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Designing Scour-Resistant Bridge Structures for Extreme Events

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ABSTRACT

Bridge failures over water are likely due to scour, often during floods and peak flow events which are becoming more common with climate change. All bridge scour failures are produced by large-scale scouring vortices formed at piers and abutments that bring higher velocity water down to erode the river bed. The purpose of this paper is to summarize scouring-vortex-preventing designs that would have prevented bridge scour failures and will prevent future failures at all flow speeds. Tests and computational fluid dynamic (CFD) studies for a large variety of pier and abutment cases show that no scouring vortices are produced. One case of rock scour under a concrete seal is discussed with application of a scAUR^{TM} retrofit design to prevent scouring vortices. Other advantages of these designs are: much lower present value of all current and probable future 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 (Lagasse et al. 2001). 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. (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.

This has motivated research on the causes of scour at bridge piers and abutments (Ettema et al. 2004) 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 (Shepherd et al. 2011; Tian et al. 2010). 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 recent study (Shepherd et al. 2011) 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. (1988) 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 statistical probabilities from past experiments and events. *Preventing scouring vortices is a new approach to preventing scour at all flow speeds*! All previous scour protection methods tolerate scouring vortices and try to reduce their effects; those methods don't always work.

Two well publicized and investigated bridge failures due to scour were discussed by Simpson and Byun (2019): 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 below. *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.

Because of the unique circumstances of each bridge, it is suggested that each bridge be designed for scour prevention, taking into account the upstream flow and geometry, rather than using data correlations with associated uncertainties. One should use peak flow levels estimated from rainfall and runoff data in an analysis to obtain the most severe scouring conditions.

After this, applications of the scAUR™ (streamlined control Against Underwater Rampage) special streamlined fairings that prevent scouring vortices will be discussed for rock scour under concrete seals and hydraulic structures. The costs of bridge failures relative to costs for application of the scAUR™ special streamlined fairings and VorGAUR™ (Vortex Generators Against Underwater Rampage) will be discussed.

The conclusions point out that that proper scouring-vortex-preventing designs would have prevented *all* of the bridge scour failures, will prevent future failures at *all* flow speeds, 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.

THE NATURE OF SCOURING VORTICES

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 1a is a sketch of the horseshoe vortex formed around the base of a pier by a separating boundary layer. The horseshoe vortex brings higher velocity downward toward the river bed, produces high turbulent shear stress on the bed, triggers the onset of rock and soil scour, and forms a scour hole (Simpson and Byun 2017). Like in tornadoes, stretching of the horseshoe vortices due to the contraction of the flow intensifies the velocities in the vortex, thus causing more scour**.** 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 for more details.) 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. Since the scouring forces on the bed material vary with river bed roughness and the **square** of the local velocity, it is clear that the best scour countermeasure is to *prevent the scouring vortices*. One needs to keep the low velocity water on the river bottom.

The flowfield around an abutment is also highly three-dimensional and involves strong separated vortex flow (Barkdoll et al. 2007). For the spill-through abutment with no scour protection, the flow is accelerated around the contraction and separates downstream of the contraction leading edge as shown in Figure 1b (Simpson and Byun 2017). 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 a deep scour hole at the downstream edge of the abutment due to the free surface vortex generated at the leading edge of the contraction. If not prevented, this deep scour hole can progress upstream and undermine the abutment.

It should be noted that riprap rock scour countermeasures are not acceptable design elements for new bridges. To avoid liability risk to engineers and bridge owners, new bridges must be over-designed to withstand 500-year superfloods, assuming that all sediment is removed from the 'scour prism' at that flowrate (Lagasse et al. 2001). Unlike temporary scour countermeasures, the scAUR™ (pronounced like 'scour') fairing designs, discussed below and by Simpson and Byun (2017), 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 (Simpson 2013). See www.noscour.com for details.

