Title Page

Title: **Scour Preventing Fairings for Bridges: Results from a Recent NCHRP-IDEA Project**

4999 words, 10 figures

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Abstract

A cost-effective optimized robust three-dimensional convex-concave hydrodynamic fairing with attached vortex generators was tested further for hydraulic structures such as bridge piers and abutments during a National Co-operative Highway Research Program (NCHRP-IDEA) project. Its shape prevents creation of scouring vortices that cause the local scour problem for any river level, speed, and angles of attack up to 20 degrees. This device exceeds requirements for HEC-23. Cost-effective versions are of stainless-steel or conventionally cast concrete that are attached to an existing or cast as part of the base of a new hydraulic structure above the footing, respectively. The vortex generators energize the decelerating near-wall flow with higher-momentum flow, resulting in a more steady, compact downstream separation and wake and substantially mitigated scour inducing vortical flow.

While previously proven by computations and model-scale flume tests, new experimental test results from the NCHRP-IDEA project confirm that scAUR™ scouring-vortex-preventing fairings prevent foundation local scour for smaller sediments, wing-wall and spill-through abutments, and full-scale piers, as well as alleviating the effects of open-bed scour on foundations.

Other advantages of this robust device over other current approaches are: (1) much lower costs for scour prevention and bridge maintenance; (2) much lower probability of bridge failure;(3) lower river levels due to lower drag and lower flow blockage around the pier or abutment; (4) much lower possibility for debris and ice buildup; and (5) greater protection of piers and abutments against impact loads.

Introduction- Background of Bridge Pier and Abutment Scour

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). It has been estimated that 60% of all bridge failures result from scour and other hydraulic-related causes (2). This has motivated research on the causes of scour at bridge piers and abutments (3) and led bridge engineers to develop numerous countermeasures that attempt to reduce the risk of catastrophe. Unfortunately, all currently used 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 (4,5). Consequently, sediment such as sand and rocks around the foundations of bridge abutments and piers is 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 (4) 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 current designs.

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 1 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 sediment scour, and forms a scour hole.

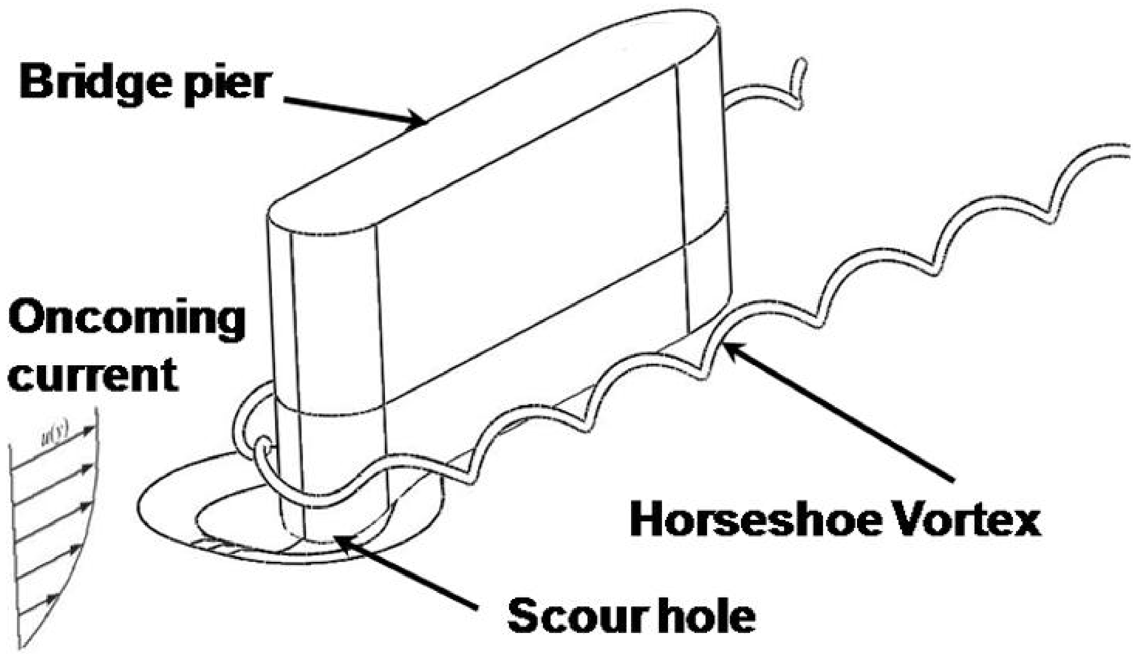

Figure 1. The formation of a horseshoe vortex around the bottom of a bridge pier with no scouring-vortex prevention.

The flowfield around an abutment is also highly three-dimensional and involves strong separated vortex flow (6). A separation bubble is formed at the upstream corner of the abutment. Unsteady shed wake vortices are created due to the separation of the flow at the abutment corners. These wake vortices are very unsteady, are oriented approximately parallel to the abutment edge and have low pressure at the vortex cores. These vortices act like small tornadoes, lifting up sediment and creating a large scour hole behind the abutment. The downflow at the front of the abutment is produced by the large stagnation pressure gradient of the approaching flow. The down flow rolls up and forms the primary vortex, which is similar to the formation of the horseshoe vortex around a single bridge pier.

