types of piers, footings, abutments, angles of attack, river swirl, and bed conditions have been tested at model scale and some at full scale and show no scouring vortices. Computational fluid dynamic studies show that no scouring vortices are produced. Other advantages of these designs are: much lower present value of all costs, lower river levels and flow blockage, lower possibility for debris and ice buildup, and greater protection of piers and abutments against impact loads.

Introduction

Removal of river bed substrate around bridge pier and abutment footings, also known as scour, presents a significant cost and risk in the maintenance of many bridges throughout the world and is one of the most common causes of highway bridge failures (1). For US bridges over water, 70% are NOT designed to withstand scour, 21000 are currently "scour critical", and 80% of bridge failures are due to scour, often during floods and peak flow events over a short time, which are becoming more common with climate change, as discussed in detail by Flint et al. (2). Lin et al. (3) examined 36 bridge failures due to scour in terms of structural, hydraulic, and geotechnical conditions. Local scour, channel migration scour, and contraction scour were responsible for 78% of failures. Sadly, many lives were lost during these failures.

This has motivated research on the causes of scour at bridge piers and abutments (4) and led bridge engineers to develop numerous scour countermeasures that attempt to reduce the risk of catastrophe. Unfortunately, all previously used scour countermeasures are temporary responses that require many recurring costs and do not prevent the formation of scouring vortices, which is the root cause of the local scour (5,6). Consequently, soil and rocks around the foundations of bridge abutments and piers are loosened and carried away by the flow during floods, which may compromise the integrity of the structure. Even designing bridge piers or abutments with the expectation of some scour is highly uncertain, since a recently released study (5) showed huge uncertainties in scour data from hundreds of experiments.

None of the conservative current bridge pier and abutment footing or foundation designs prevent scouring vortices, which are created when the flow interacts with underwater structures, so the probability of scour during high water or floods is present in all previous designs. Baker et al. (7) point out that designs to avoid catastrophes should be based on extreme events and that there is a need for more physical understanding of flood processes and situations, rather than just using statistics.

Here two well publicized and investigated bridge failures due to scour are discussed: the Schoharie Creek Bridge pier collapse of 1987 and the Loon Mountain abutment collapse of 2011. These failures could have been avoided if scour-vortex-prevention designs had been used.

The nature of scouring vortices is briefly discussed. ALL bridge scour failures are produced by large-scale scouring vortices formed at piers and abutments that bring high velocity water down to the river bed. Since the scouring forces on the bed material vary with the SQUARE of the local velocity, it is clear that the best scour countermeasure is to PREVENT THE SCOURING VORTICES.

After this, applications of the scAUR™ special streamlined fairings and the VorGAUR™ vortex generators that prevent scouring vortices will be discussed for the Schoharie Creek Bridge and Loon Mountain Bridge cases. The costs of these bridge failures and costs for application of the scAUR™ special streamlined fairings and VorGAUR™ vortex generators will be discussed. The conclusions point out that that <u>scouring-vortex-preventing designs</u> would have prevented ALL of the bridge scour failures, will prevent future failures <u>at all flow speeds,</u> have much lower present value of all costs, lower river levels and flow blockage, lower possibility for debris and ice buildup, and greater protection of piers and abutments against impact loads.

<u>Failure of the Schoharie Creek Bridge</u>

The early April rains of 1987 were intense. Streams that were already high from rainfall and snow melt from the previous week rose quickly with the new amounts of water. Streams flooded. Witnesses said the Schoharie Creek, normally just six feet deep and shallow enough to drive a farm tractor through, was more than 10 feet above flood level and about 25 feet deep. According to a 1989 report by the U.S. Geological Survey of the Department of the Interior, the 1987 flood along the Schoharie was the third largest since record tabulation began during the early 1900s; only the floods of October 1955 and March 1980 were bigger. A 60-foot section of the 540-foot-long bridge fell 110 feet into the creek about 10:45 a.m (8).

Using a number of referenced investigations, Lin et al. (3) discussed the Schoharie Creek Bridge collapse of April 5, 1987 that left 10 people dead. This bridge had two spans over the Schoharie Creek near Amsterdam, New York. The bridge suffered severe scour after a spring flood, which caused collapse of Pier 3 and subsequent Spans 3 and 4 (Figures 1, 2, and 3). The 50-year flood event with a velocity of 4.6 m/s was a result of a combination of heavy rainfall and snowmelt, according to the NTSB (9). The high flood rate created an approximately 3 m deep scour hole around Pier 3. The Schoharie Creek Bridge was supported by spread footings with limited embedment into the riverbed. The spread footing under Pier 3 rested on highly erodible soils (i.e. layers of gravel, sand, and silt). Causes of the bridge failure were investigated after the bridge collapse.

It was found that the collapse was attributable to a number of design and maintenance deficiencies, such as insufficient embedment of the spread footing, the erodible bearing soil layer, the use of erodible backfill for the footing excavation, and inadequate riprap protection, inspection, and maintenance. The scour was aggravated by a combination of other factors. For example, the flood velocity was higher than anticipated in the original design; debris accelerated downward scour; berms increased the floodwater under the bridge; and a high hydraulic gradient formed between upstream and downstream in the spring. Failure was also related to insufficient design of the bridge structure for scour conditions. For example, the superstructure bearings allowed for the uplift and slide of the superstructure from the piers; simple spans without any redundancy were utilized; the lightly reinforced concrete piers had limited ductility; and deficient plinth reinforcement resulted in sudden cracking of the plinth instead of a hinging failure.