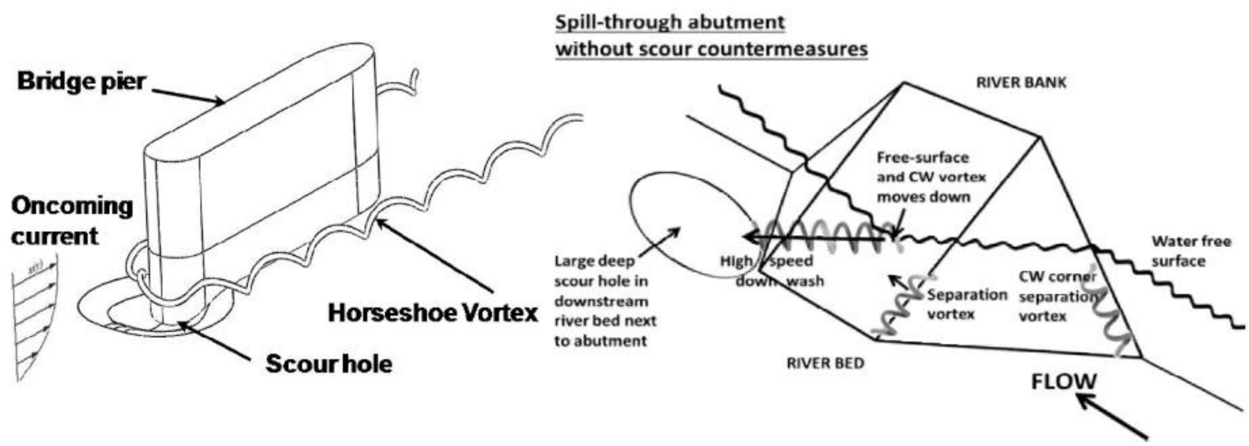


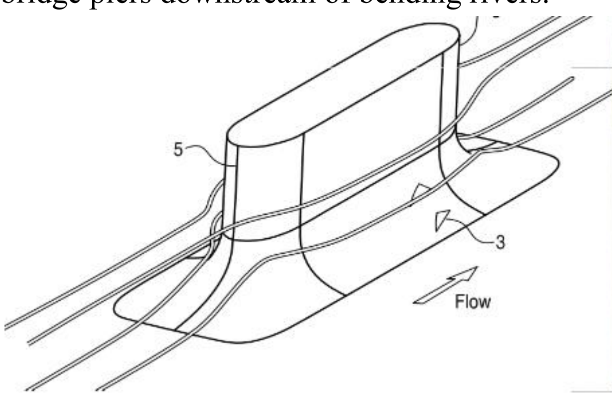
Figure 1. (a, left) The formation of a horseshoe vortex around the bottom of a bridge pier with no scouring-vortex prevention. (b, right) Flow structure around the spill-through abutment with no scouring vortex protection.

FEATURES OF SCAUR™ THAT PREVENT SCOURING VORTICES

As discussed in more detail by Simpson (2013) and Simpson and Byun (2017), using the knowledge of how to prevent the formation of discrete vortices and separation for junction flows (Simpson 1989, 1996, 2001) prior to the NCHRP-IDEA-162 project, AUR developed, proved using model-scale tests, and patented new local-scouring-vortex-prevention scAUR™ designs. As described in these patents, a key streamlined fairing design requirement is that the surface shape produces surface pressure gradients that limit the flux of new vorticity at the surface so discrete vortices are not formed. It is possible to select a surface shape that meet this requirement for all water speeds. No one before has used this design feature, thus leading to the patents.

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 2) or abutment and reduces 3D separation downstream of the bridge pier or abutment with the help of the VorGAUR™ vortical flow separation control (Figure 2). This is in contrast to a fairing shape used in an unpublished FHWA study which did not prevent discrete vortex formation or scour for flows at angles of attack. Versions of scAUR™ for high-angle-of-attack flows use a dog-leg arrangement. A modified tail provides additional scour prevention for piers that are close together. Bridge owners receiving US federal funds are no longer prohibited from using patented or proprietary products in designs (FHWA 2019).

Based on the past published work on scour and the experience of AUR (Simpson 1989, 1996, 2001), more physical evidence and insights support the idea that these scour vortex preventing devices 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 (Ettema 2004; Shepherd et al. 2004, 2011) support the conclusion that scour predictive equations, developed largely from laboratory data, over predict 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 computational fluid dynamics (CFD) studies by AUR, which is discussed by Simpson and Byun (2017), show that scAUR™ and VorGAUR™ designs also prevent scouring vortices around bridge piers downstream of bending rivers.



