Designing Scour-Resistent Bridge Structures for Extreme Events

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ICSE-10 Proceedings -Track K - Scour & Erosion

Countermeasures & Mitigation pp. 1260-1269

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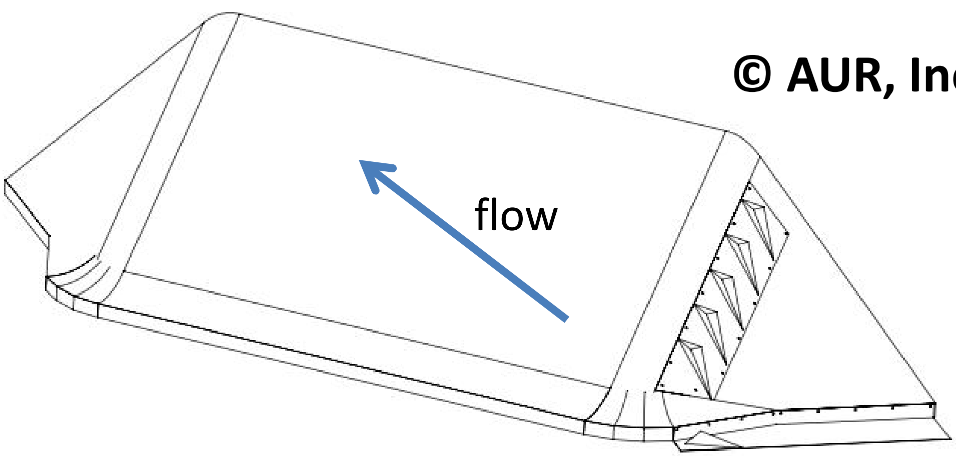
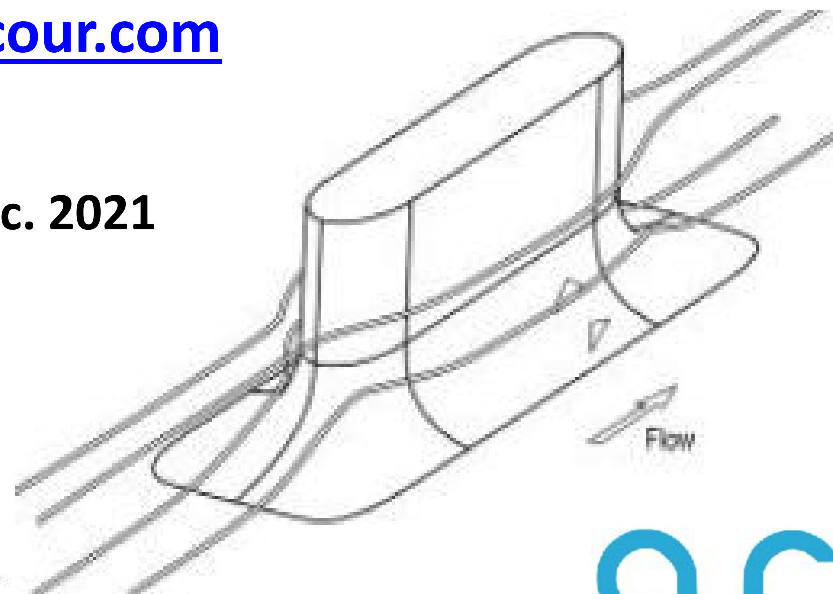




Introduction and Background of Dr. Simpson

➢ An internationally recognized fluid dynamics researcher, inventor, and author on vortex producing "juncture flows", such as those that occur in bodies of water around hydraulic structures such as bridge piers and abutments, and surface roughness effects on flow. Past President & Fellow AIAA; Fellow ASME, M. ASCE.

➢ Consultant and advisor to NASA on reducing adverse aspects of "juncture flows" between airplane wings and a fuselage.

➢ For over 30 years his US Navy sponsored research at Virginia Tech, where he was the Jack E. Cowling Professor of Aerospace and Ocean Engineering, provided much data for the prevention of acoustic noise producing vortices on submarines.

➢ Over the last years, he has applied this fluid dynamics background to designing and testing the scouring-vortex preventing streamlined fairings **scAUR™** for bridge piers and abutments.

➢ Novel tetrahedral vortex generators **VorGAUR™** create counter-rotating vortices that oppose the effects of scouring vortices & prevent debris collection.

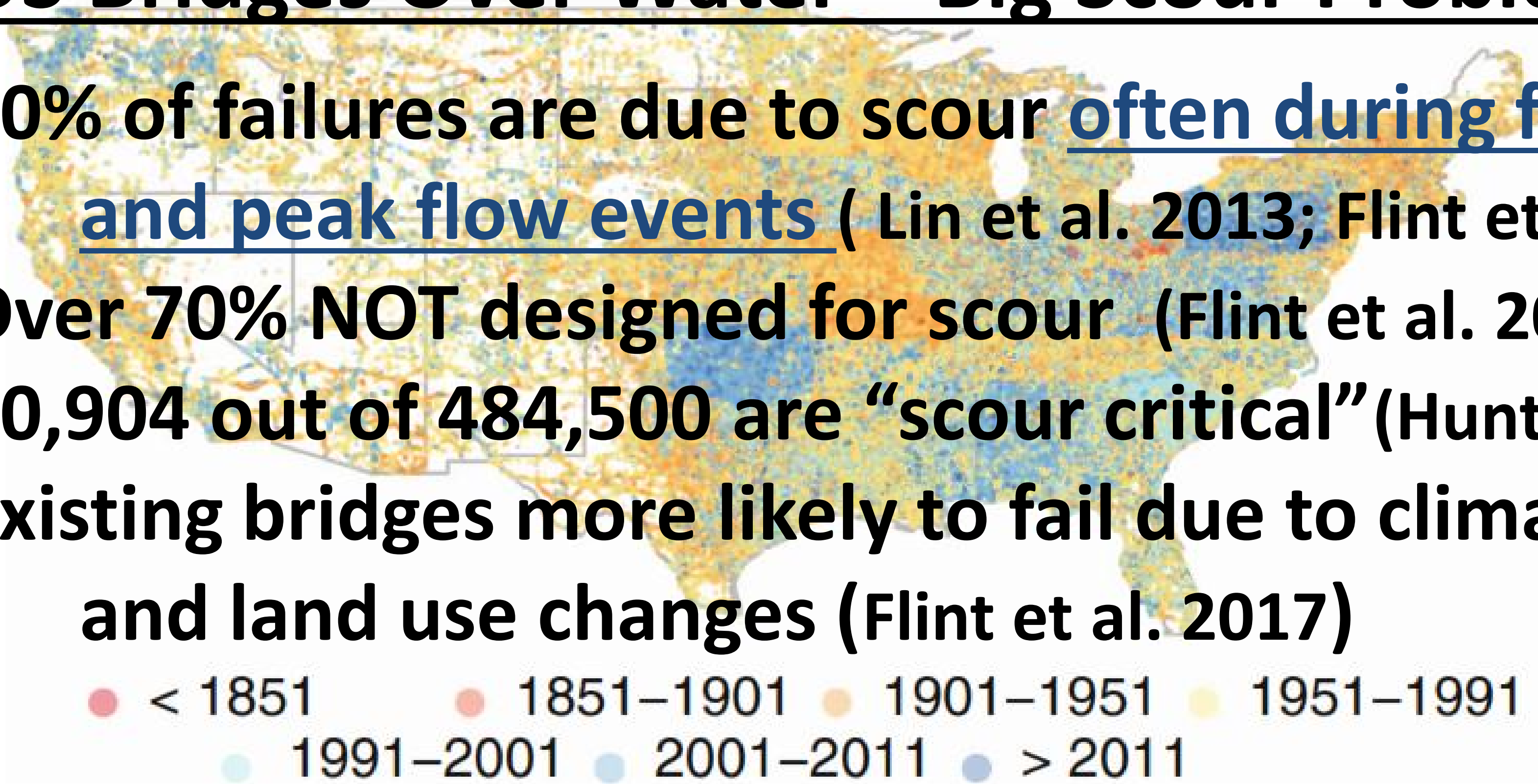
➢ **US Patents 8348553, 8434723, and 9453319 awarded.**

➢ Model and full-scale tests under the sponsorship of the National Co-operative Highway Research Program **(NCHRP-IDEA Report 162)** have proven these designs.

➢ Cost-effective stainless steel retrofits for existing bridges and concrete forms for new bridges are available for various bridge and river-bed situations.

<u>US Bridges Over Water – Big Scour Problem</u>

- **80% of failures are due to scour <u>often during floods and peak flow events</u> (Lin et al. 2013; Flint et al.)**
- **Over 70% NOT designed for scour (Flint et al. 2017)**
- **20,904 out of 484,500 are “scour critical”(Hunt 2009)**
- **Existing bridges more likely to fail due to climate and land use changes (Flint et al. 2017)**



(Color) Continental U.S. bridges over water by construction year; approximately 370,000 of 504,000 were built before 1991, when new scour design provisions were adopted (range: 1697–2011; median: 1973) (data from FHWA 2012)

Madeleine M. Flint et al. 2017 **Historical Analysis of Hydraulic Bridge Collapses in the Continental United States,** ***ASCE Journal of Infrastructure Systems***, 2017, 23(3): -1--1 © ASCE, ISSN 1076-0342.

Outline of Topics

Bridge failures due to scour show that scouring-vortex-preventing designs would have prevented the scour failures and will prevent future failures at all flow speeds.