In a UPI press report (10) on April 2, 1988, the National Transportation Safety Board reviewed a NY State Disaster Preparedness Commission report that blamed erosion by floodwaters that ate away the soil around and beneath the bridge's supports and shallow 'spread' footings of the bridge piers. Unlike supports anchored into bedrock by pilings, the span's footings rested on soil. Further, the report concluded, while the bridge's design drawings called for heavy rock fill -- called 'riprap' -- to be placed around the footings beneath the stream bed, soil was found there instead. And much of the riprap that was put above the streambed had rolled downstream since the bridge was built in 1954, the report found. The NY State Commission of Investigations denounced the NY State Thruway Authority for an 'inadequate bridge inspection program.' The authority was criticized for, among other things, an April 1986 inspection that failed to evaluate the condition of the riprap. One of the inspectors told NTSB investigators that he gave the footings passing grades even though he did not actually look at them. The retired inspector also testified he assumed the footings were secured by piles.

The price of the disaster was about $45 million, including the cost of building the new bridge, rerouting traffic around the remains of the old one, and lost toll revenue. In addition, NY State and the NY State Thruway Authority faced two dozen lawsuits filed by family members of the victims, insurors and others for more than $42 million.

Figure 1. Schoharie Creek Bridge collapse (from Wikipedia https://en.wikipedia.org/wiki/ Schoharie_Creek _Bridge_collapse)

Figure 2. Photograph of a surviving Schoharie Creek bridge pier.

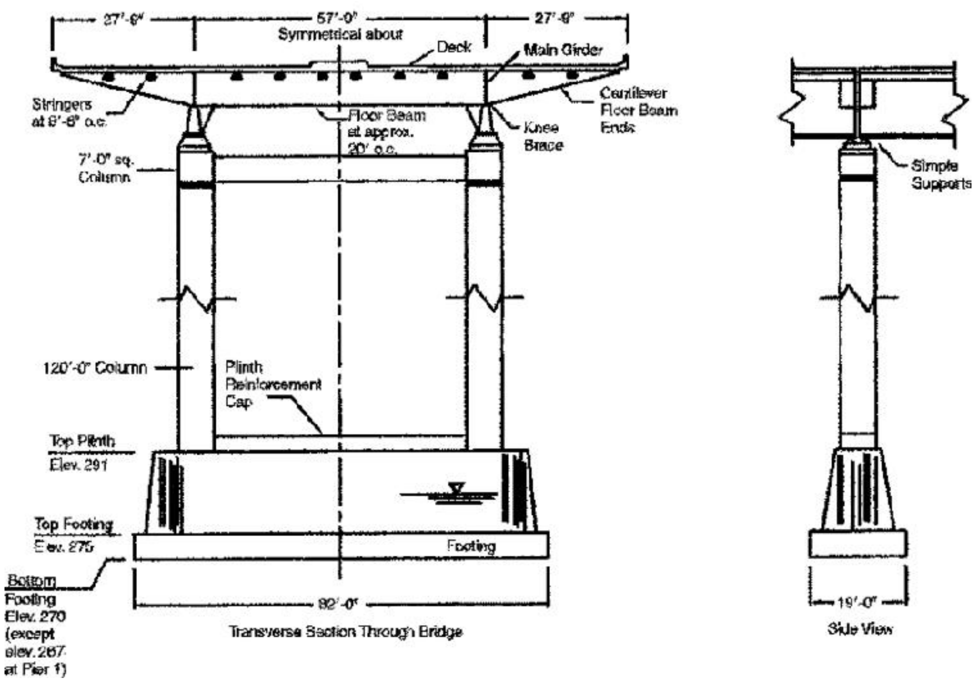

Figure 3. Sections showing the Schoharie Creek Bridge pier supported on a spread footing (From (9), NTSB, 1988).

<u>The Loon Mountain Bridge Abutment Failure</u>

In August 2011 high water due to Tropical Storm Irene washed out an abutment of the Loon Mountain Bridge (Figure 4). This bridge abutment was on the outer bank in a bend in the river, so swirling flow brought high velocity into the outer river bank, causing quick erosion and loss of soil and rock under the concrete part of the abutment. Temporary repairs of the bridge were made, but a new bridge was constructed at a cost of over $9 million (11).

Figure 4. Photo of the failed Loon Mountain Bridge abutment.

The Nature of Scour

The bridge foundations in a water current, such as piers and abutments, change the local hydraulics drastically because of the appearance of large-scale unsteadiness and shedding of coherent vortices, such as horseshoe vortices. Figure 5a is a sketch of the horseshoe vortex formed around the base of a pier by a separating boundary layer. The horseshoe vortex produces high bed shear stress, triggers the onset of rock and soil scour, and forms a scour hole (12). The "strength" of a horseshoe vortex varies with the approach velocity U times the width W of the pier nose or UW (See www.noscour.com.) Note that a wider pier nose exacerbates the scouring velocities on the river bed. The 19 foot wide Schoharie Creek pier nose created intense scouring horseshoe vortices.

The flowfield around an abutment is also highly three-dimensional and involves strong separated vortex flow (13). For the spill-through abutment with no scour protection, the flow is accelerated around the contraction and separated downstream of the contraction leading edge as shown in Figure 5b (12). There is a free surface level difference before and after the contraction leading edge due to the free surface vortex formation. The spill-though abutment has the scour hole at the downstream of the model with the similar order of depth of the vertical square corner wall due to the free surface vortex generated at the leading edge of the contraction.