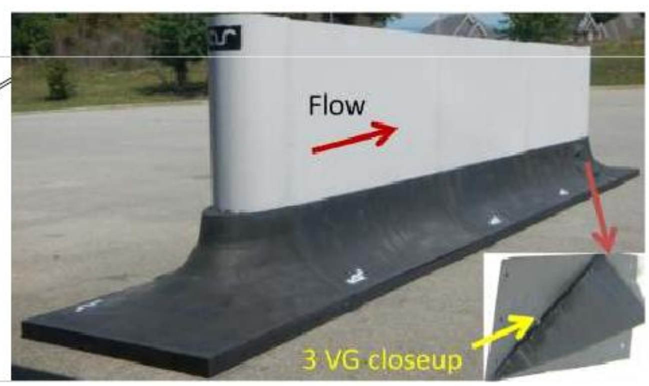


Figure 2. (left) scAUR™ fairing around a pier (5) with VorGAUR™ vortex generators (3) that produce no scouring vortices. (right) Example stainless steel scAUR™ retrofit (black) for a pier. VorGAUR™ vortex generators create vortices that bring low-speed flow up to prevent scour at the pier downstream end.

RECENT NCHRP-IDEA-162 PROJECT BY AUR PROVES THAT scAUR™ IS EFFECTIVE

This project focused on providing more evidence that the scAUR™ and VorGAUR™ concepts and designs work at full scale in preventing scour-producing vortices and for a wider range of geometries and conditions. Simpson and Byun (2017) summarized the results, which were all successful. Task I dealt with selecting a scour-critical bridge in Virginia for prototype installation (Simpson 2013). Further CFD work on the effect of pier size or scale (Task II) (Figure 3) 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™ designs were further developed (Task VII). 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 (Simpson 2013; Simpson and Byun 2017). These designs 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.

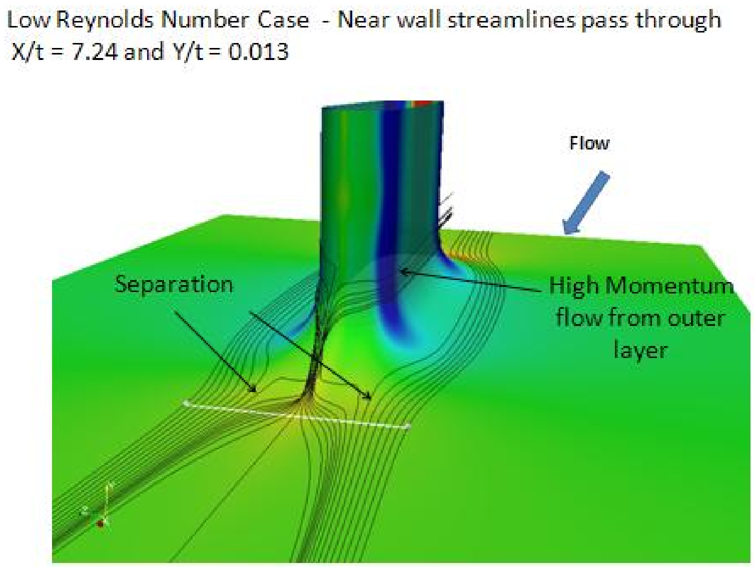


Figure 3. Low Reynolds number case CFD calculated flow streamline patterns around a scAUR™ streamlined bridge pier fairing. Flow indicates no discrete vortex formation on nose and sides (Simpson and Byun 2017).

DESIGN TO PREVENT SCOURING-VORTICES FOR A SPECIFIC BRIDGE CASE

Each bridge has a number of specific unique features that affect the design to prevent scouring vortices at the river bed next to a pier or abutment. One or two dimensional calculations with correlations of laboratory data or full-scale data of past scour are not likely to apply for this case. Consequently, it is prudent to use a physics-based approach with a proven turbulence model in a fully three-dimensional Navier-Stokes computational fluid dynamics (CFD) code. This will produce more detailed results of the flow around the bridge hydraulic structures. AUR uses the v2F model in an OpenFOAM code. Many important features of 3-D flows are closely modeled by this code and model.