- **New Approach to Prevent Scour at all Flow Speeds: Prevent Scouring Vortices & Create Counter-Rotating Vortices**
- **The Nature of Scouring Vortices**
- **Proven Features of scAUR™ that Prevent Scouring Vortices**
- **Recent NCHRP-IDEA-162 Project by AUR Proves that scAUR™ and VorGAUR™ are Effective**
- **Design to Prevent Scouring Vortices for a Specific Bridge**
- **Scouring-Vortex Prevention Applied to Rock Scour – Use of scAUR™ and VorGAUR™**
- **Cost of Bridge Failures and Cost-effective scAUR™ and VorGAUR™ Designs**
- **Conclusions**

MOTIVATION - Avoid Future Bridge Failures due to Scour

Failure of the Schoharie Creek Bridge, NY State Thruway, April 5, 1987

Photo by Sid Brown, https://dailygazette.com/article/2017/04/04/thruway-bridge-collapse-of-1987-it-sounded-like-a-bomb-going-off

Wikipedia https://en.wikipedia.org/wiki/Schoharie_Creek _Bridge_collapse)

- **Stream flooded from high April 1987 rainfall and snow melt.**
- **Normal 6 foot water depths rose to 25 feet - third highest in recorded history.**
- **The high flood speed (15 fps) created an approximately 10 foot deep by 30 foot wide scour hole around Pier 3.**
- **Two 60-foot sections of the 540-foot-long bridge fell 110 feet into the creek.**
- ***Five vehicles fell into the creek and ten occupants died.***

Causes of the Schoharie Creek Bridge Failure

A number of design and maintenance deficiencies

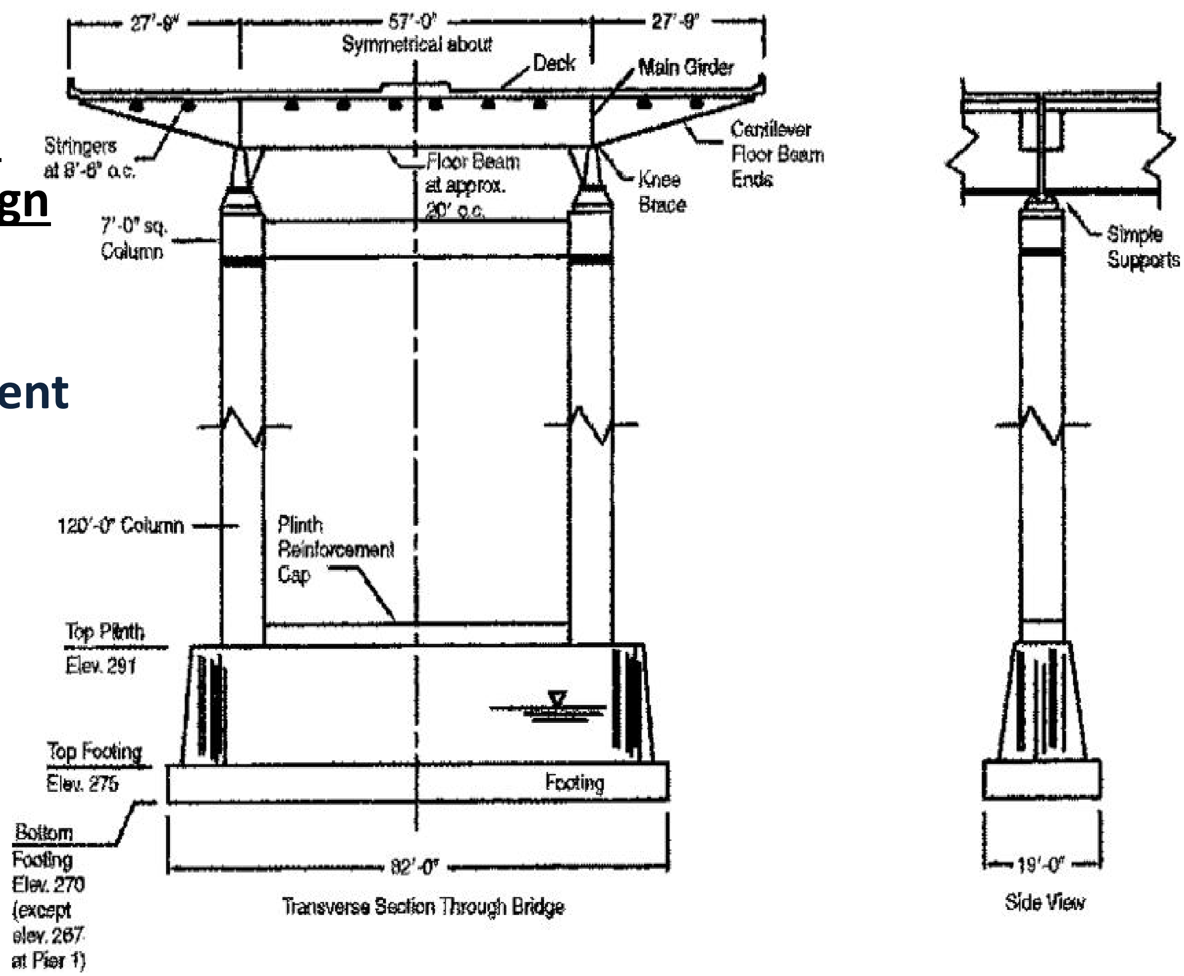
<u>Flood velocity was higher than anticipated in the original design</u>

Piers supported by spread footings with limited embedment into the riverbed.

Spread footing under Pier 3 rested on highly erodible soils (i.e. layers of gravel, sand, and silt) and backfill

Inadequate "riprap" rock protection

Inadequate inspection and maintenance.



Sections showing the Schoharie Creek Bridge pier supported on a spread footing . From NTSB, 1988.

Other Aggravating Factors in the Schoharie Creek Bridge Failure

- **Debris accelerated the downward scouring flow.**
- **Berms increased the floodwater speed under the bridge.**
- **A high hydraulic gradient formed between upstream and downstream in the spring.**
- **Insufficient design of the bridge structure for scour conditions:**

>> 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;

photo credit: U.S. Department of the Interior, U.S. Geological Survey

>> Deficient plinth reinforcement resulted in sudden cracking of the plinth instead of a hinging failure.

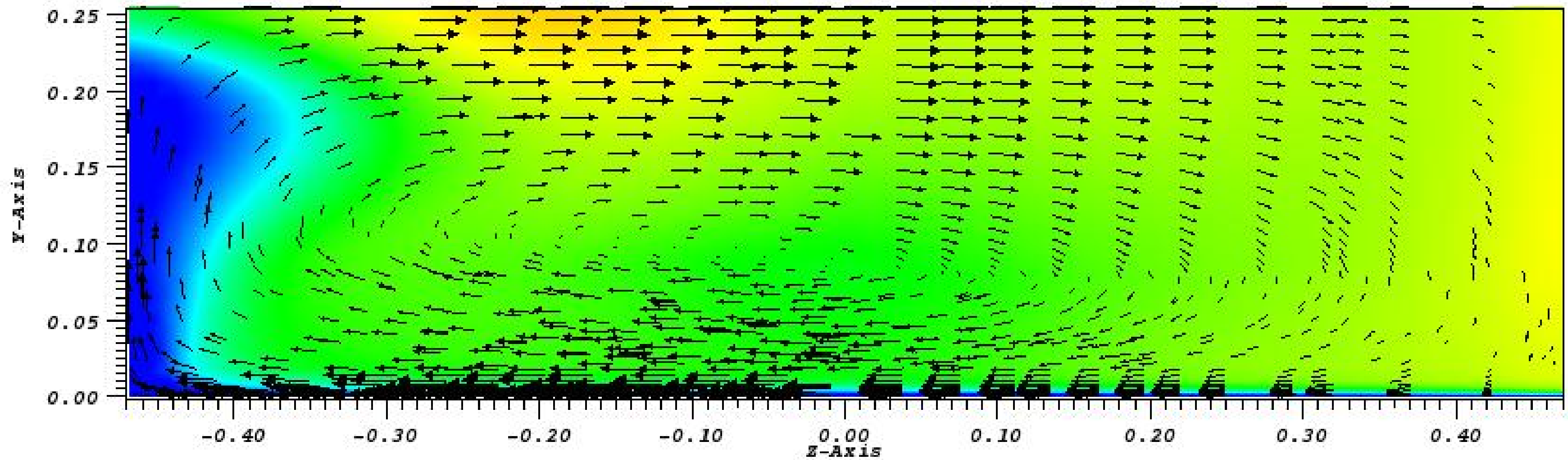
Some Observations and Practical Tips for Assessing the Potential for Scour and Catastrophic Bridge Failure

- **No earlier bridge pier and abutment footing or foundation design prevents scouring vortices.**
- **Designs should be based on extreme events.**
- **Use the physical understanding of flood processes and situations, not just statistical probabilities from past experiments, codes, and events.**

Piers and Abutments downstream of river turns and bends are particularly susceptible to scour High velocity surface water hits outer bank, moves to the bottom of the river and scours hydraulic structures – **modify scAUR™ shape to account for swirl.**

Mean flow stream-wise vortices are produced after a river bend. **CFD by AUR, Inc.**

Inner radius **Outer radius**



The Loon Mountain Bridge Abutment Failure

In August 2011 high water due to Tropical Storm Irene washed out an abutment of the Loon Mountain, New Hampshire Bridge.

This bridge abutment was on the outer bank in a bend in the river, so swirling flow brought high velocity water into the outer river bank, causing quick erosion and loss of soil and rock under the concrete part of the abutment.