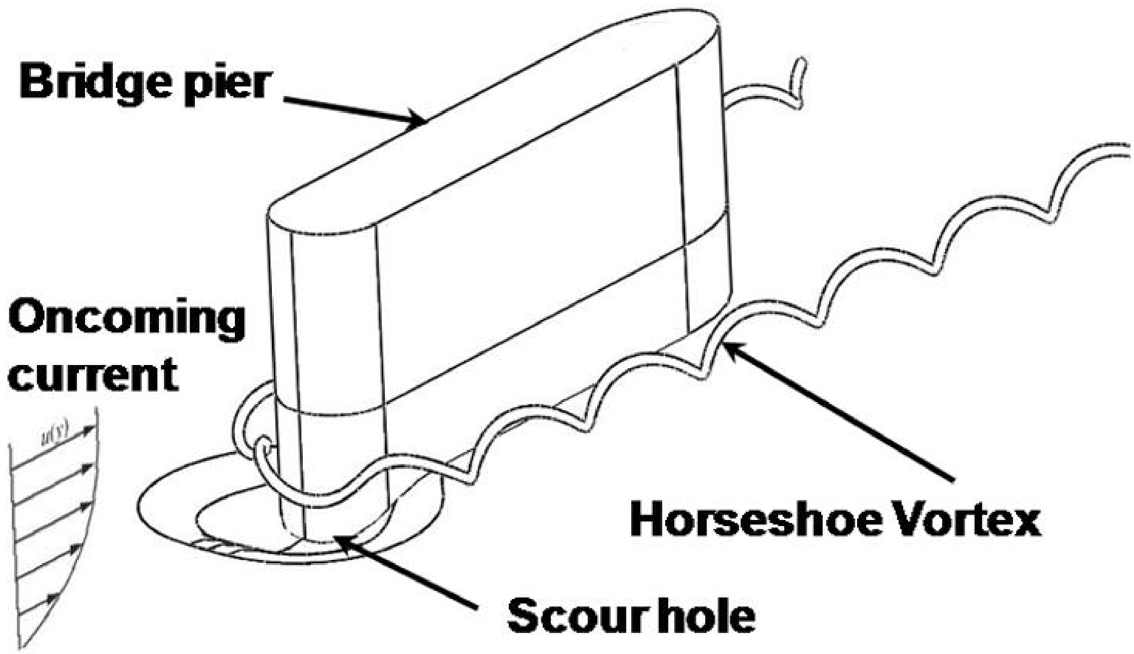

Figure 5a. The formation of a horseshoe vortex around the bottom of a bridge pier with no scouring-vortex prevention.

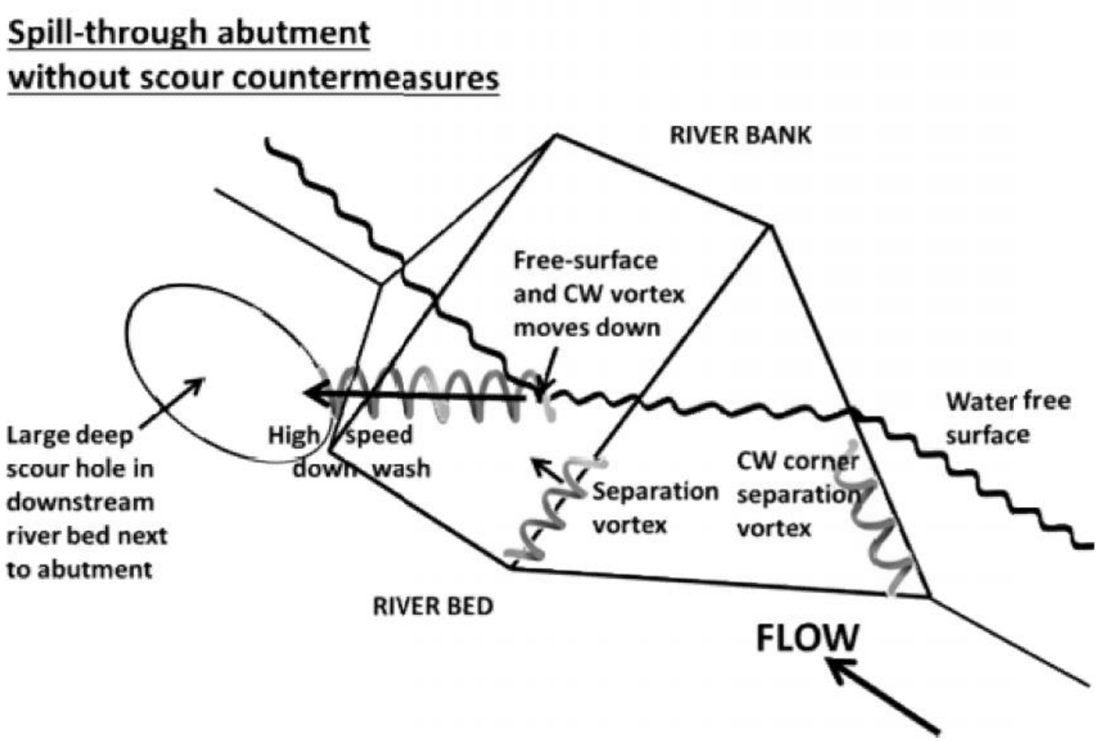

Figure 5b. Flow structure around the spill-through abutment with no scouring vortex protection.

It should be noted that rip rap scour countermeasures are not acceptable design elements for new bridges (1). <u>To avoid liability risk to engineers and bridge owners, new bridges must be over-</u>

designed to withstand 500-year superfloods, assuming that all sediment is removed from the 'scour prism' at that flow rate (1). Unlike temporary scour countermeasures, the streamlined control Against Underwater Rampage fairing scAUR™ (pronounced like 'scour') designs, discussed below and by Simpson and Byun (12), avoid liability risk by preventing or drastically diminishing the scour prism and reducing the cost of new bridge engineering and construction. This greatly reduces the probability of failure, by the tenets of catastrophic risk theory (14). See www.noscour.com for more details.

Features of scAUR™ that Prevent Scouring Vortices

As discussed in more detail by Simpson and Byun (12, 14), using the knowledge of how to prevent the formation of discrete vortices and separation for junction flows (15, 16, 17) prior to the NCHRP-IDEA-162 project, AUR developed, proved using model-scale tests, and patented new local-scouring-vortex-prevention scAUR™ products. The scAUR™ design fundamentally alters the way the river flows around a pier or abutment. The scAUR™ scouring-vortex preventing fairing, US Patent No. 8,348,553, and VorGAUR™ tetrahedral vortex generators, US Patent No. 8,434,723, are practical long-term permanent solutions. Piecewise continuous slope and curvature surface versions from sheet metal have been proven to produce the same result (US Patent no. 9,453,319, Sept. 27, 2016). A hydraulically optimum pier or abutment fairing prevents the formation of highly coherent vortices around the bridge pier (Figure 6) or abutment and reduces 3D separation downstream of the bridge pier or abutment with the help of the VorGAUR™ vortical flow separation control (Figure 6). This is in contrast to a fairing shape used in an unpublished FHWA study which did not prevent scour for flows at angles of attack. Versions for high angle of attack flows use a dog-leg arrangement. A modified tail provides addition scour prevention for piers that are close together.