One needs information on the upstream 3-D river bed and banks geometry and the size and distribution of the surface roughness that will affect the shearing stress on the flow. The three-dimensional inflow to the river at least 10 river widths upstream should be used**.** If the bridge is downstream of a bend of the river, the piers and abutment are particularly susceptible to scour. The high velocity surface water hits the outer river bank, moves to the bottom of the river and scours hydraulic structures. One would need information on the resultant flow distribution to be able to modify the scAUR™ shape to account for swirl.

It is prudent to be ready for flood conditions that are likely to happen sometime (Flint et al. 2017), so data on the maximum river flowrate that has been observed are needed. This is the flow condition that should be used in the CFD computations. Use the highest flowrate outlier points in the USGS and other data, which suggest catastrophic conditions, rather than an average flowrate from data (Baker 1988; Flint et al. 2017). Sources of maximum river flowrate information include maximum rainfall historical data from rain gages and radar used in regression equations. A surface runoff analysis should also be used.

SCOURING-VORTEX PREVENTION APPLIED TO ROCK SCOUR

A heavily used large long bridge is downstream of a bend in a river and has the most severe scour under the pier seals of any relatively new bridge in this state. Swirling flow produced by the bend in the river brings the highest velocity surface water down to the river bottom. The limestone under the base seals of the piers, which do not have pilings, has been partially scoured away, not the concrete seals. One pier has lost 40% of its load-bearing strength and 70% of its moment-bearing strength. The loss of this bridge would devastate the local rural economy.

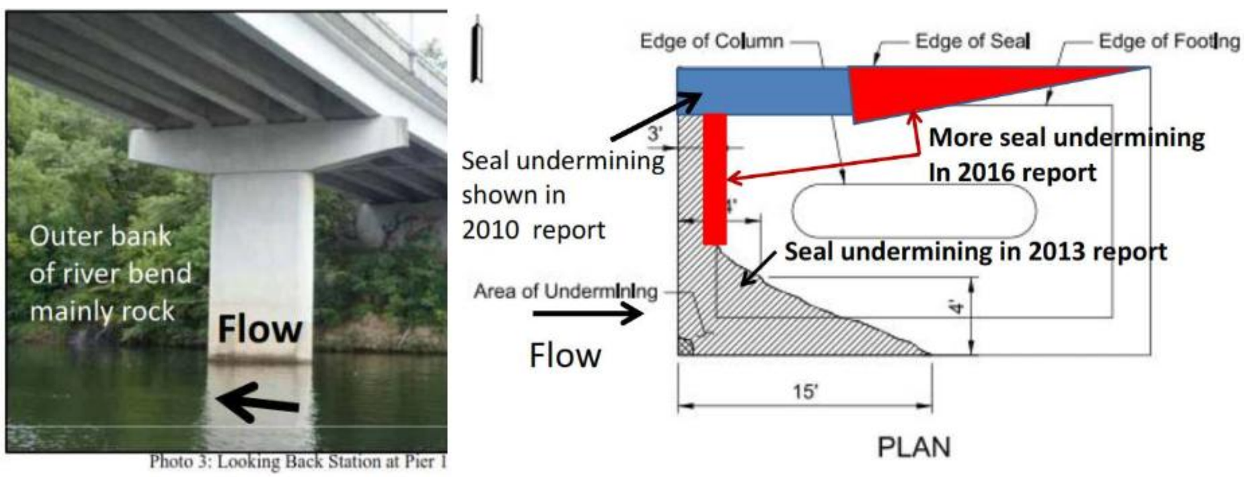


Figure 4 . Pier with severe seal scour (left). The 2010, 2013, and 2016 state bridge inspection reports show progression of limestone rock scour under the concrete.

The scour that occurs around the seal foundation is due to the near-surface high velocities produced by horseshoe vortices formed around the model, such as shown in Figure 5 below. Model flume test scour results shown in Figure 6 below are very similar to full-scale case loss of limestone in Figure 4 above.