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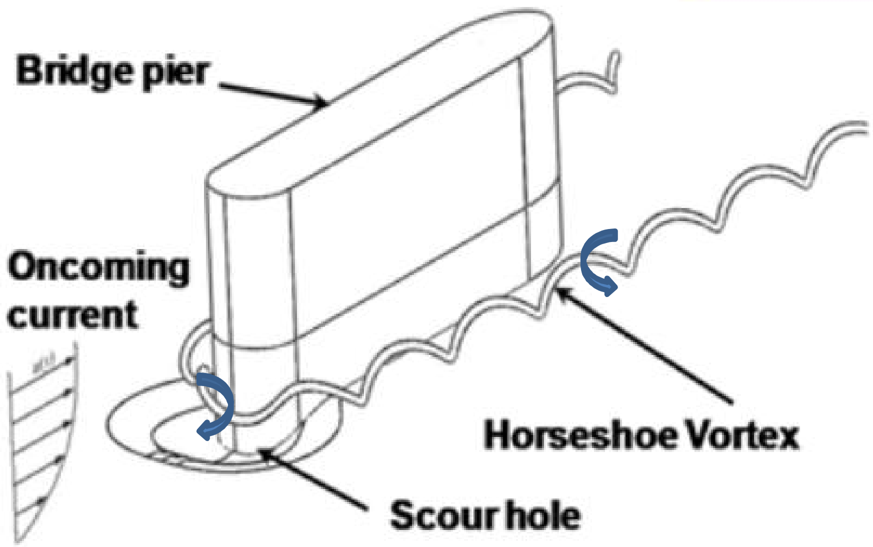
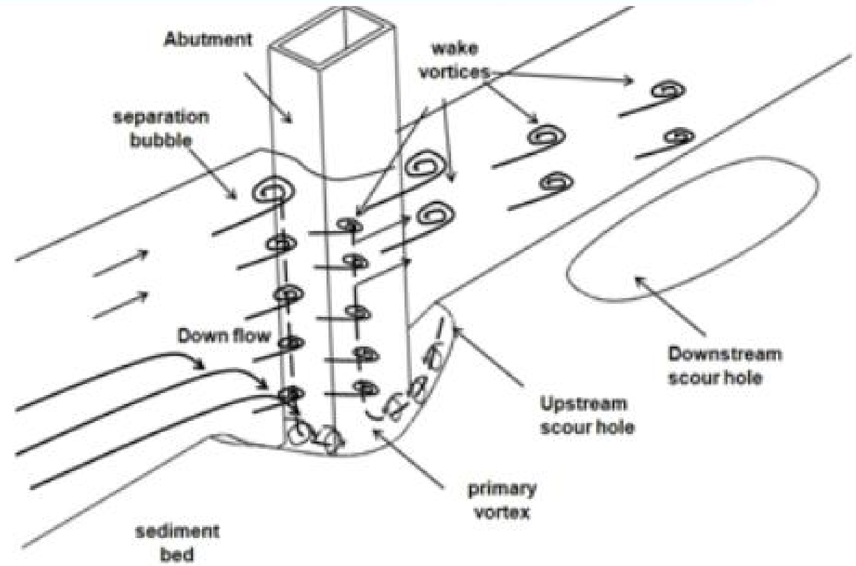
Causes of Bridge Scour





Bridge scour is produced by discrete vortices formed around unprotected piers (left above) and abutments (right). Many near catastrophes and loss of life have occurred, as shown in examples

LIKE TORNADOS - VORTEX STRETCHING INCREASES VELOCITY

$V_2 = V_1(A_1/A_2)^{1/2} = \Gamma/(\pi d_2)$ = Strength of Vortex/(Perimeter of Vortex)

V_1 , V_2 rotational velocity components of vortex

A_1 , A_2 cross-sectional area of vortex

diameter d of vortex.

TM

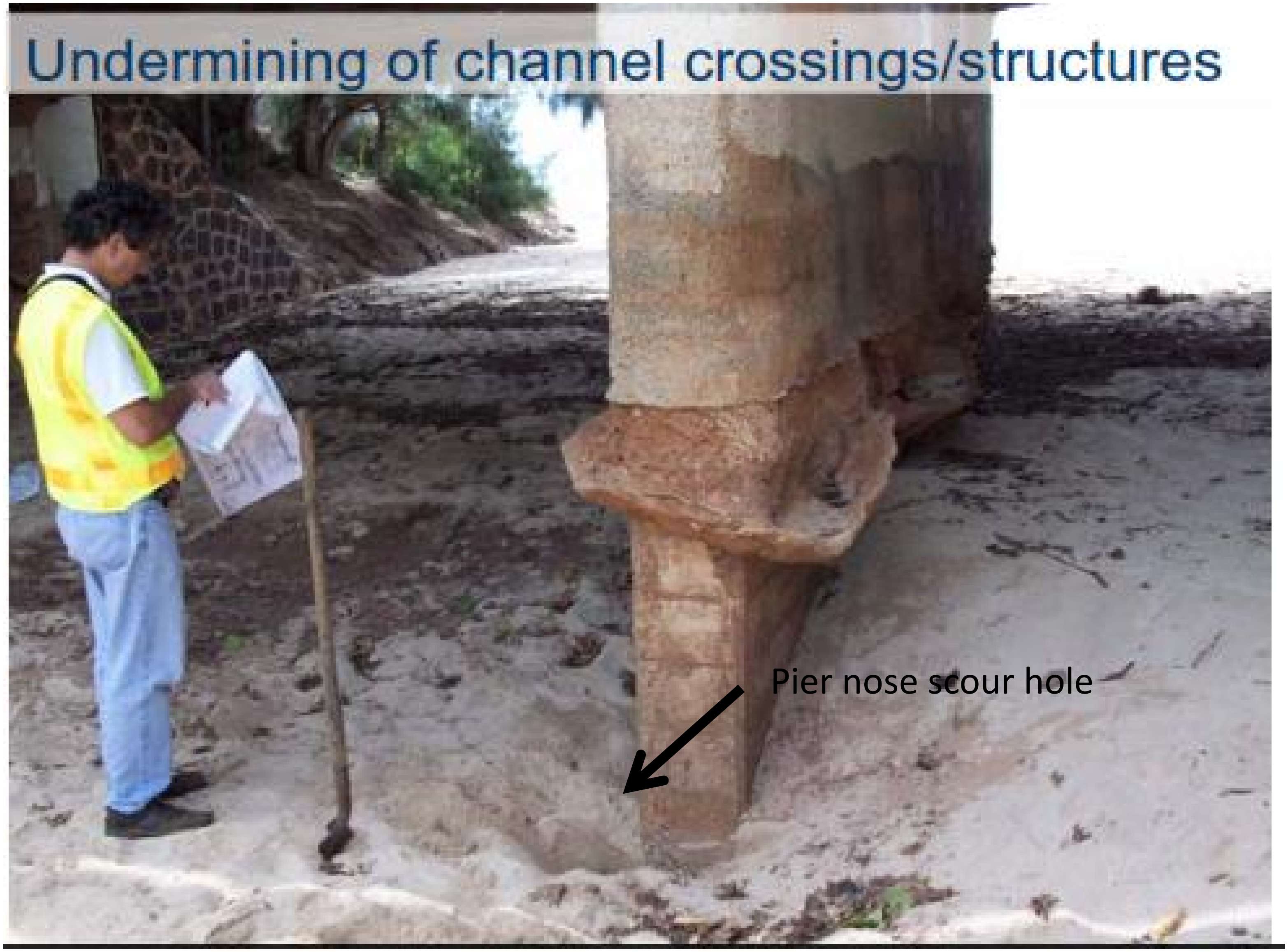
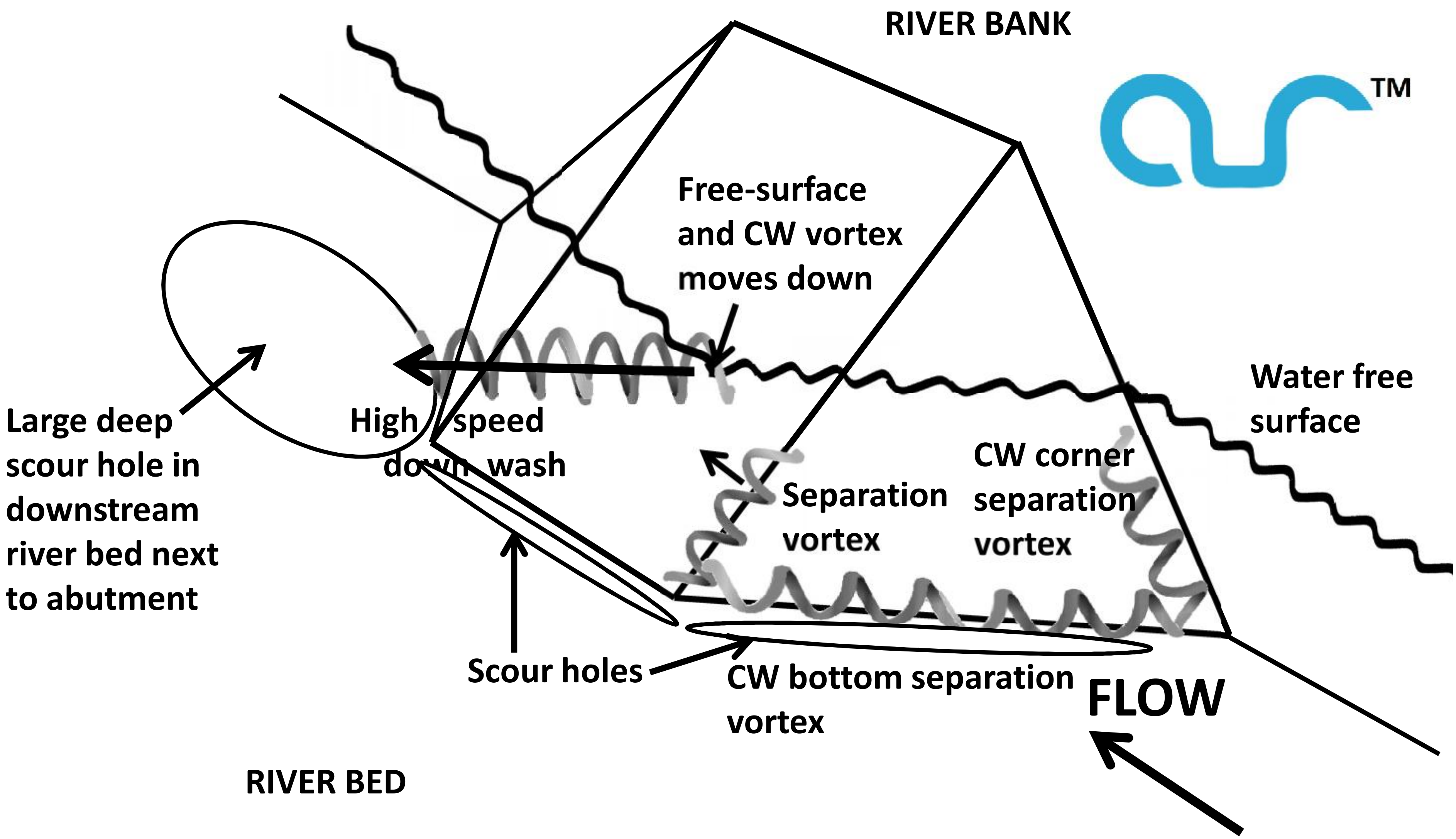