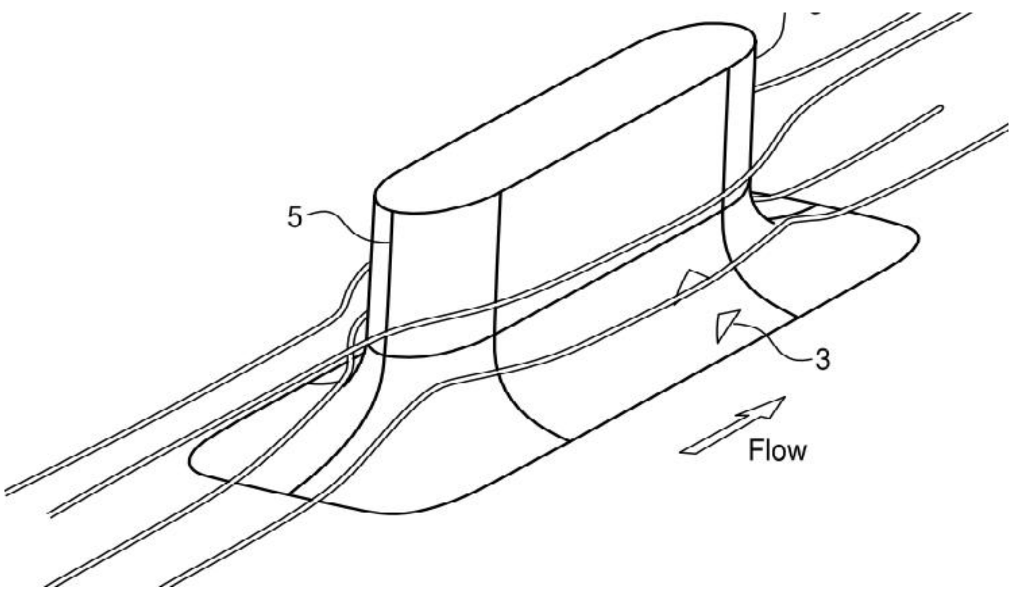

Figure 6. scAUR™ fairing around a pier (5) with VorGAUR™ vortex generators (3) that produce no scouring vortices.

Based on the past published work on scour and the experience of AUR (15, 16, 17), more physical evidence and insights support the idea that these scour vortex preventing devices will work better at full scale than model scale. Scouring forces on river bed materials are produced by pressure gradients and turbulent shearing stresses, which are instantaneously unsteady. At higher Reynolds numbers and sizes, pressure gradients and turbulent fluctuation stresses are lower than at model scale, so scour at the same flow speed is lower. **Work by others** (4,5,18) **supports the conclusion that scour predictive equations, developed largely from laboratory data, overpredict scour on full-scale underwater structures. Thus, the scAUR™ and VorGAUR™ work as well or better in preventing the scouring vortices and any scour at full scale as at the proven model scale.** Other CFD by AUR, which is discussed by Simpson and Byun (12), shows that scAUR™ and VorGAUR™ products also prevent scouring vortices around bridge piers downstream of bending rivers.

<u>Recent NCHRP-IDEA-162 Project by AUR Proves that scAUR™ is Effective</u>

This project focused on providing more evidence that the scAUR™ and VorGAUR™ concepts and products work at full scale in preventing scour-producing vortices and for a wider range of geometries and conditions. Simpson and Byun (12) summarized the results, which were all successful. Task I dealt with selecting a scour-critical bridge in Virginia for prototype installation (14). Further computational work on the effect of pier size or scale (Task II) (Figure 7) and model flume tests for other sediments (Task III), other abutment designs (Task IV.A), and for open bed scour conditions (Task IV.B) were done to expand confidence in these concepts and designs. Constructed full-scale prototypes (Task V) were tested (Task VI). Cost-effective manufacturing and installation of scAUR™ and VorGAUR™ products were further developed (Task VII).

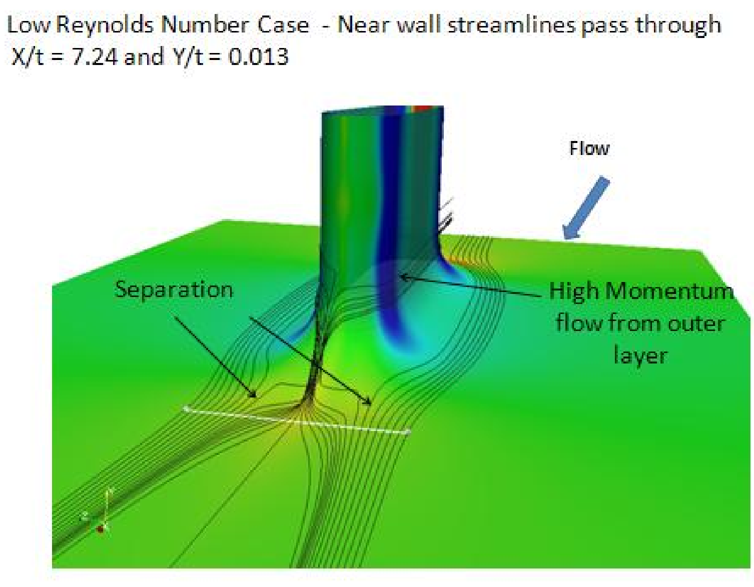

Figure 7. Low Reynolds number case CFD calculated flow streamline patterns around a scAUR™ streamlined bridge pier fairing. Flow indicates no discrete vortex formation on nose and sides (12).