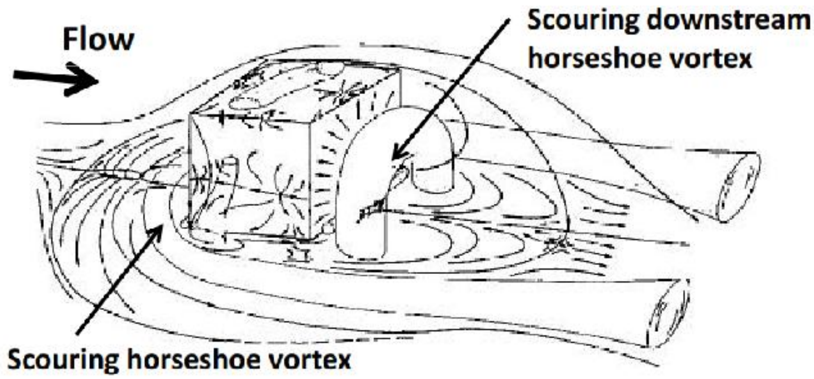


Figure 5. The flow behavior around a seal is like around a surface-mounted cube represented well by Martinuzzi and Tropea (1993).

Figure 6. Case 39: Base seal model in the AUR flume. Results after one hour test run. Scour under model very similar to full-scale case limestone loss in Figure 4 above.

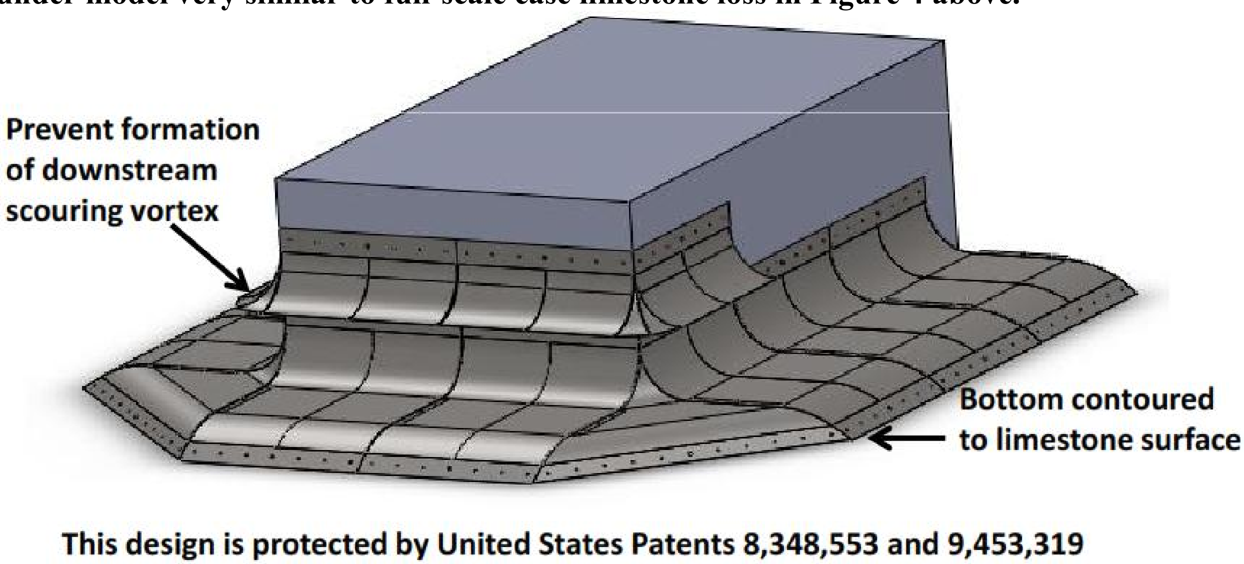


Figure 7. SELECTED PROVEN DESIGN. Case 43: Seal model with C-shaped extended ramp on the front and both sides.

Figure 7 shows the *only* scouring-vortex-preventing retrofit design for foundation rock scour prevention for this seal. It uses cost-effective modular stainless steel units that can be attached to the concrete seal using standard methods over a short time. *The permanent solution* - prevent the swirling flow from reaching the limestone under the seal. Traditional scour countermeasures do not do this. Just filling the gap under the seal with concrete under pressure does not restore support under the seal less vertical containment plates at the edges of the seal are used in a strong structure, as in this design. Without the ramps and streamlined fairings to prevent scouring vortices, a repaired seal would scour rock under the repaired concrete and defeat the repair.

This streamlined fairing design was added to the seal model in Figure 6 and tested in the AUR flume with no scour, as shown in Figure 8 below. This project will restore the strength of these piers using accepted methods, and fabricate and install a scouring-flow-altering stainless steel streamlined fairing design that permanently prevent future scour under the seal.