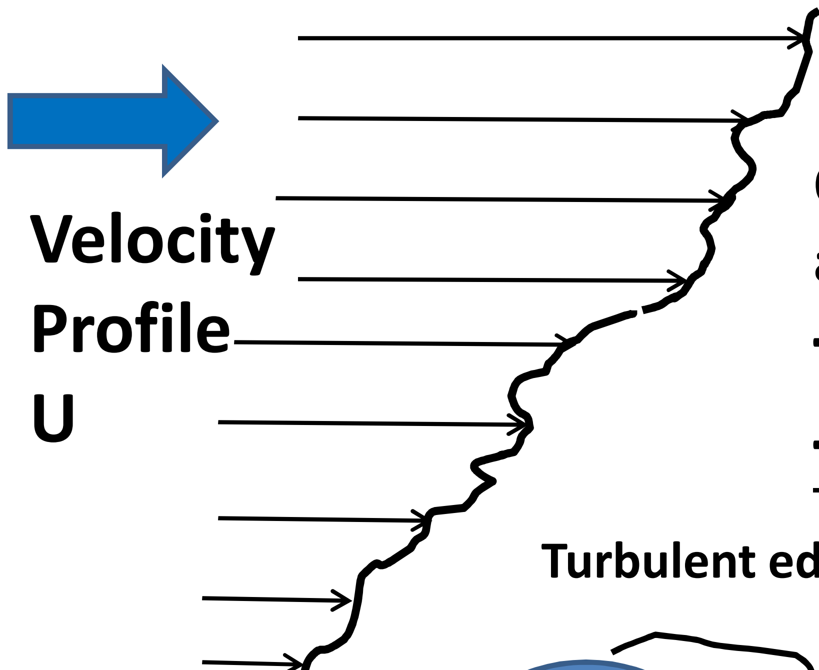
Photo from **Introduction to Sediment Transport Modeling Using HEC-RAS** by Marty Teal, ASCE Continuing Education Course, AWI031414

Spill-through abutment without scour countermeasures



Fundamental Mechanism of Scour on River Bed

Turbulent flow over river bed



<u>Shields Number Θ</u> describes incipient motion of bed material

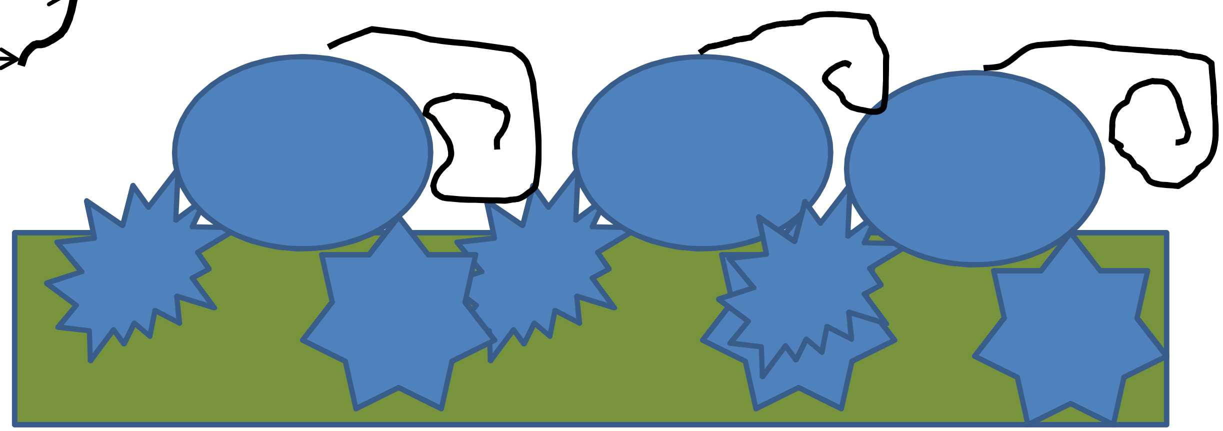
$$\theta = \frac{\tau}{(\rho_p - \rho) g d}.$$

Θ = ratio of effective shear force to apparent weight; motion is F($Re_{particle}$)

τ = turbulent shear stress

<u>τ varies with U^2 & roughness</u>

Turbulent eddies created over bed materials



KEEP U LOW!

River bed of sand, dirt, gravel, and rocks

What Can Be Done to Prevent Scouring Vortices??

Which bridge pier and abutment features cause vortices that cause scour? Surfaces that cause discrete vortices that cause higher velocity water to move down to the bottom of the river.

> The more blunt the nose of a pier or abutment, the greater the downflow and the stronger the vortex and the scouring.

> Vortex strength scales on the approach velocity U and the width w of the pier. Vortex strength varies like Uw.

- **Stretching of vortices due to contraction of the flow intensifies the velocities in the vortex, thus causing more scour.**

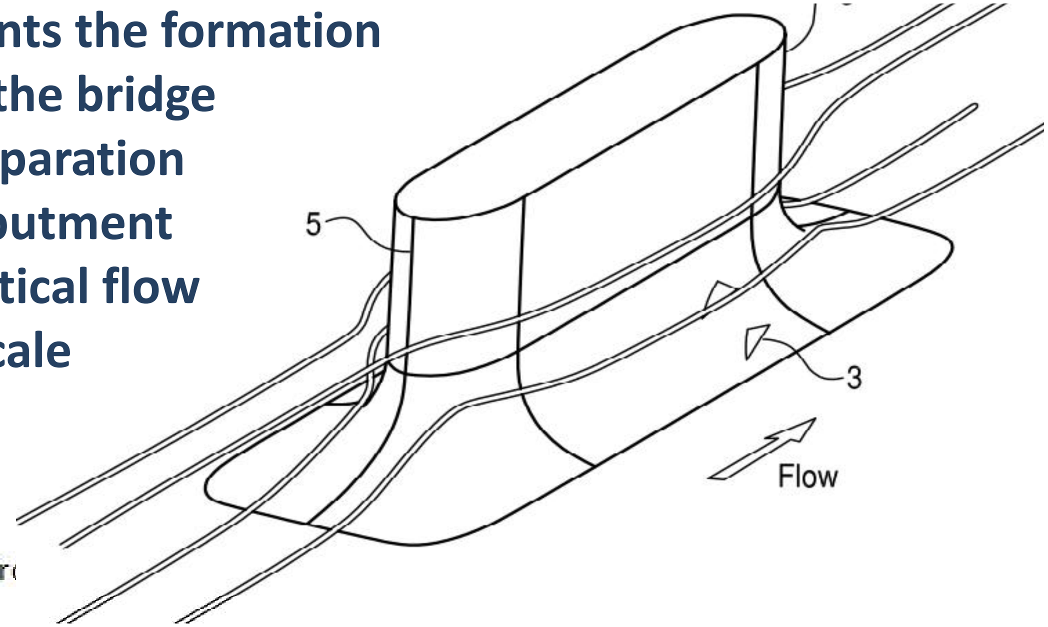
Simpson, R. L., 2001, "Junction Flows," Annual. Rev. Fluid Mech., Vol. 33, pp. 415–43.

What can be done to prevent vortices that cause scour? ***Use (1) surface shapes that prevent the formation of discrete scouring vortices*** **and (2) tetrahedral vortex generators that cause the higher velocity flow to stay on top of the river and counteract the scouring vortices.**

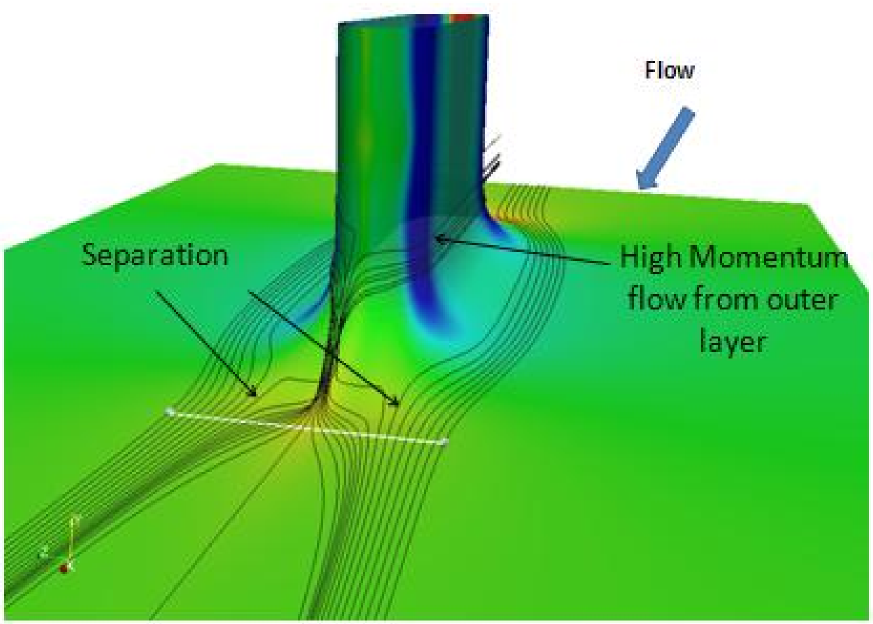
TM

Proven Features of scAUR™ that Prevent Scouring Vortices

The patented scAUR™ design prevents the formation of highly coherent vortices around the bridge pier or abutment and reduces 3D separation downstream of the bridge pier or abutment with the help of the VorGAUR™ vortical flow separation control. Proven at full-scale by the NCHRP-IDEA-162 tests.