<u>Application of scAUR™ and VorGAUR™ products to the Schoharie Creek Bridge</u>

The basic scAUR™ fairing design for a retrofit to the Schoharie Creek Bridge piers is shown in

Figure 8. The ramp portion and vortex generators (Figure 9) add protection of the exposed sides of the pier by bringing soil and rocks toward the pier. Figure 10 shows example stainless steel construction of the scAUR™. Because the Schoharie Creek Bridge pier is 19 feet wide, a new proprietary transition section has been developed that fits between a 9 foot wide leading edge ramp portion and fairing nose (Figure 9) and the maximum pier width. As discussed below with the Costs, had this design been implemented before 1987, there would have no bridge failure due to scour.

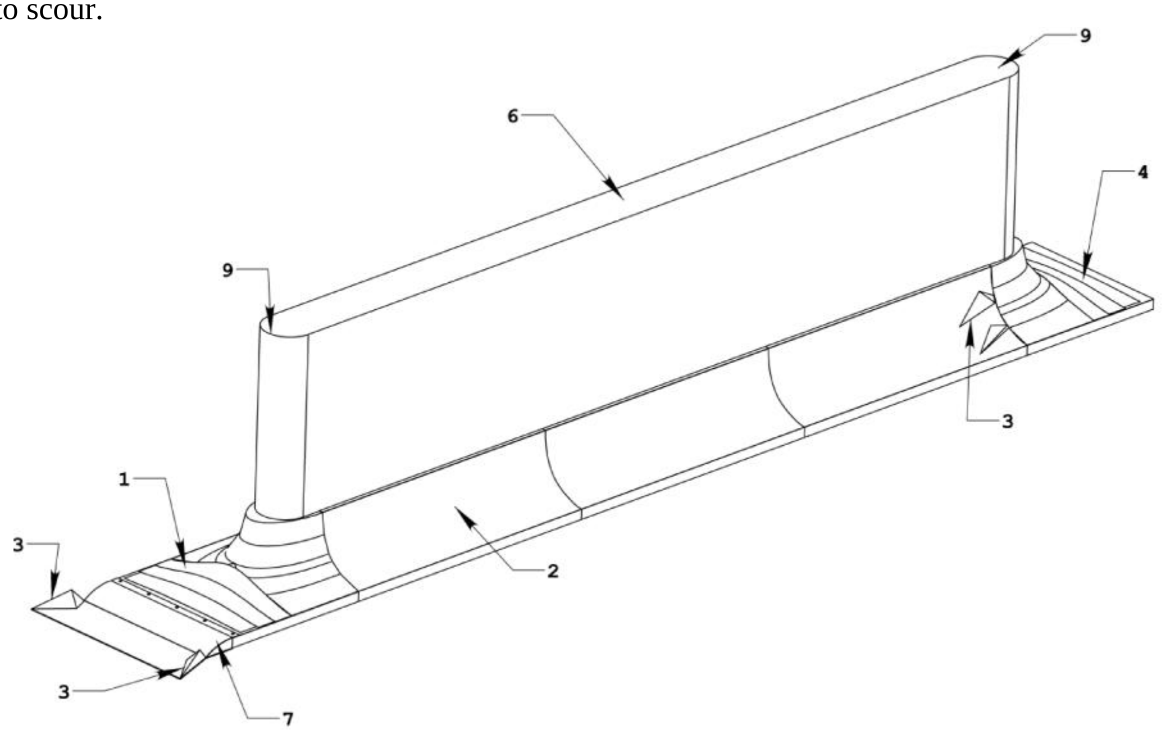

Figure 8. Flow from left to right. Drawing of a full-scale sheet metal scAUR™ retrofit fairing with VorGAUR™ for a pier (6) with piece-wise continuous concave-convex curvature surfaces, with individual sections or pieces of nose surface (1); for the side of the pier (2); and the stern or tail, with individual sections or pieces of surface (4). The leading edge ramp (7) and pier foundation protecting VGs (3) are mounted on leading edge plate and (3) mounted on (1) and (2) protect the foundation from open-bed scour.

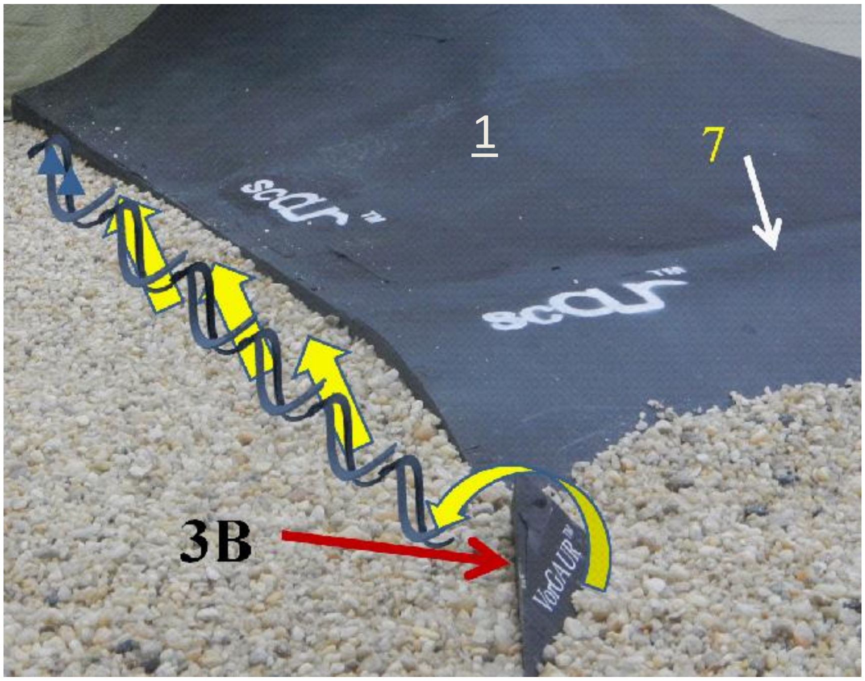

Figure 9. Illustration of a VorGAUR^{TM} vortex generator at left upstream ramp (7) corner that creates a CCW vortex that brings open-bed scour gravel toward the foundation.