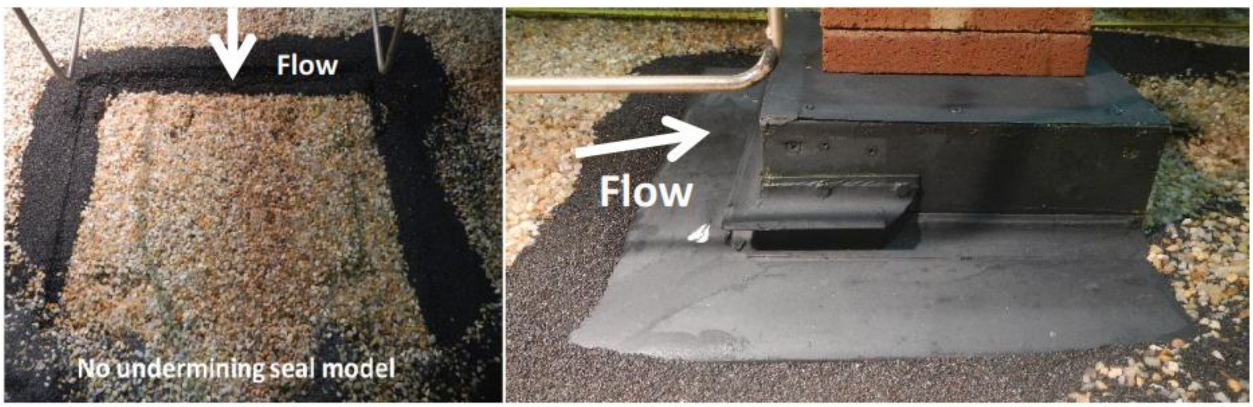


Figure 8. Case 43: Seal model with C-shaped extended ramp on the front and both sides. The streamlined ramps and fairings produced no scour undermining of the seal or ramps. Results after one hour flume test run.

COST OF THE BRIDGE FAILURES AND COST-EFFECTIVE MANUFACTURING AND INSTALLATION OF scAUR™ AND VorGAUR™ DESIGNS

Before the NCHRP-162 project, AUR performed a cost-benefit analysis of scAUR™ with VorGAUR™ designs as compared to currently used scour countermeasures (Simpson 2013). Published information on these currently used countermeasures shows that periodic 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. When one includes the present value of future costs, repetitive temporary scour countermeasures are more expensive (Simpson and Byun 2017, 2019).

There is no situation where scAUR™ and VorGAUR™ designs, as shown in Figure 2 for a stainless steel pier retrofit, cost more than current countermeasures. There is no situation where any type of scour is worse with the use of the scAUR™ and VorGAUR™ designs than without them. The more frequent that scouring floods occur, the more cost effective are scAUR™ and VorGAUR™. Clearly, scAUR™ and VorGAUR™ designs are practical and cost-effective for US highway bridges (Simpson and Byun 2017).

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. 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* (Simpson 2013; Simpson and Byun 2017).

For new construction, the estimates were done on the basis of added cost. This means determining the incremental increase in the total cost of the bridge project that can be attributed to the scAUR™ design 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™ design installation. Clearly, since the new construction cost is about 1/3 of retrofit costs, the best time to include the scAUR™ fairing on piers and abutments is during new construction (Simpson 2013).

Simpson and Byun (2019) discuss the liability costs associated with injuries and the loss of life in bridge failures due to scour. For the Schoharie Creek Bridge collapse, prior to the failure both piers could have been protected permanently from scouring vortices for all water flow speeds for **0.45%** of what was eventually spent after failure. For the Loon Mountain Bridge abutment collapse, prior to the failure the abutment could have been permanently protected from scouring vortices for all water speeds for less than **0.9%** of what was spent after the abutment collapse.

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. Bridge owners receiving US federal funds are no longer prohibited from using patented or proprietary products in designs.

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.

A successful scAUR™ streamlined fairing design was discussed to prevent rock scour under concrete seals and hydraulic structures. The costs of bridge failures is 100 times more than costs for application of the scAUR™ special streamlined fairings and VorGAUR™ vortex generators. Other advantages of these designs are much lower present value of all current and probable future 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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