Low Reynolds Number Case - Near wall streamlines pass thr
X/t = 7.24 and Y/t = 0.013

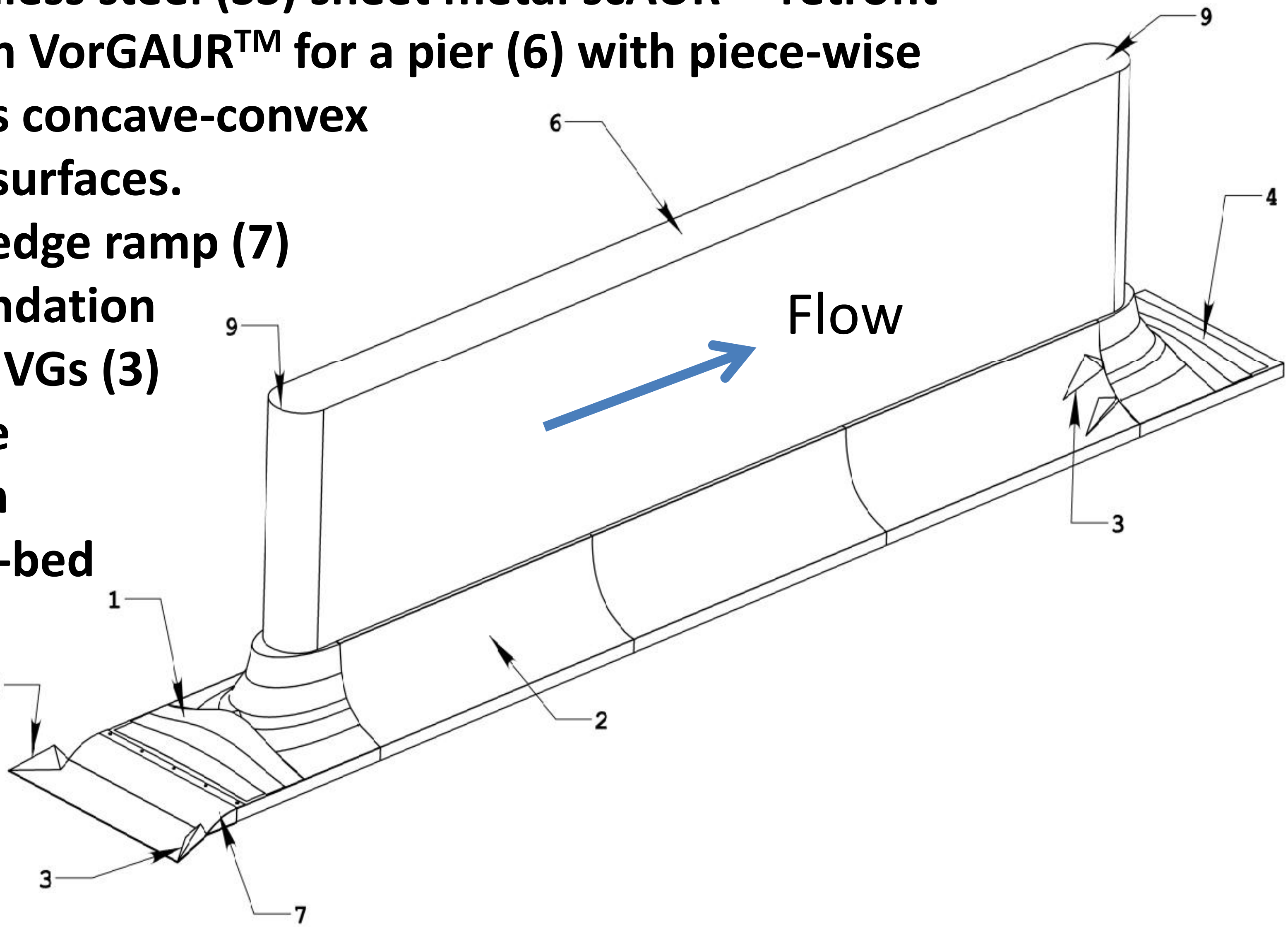


Streamlines around a scAUR™ fairing around a pier (5) with VorGAUR™ vortex generators (3) that produce no scouring vortices.

Application of ScAUR™ and VorGAUR™ Products to the Schoharie Creek Bridge

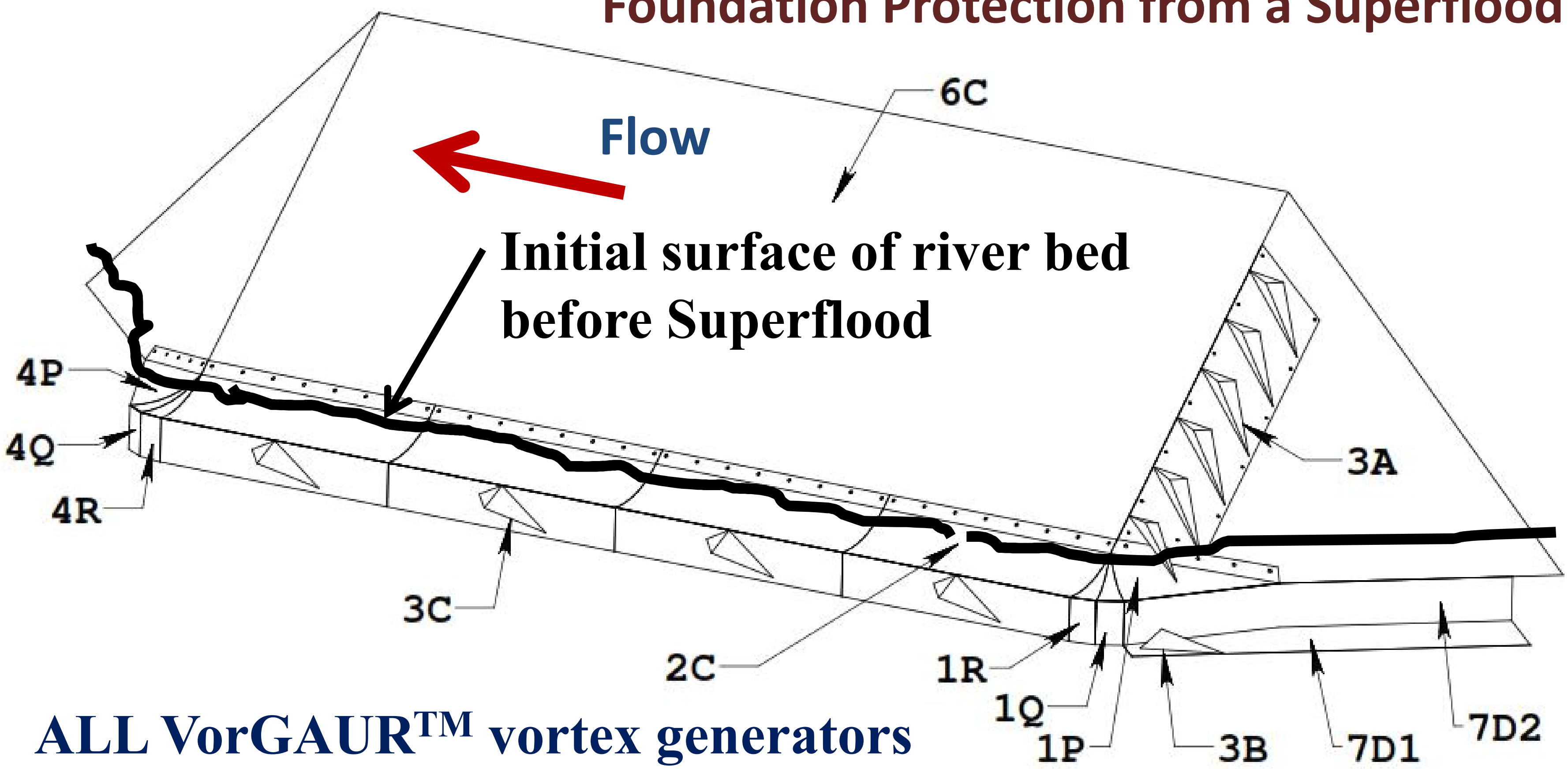
> Use stainless steel (SS) sheet metal scAUR™ retrofit fairing with VorGAUR™ for a pier (6) with piece-wise continuous concave-convex curvature surfaces.

> Leading edge ramp (7) & pier foundation protecting VGs (3) protect the foundation from open-bed scour.



Application of scAUR™ and VorGAUR™ SS Products to the Loon Mountain Abutment

Spill-through Abutment with VorGAUR™ Vortex Generators (3C) for Added Foundation Protection from a Superflood

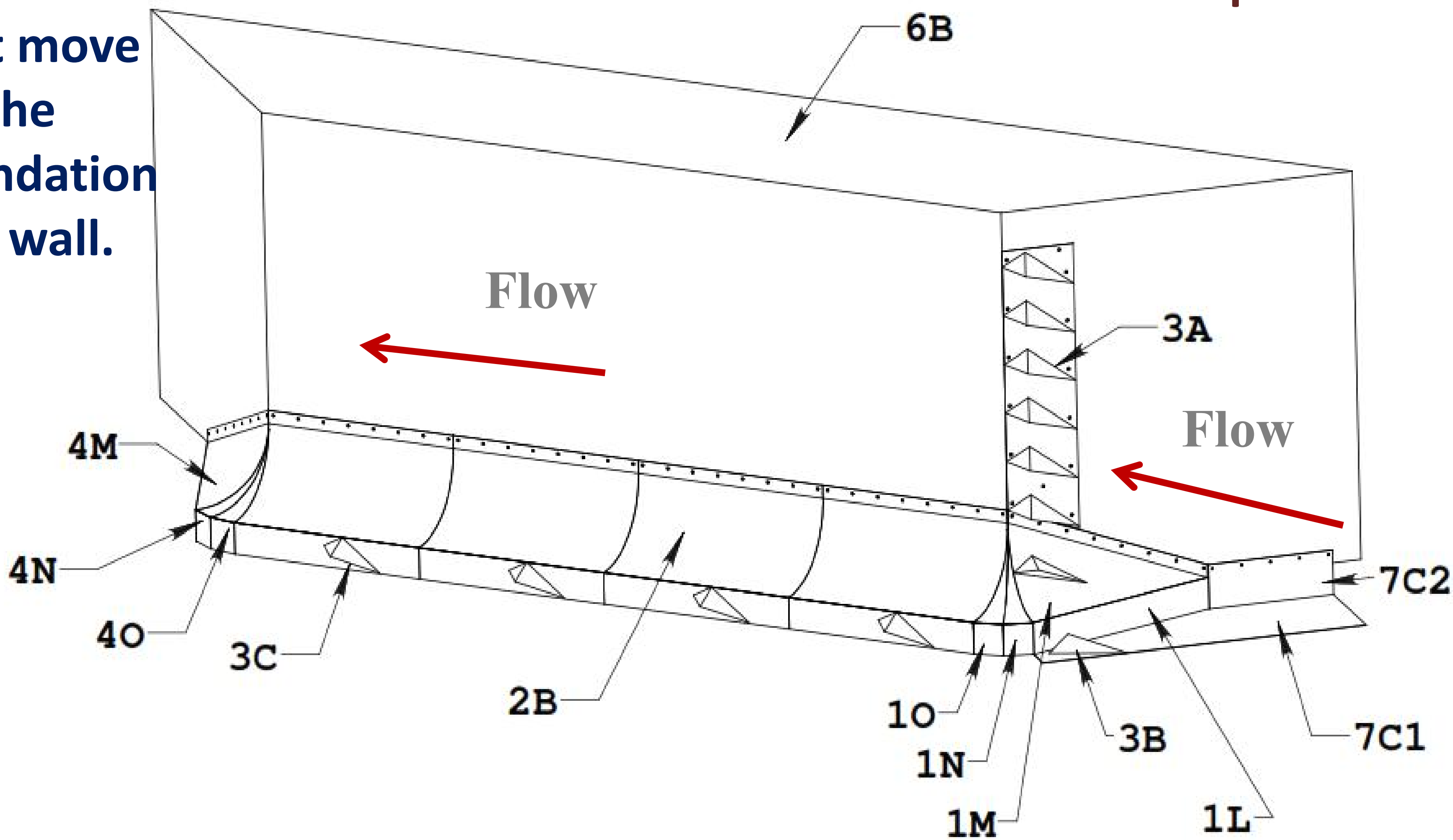


ALL VorGAUR™ vortex generators produce stream-wise vortices that move up the foundation and wall, bringing river-bed material toward the abutment

Application of scAUR™ and VorGAUR™ SS Products to the Loon Mountain Abutment

ALL vortex generators produce stream-wise vortices that move up the foundation and wall.