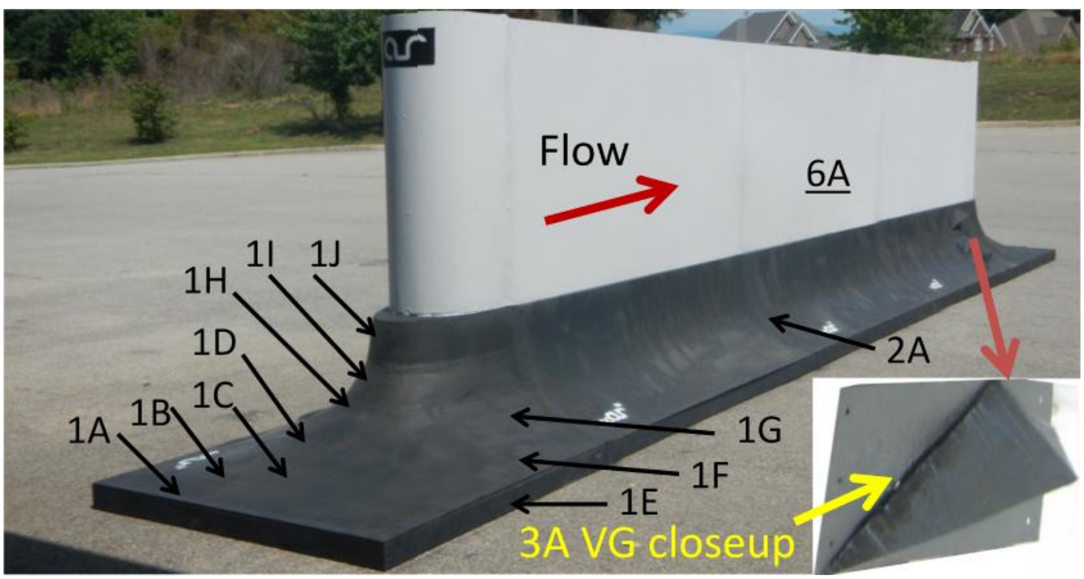

Figure 10. Example stainless steel scAUR^{TM} retrofit (black) for a pier. VorGAUR^{TM} vortex generators create CW vortices that bring low-speed flow up to prevent scour.

<u>Application of scAUR^{TM} and VorGAUR^{TM} products to the Loon Mountain Abutment Collapse</u>

Figure 11 shows a scAUR^{TM} with VorGAUR^{TM} design for a spill-through abutment that prevents all of the scouring vortices shown in Figure 5b. Figure 12 shows a scAUR™ with VorGAUR™ design for a wing-wall abutment. Had either of these designs been used with the original construction of the Loon Mountain Bridge, the abutment would not have failed. Even after the 2011 collapse of the abutment, these designs and protective bank technologies could have been used to repair the bridge and prevent bank erosion, rather than incur the cost of a new bridge.