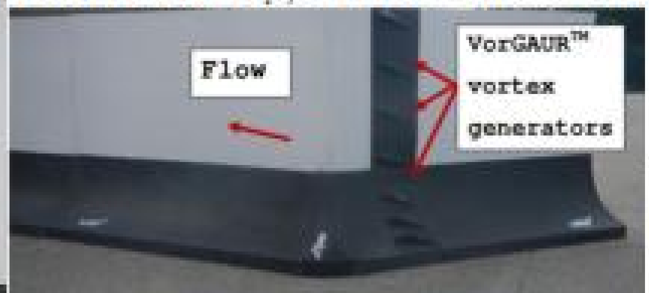
Wing-wall Abutment with VorGAUR™ Vortex Generators (3C) for Added Foundation Protection from a Superflood



Permanent Solution: scAUR™ and VorGAUR™ Products

Modular Stainless Steel (SS) Retrofits for Existing Bridges

Greatly extends bridge life! Modules quick and easy to install.

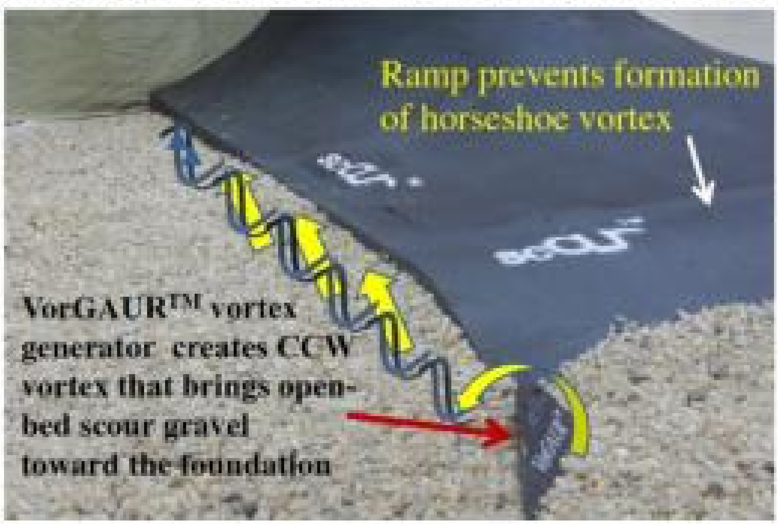


Example stainless steel scAUR™ retrofit (black) for a 45° wing-wall abutment. Note SS vortex generators.

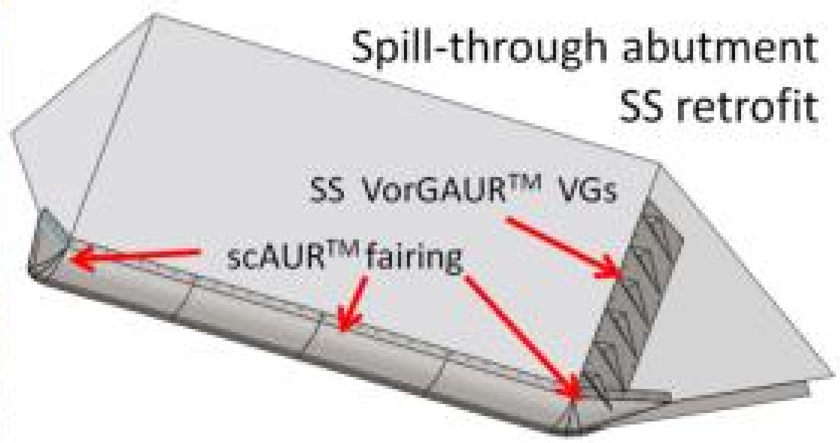
Example stainless steel scAUR™ retrofit (black) for a pier.

VorGAUR™ vortex generators create CW vortices that bring low-speed flow up to prevent scour.

Ramp and VorGAUR™ vortex generator bring open-bed scour material toward a pier



Pre-fabricated interlocking modules permit quick and exact assembly and preserve the scAUR™ shape

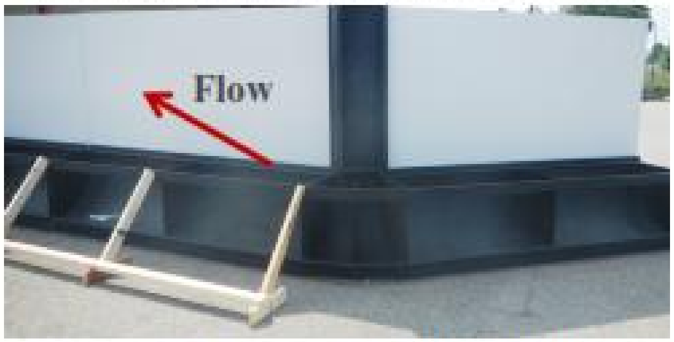


Permanent Solution: scAUR™ and VorGAUR™ Products

scAUR™ Steel Concrete Forms for New Construction

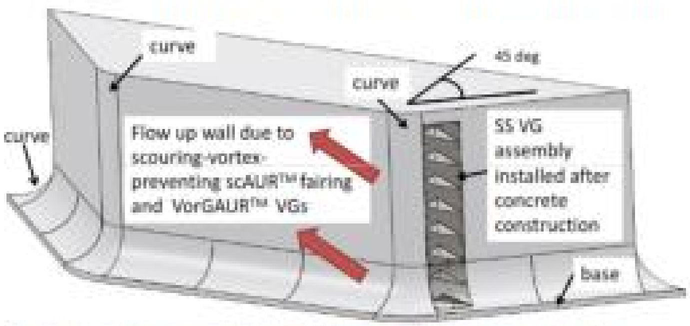
The best time to install at a fraction of retrofit cost!

Wing-wall abutment concrete forms

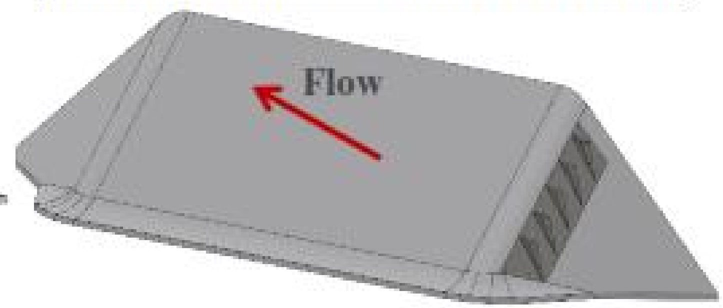


Spill-through abutment forms

Completed new construction abutment



Completed new spill-through abutment



Forms for new Piers

Modular interlocking forms permit quick and exact assembly and preserve the scAUR™ shape

Standard rebar methods for foundation construction

AUR, Inc.