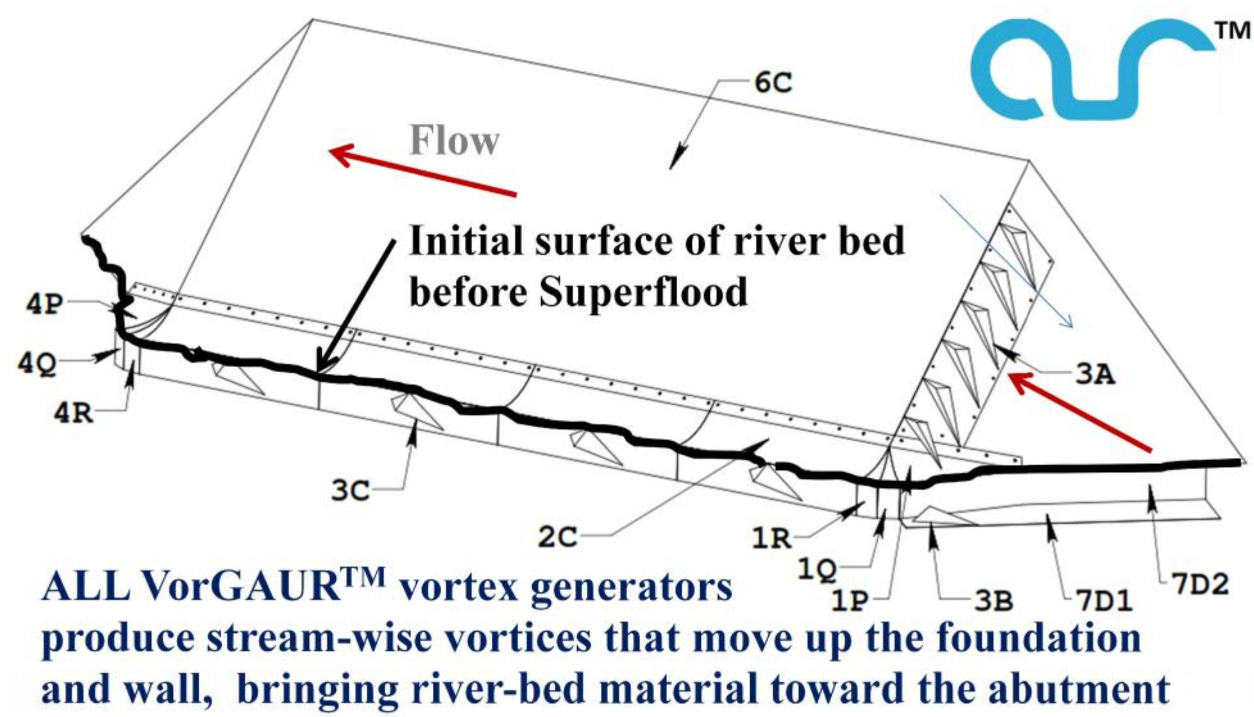

Figure 11. Drawing of full-scale sheet metal scAUR™ retrofit fairing with VorGAUR™ for a spill-through abutment (6C) with piece-wise continuous concave-convex curvature surfaces consisting of individual sections or pieces of surface (1P), (1Q), (1R), (2C), (4P), (4Q), and (4R) within definable tolerances that produce the same effects as continuous concave-convex-curvature surfaces. Vortex generators (3A) reduce the flow separation and free-surface vortex effects while VG (3B) mounted on leading edge horizontal plate (7D1) connected to vertical plate (7D2) and VG (3C) protect the foundation from open-bed scour. Patent drawing (US Patent 9453319).

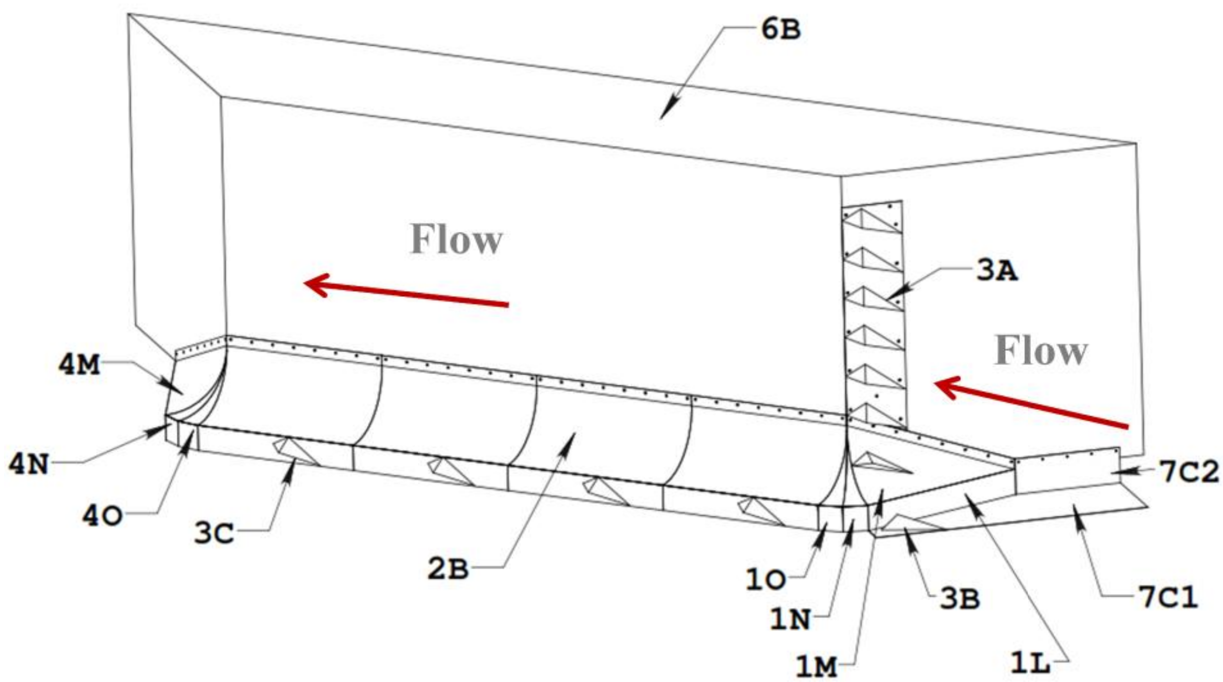

Figure 12. Drawing of full-scale sheet metal scAUR™ retrofit fairing with VorGAUR™ for a wing-wall abutment (6B) with piece-wise continuous concave-convex curvature surfaces consisting of individual sections or pieces of surface (1L), (1M), (1N), (1O), (2B), (4M), (4N), and (4O) within definable tolerances that produce the same effects as continuous concave-convex-curvature surfaces. Vortex generators (3A) reduce the flow separation and free-surface vortex effects while VG (3B) on leading edge horizontal plate (7C1) that is connected to vertical plate (7C2) and VG (3C) protect the foundation from open-bed scour. Patent drawing (US Patent 9453319).

Cost of the Bridge Failures and Cost-effective Manufacturing and Installation of scAUR™ and VorGAUR™ Products

Before the AUR NCHRP project, AUR performed a cost-benefit analysis of scAUR™ with VorGAUR™ as compared to current scour countermeasures *(14).* Published information shows that current expenses are required for scour monitoring, evaluation, and anti-scour mitigation design and construction, usually with rip-rap. For a bridge closed due to scour, the cost to motorists due to traffic detours is estimated to be as great as all other costs combined, but were not included in the analysis *(14).*

There is no situation where scAUR™ and VorGAUR™ products cost more than current countermeasures, as shown in Figure 13 for stainless steel retrofits. There is no situation where any type of scour is worse with the use of the scAUR™ and VorGAUR™ products than without them. The more frequent that scouring floods occur, the more cost effective are scAUR™ and VorGAUR™. Clearly, scAUR™ and VorGAUR™ products are practical and cost-effective for US highway bridges (14).

In order to further reduce costs and increase the versatility of the scAUR™ and VorGAUR™

products, multiple manufacturing alternatives were considered. The required labor, materials, time, logistics, and practical issues were examined and used to evaluate manufacturing alternatives (14). Since the NCHRP-IDEA-162 project, detailed full-scale cost-effective versions have been developed for installation. An installed welded stainless steel (SS) scAUR™ retrofit bridge fairing is cost-effective, being about half of all costs for precast or cast-in-place concrete manufacturing and installation (14). Its corrosion resistance gives it a lifetime of 100 years even in seawater environments, using a proper thickness, construction methods, and type of SS. It is an effective way to reduce weight and the cost associated with casting custom reinforced concrete structures. Another benefit is that the SS VorGAUR™ vortex generators can be welded directly onto the side sections instead of having to be integrated into the rebar cage of the reinforced concrete structure. **Even for bridges with little life left, current temporary countermeasures are much more expensive when the present value of future expenses is considered (14).**

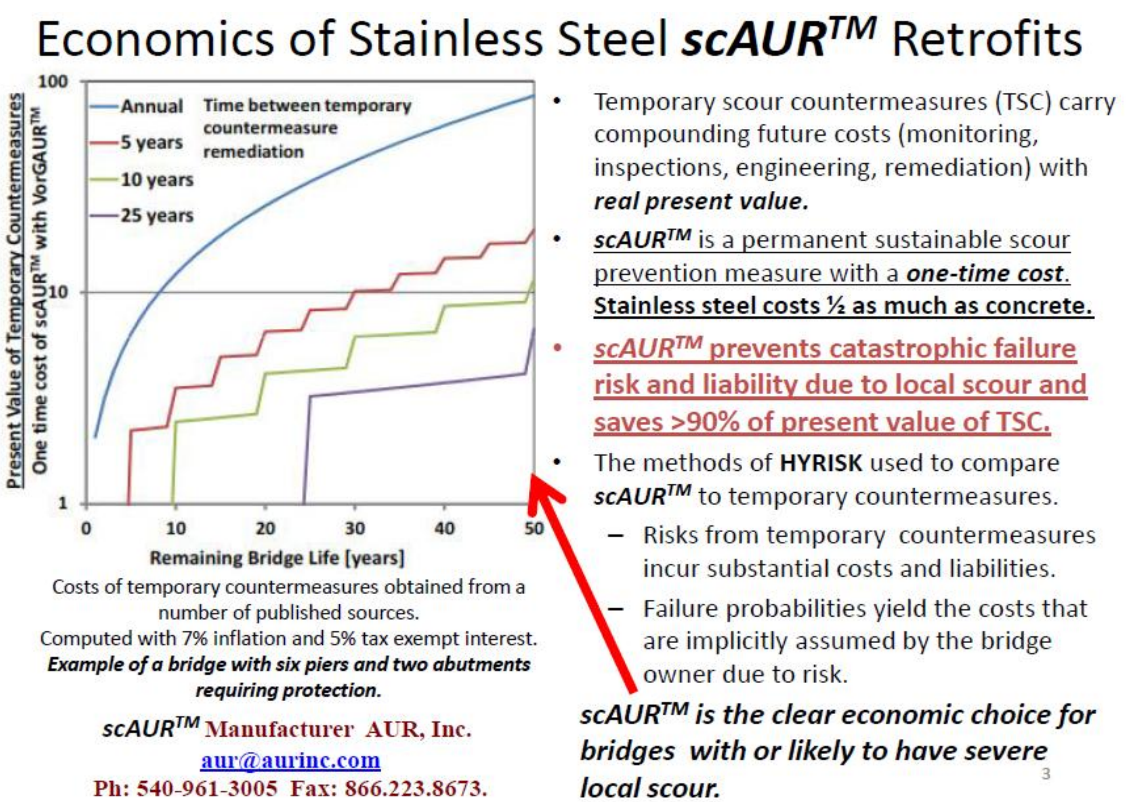

Figure 13. Economics of stainless steel retrofits.

Compared to component fabrication, there are significantly more uncertainties and assumptions for installation cost estimates. Location, accessibility, labor availability, material availability, and water level are all relevant issues that affect the cost. Contractor bids will be the best way of ultimately determining the cost. For new construction, the estimates are done on the basis of added cost. This means the incremental increase in the total cost of the bridge project that can be attributed to scAUR™ since laborers, contractors, and equipment are already involved in new construction. If a cofferdam is required or other site conditions produce extra costs, it affects the project as a whole and not just scAUR™ installation.

For the Schoharie Creek Bridge collapse, the estimated cost of the disaster and for recovery was at least $45M, as mentioned above. Of the $42M in civil lawsuits, at least $10M was awarded. For the bridge pier shown in Figure 3, it would cost today about $250K for installation of a stainless steel retrofit scAUR™ with VorGAUR™ for one pier under dry weather conditions. Given about a factor of 2 inflation factor since 1987, this would have been about $125K in 1987. Thus, for about $250K in 1987 or 0.45% of what was eventually spent, both piers could have been protected permanently from scouring vortices for all water flow speeds.

For the Loon Mountain Bridge abutment collapse, about $8M was spent on temporary repairs and a new replacement bridge. For either the spill-through (Figure 11) or wing-wall (Figure 12) abutment, it would have cost about $71K in 2011 to install stainless steel retrofit scAUR™ with VorGAUR™ components PRIOR to the collapse. Thus, for less than 0.9% of what was spent after the abutment collapse, the abutment could have been permanently protected from scouring vortices for all water speeds.

Conclusions

Many bridges over water around the world are susceptible to scour of supporting rocks and soil during peak flow events such as floods. Since scouring forces vary with the velocity-squared and scouring vortices are generated around piers and abutments, it is desirable to prevent these vortices. This is what the scAUR™ with VorGAUR™ designs and components accomplish - prevent the formation of scouring vortices for all flow speeds.

Only 2 cases of bridge failures due to scour have been presented, but many others could have been presented with similar conclusions. In every case, expenditure of a small amount prior to the failure would have saved 100 times or more funds for a recovery. This, of course, does not include the loss of life that may occur by the failure.

Designs for various types of piers, footings, abutments, angles of attack, river swirl, and bed conditions have been tested at model scale and some at full scale and show no scouring vortices (12, 14). Computational fluid dynamic studies show that no scouring vortices are produced. Other advantages of these designs are: much lower present value of all costs, lower river levels and flow blockage, lower possibility for debris and ice buildup, and greater protection of piers and abutments against impact loads.

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