scAUR™ & VorGAUR™ Applied to Prevent Bedrock Scour

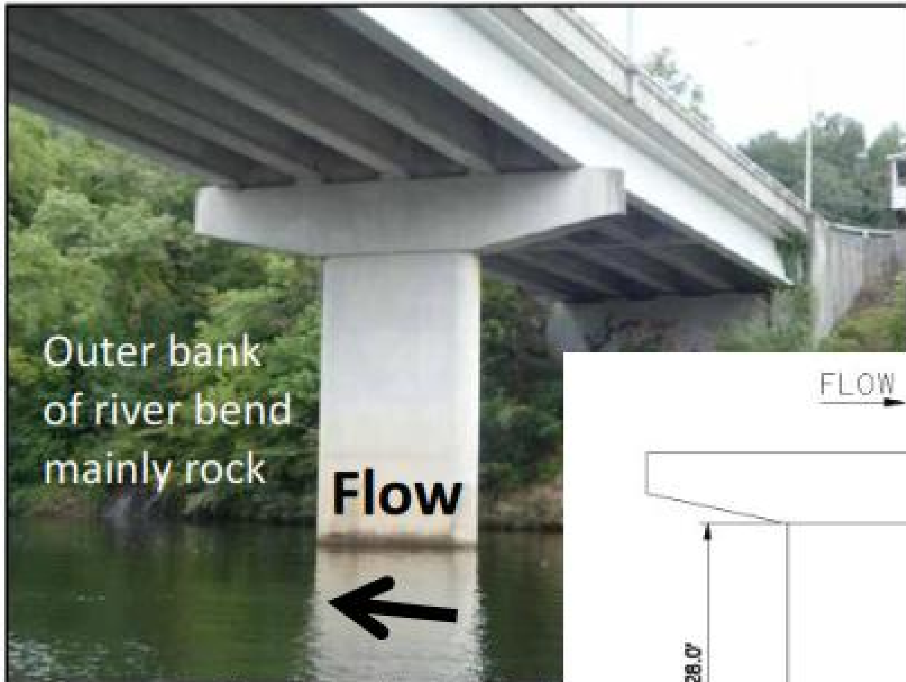
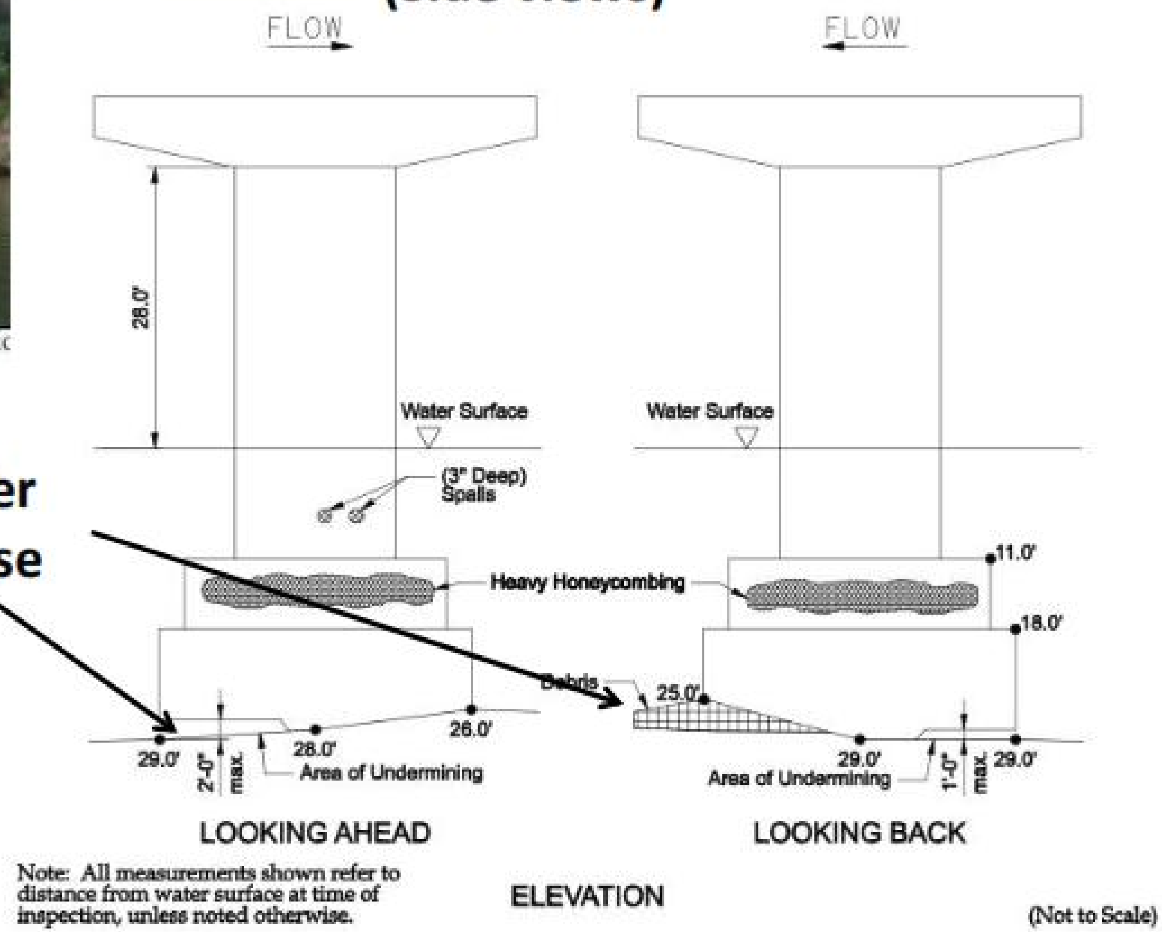


Photo 3: Looking Back Static

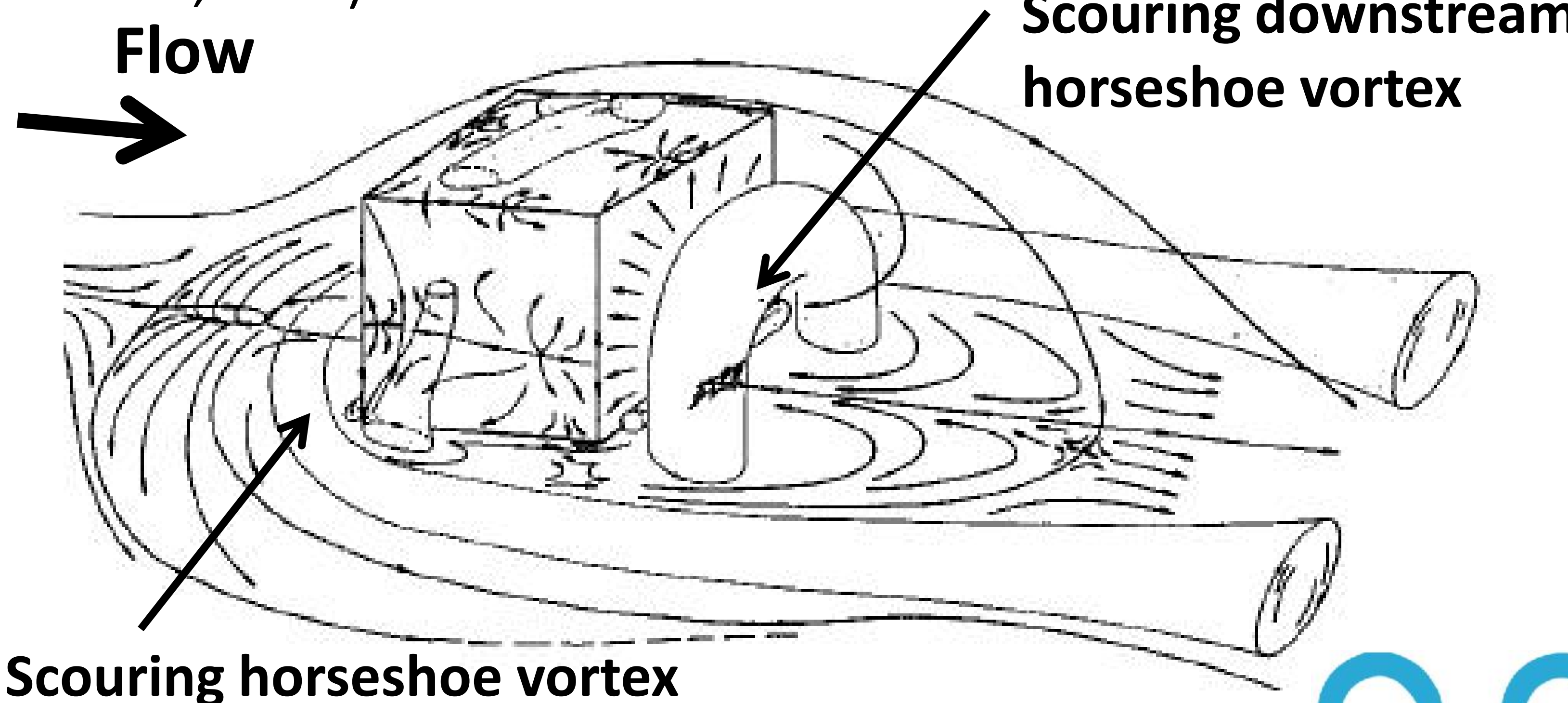
2010, 2013, and 2016 State Bridge Inspection Reports Show Progression of Scour of Limestone under the Seal (Side views)



Undermined gaps under the seal filled with loose debris

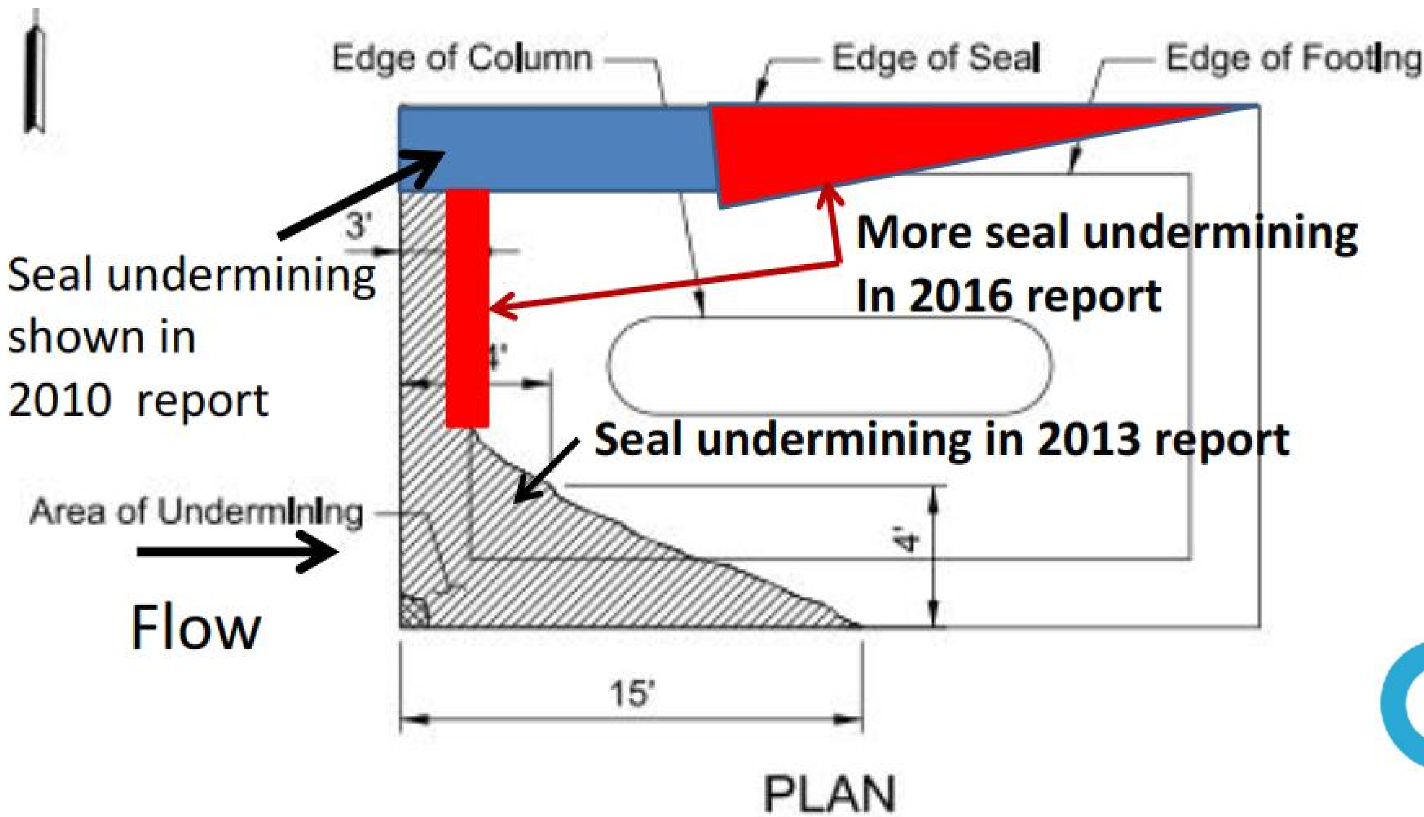
Flow Behavior Around a Seal

The scour that occurs around the seal foundation is due to the near-surface high velocities produced by horseshoe vortices formed around the model. This flow behavior around a surface-mounted cube has been represented well by Martinuzzi and Tropea (J. Fluids Eng., ASME, Vol. 115, pp 85 -92, 1993).



2010, 2013, and 2016 State Bridge Inspection Reports Show Progression of Limestone Scour under the Seal

PLAN VIEW of undermined areas of a concrete seal under the pier over scoured limestone. Pier has lost over 35% of its original weight strength and 65% of the clockwise moment strength against the counter-clockwise moment imposed by the bridge structure and the traffic load. Tests in AUR Flume duplicated the scour. Tests with scAUR™ products prevented the scour.

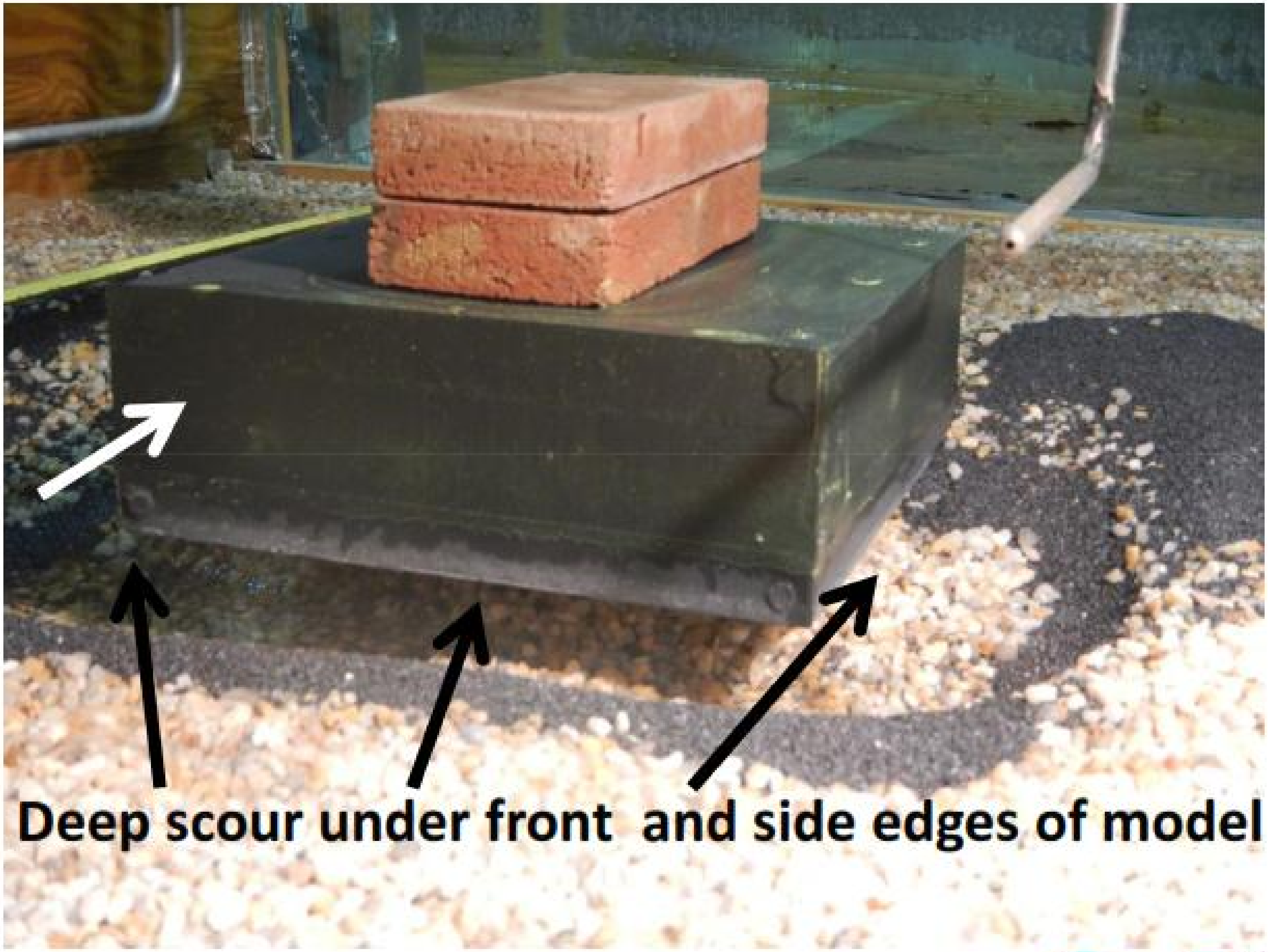


AUR Flume Tests

Case 39: Base seal model in the flume

RESULTS AFTER ONE HOUR TEST RUN

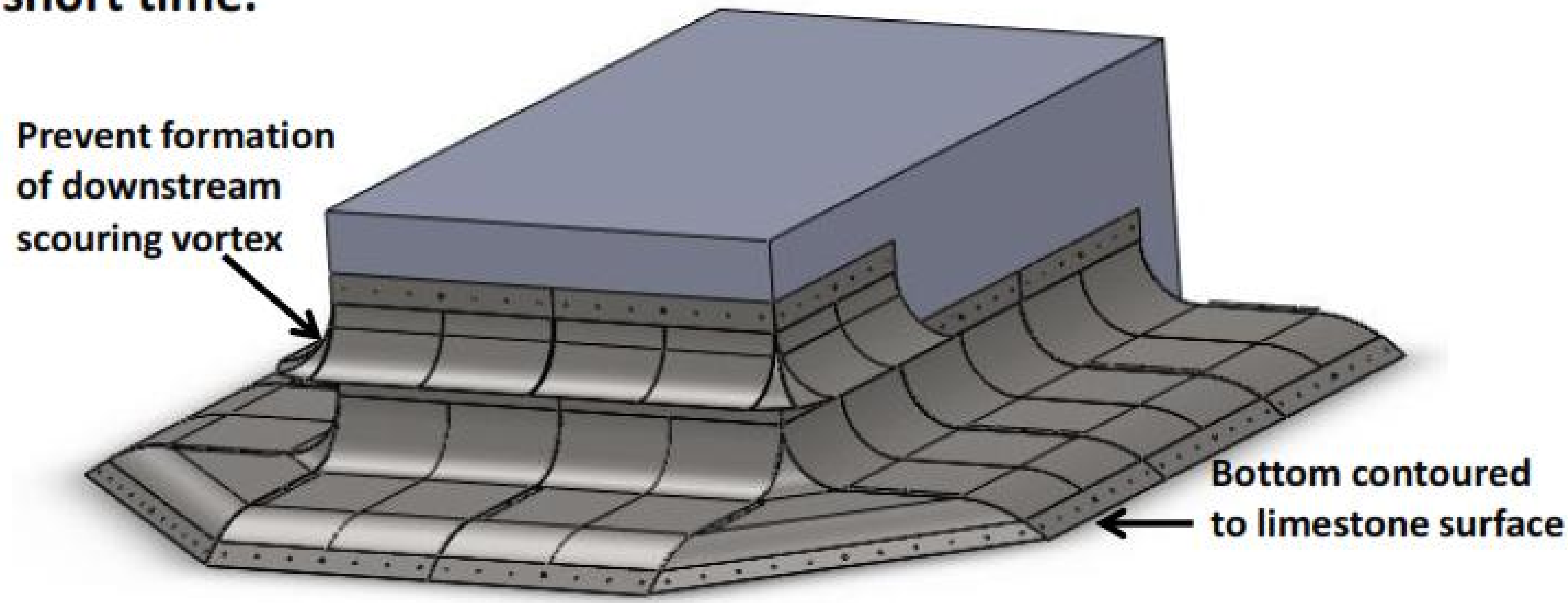
Flow



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

< Is the ONLY scouring-vortex-preventing design for foundation rock scour prevention.

< Uses cost-effective modular stainless steel units that can be attached to the concrete seal using standard methods over a short time.



This design is protected by United States Patents 8,348,553 and 9,453,319

™

AUR Flume Tests

Case 43: Seal model with C-shaped extended ramp on the front and both sides

RESULTS AFTER ONE HOUR TEST RUN

Note that the streamlined ramps and fairings have prevented scour near and under the seal and downstream.

PERMANENT COST-EFFECTIVE SOLUTION

1. Through many years of design and testing, streamlined scAUR™ fairings with VorGAUR™ counter-rotating vortex generators PREVENT THE VORTICES THAT CAUSE SCOUR AT ALL FLOW SPEEDS.
2. Save up to 90% of current scour-countermeasures-related expenses over the life of a bridge.
3. Analysis of bridge failures show that scAUR™ with VorGAUR™ costs < 1% of liability & replacement costs.
4. Proven prevention of scour in laboratory and full-scale testing for many configurations for piers and abutments, including flows up to 45 degrees angle of attack, bridges downstream of river bends and swirling flows, narrow passages, flows with open bed scour, isolated & groups of piles, bedrock scour.

Conclusions

> Many bridges over water are susceptible to scour of supporting rocks and soil by vortices created at the structure during peak flow events such as floods.

> scAUR™ with VorGAUR™ designs and components prevent the formation of scouring vortices for all flow speeds.

> In every case of failure, 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.

Conclusions (Cont.)

> 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 (CFD) 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.

Contact Us for More Information About Other Cases or If You Have Questions

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