It should be noted that rip rap countermeasures are not acceptable design elements for new bridges (1). 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 flow rate (1). Unlike temporary scour countermeasures, the streamlined control Against Underwater Rampage fairing scAUR™ (pronounced like 'scour') designs 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 (7).

Features of scAUR™ that Prevent Scouring Vortices

Using the knowledge of how to prevent the formation of discrete vortices and separation for junction flows (8,9,10), prior to this NCHRP-IDEA 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. A hydraulically optimum pier or abutment fairing 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 (Figure 2).

Recently NCHRP research using hundreds of sets of scour data (4) shows that model-scale bridge scour experiments produce much more severe scour depth to pier size ratios than the scour depth to pier size ratios observed for full-scale cases due to scale or size effects. Thus, the scAUR™ fairing will work just as well in preventing the scouring vortices and any scour at full scale as at the proven model scale.

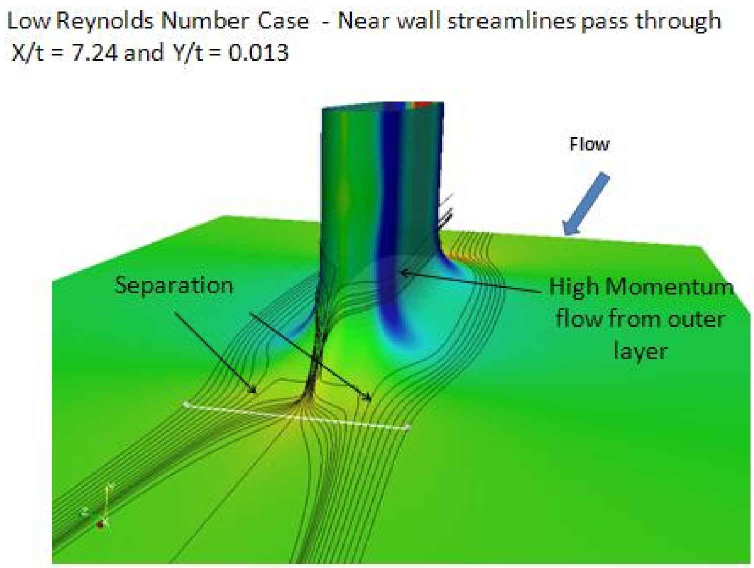

Figure 2 Low Reynolds number case CFD calculated flow streamline patterns around a scAUR^{TM} streamlined bridge pier fairing. Flow indicates no discrete vortex formation on nose and sides.

<u>**Current NCHRP-IDEA Project**</u>

This project focused on providing more evidence that the scAUR^{TM} and VorGAUR^{TM} concepts and products work at full scale in preventing scour-producing vortices and for a wider range of geometries and conditions. Task I, which is not dicussed further here, dealt with selecting a scour-critical bridge in Virginia for prototype installation (7). Further computational work on the effect of pier size or scale (Task II) 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, not discussed here) were tested (Task VI). Cost-effective manufacturing and installation of scAUR™ and VorGAUR™ products were further developed (Task VII).

<u>TASK II – Computational Fluid Dynamic (CFD) Calculations for a Full-scale Pier compared to low Reynolds Number Model-scale CFD</u>

While much previous AUR computational and experimental work at model size ($Re_t = 1.34x10^5$, pier width t = 0.076m) was done to prove these designs, Reynolds number and bridge pier size effects were examined using computations to confirm the applicability of these products at full scale ($Re_t = 2.19x10^6$, t = 0.624m). Since the V2F Reynolds-averaged Navier-Stokes (RANS) model in the Open Foam code is proven to accurately compute 3D flows and the presence of any separation or discrete vortices (7,8,9,10,11,12), then the behavior of mean streamlines, the local non-dimensional surface pressure coefficient C_p, and the local surface skin friction coefficient C_f are sufficient to determine if any separation or discrete vortices are present(7).

Figure 2 shows a perspective view from downstream of near-wall streamlines that pass through X/t = 7.24 at Y/t = 0.013, where t is the pier width. No vortices or separation are observed upstream of the stern or tail of the pier and there are similar streamline features for both Reynolds numbers. An important feature in the C_p and the C_f results is the lack of any abrupt changes in the slope of C_p or C_f over a short distance, which means that there is no discrete vortex formation and separation. The non-dimensional drag on the pier is clearly lower for the higher Reynolds number case because C_f is always lower and the overall drag is an integral of the surface shearing stress over the pier surface area. In addition, these results show lower flow blockage than without the scAUR™ and VorGAUR™ products because low velocity swirling high flow blockage vortices are absent. As a result, water moves around a pier or abutment faster near the river surface, producing a lower water level at the bridge and lower over-topping frequencies on bridges during flood conditions for any water level when no discrete vortices are present.

Based on the past published work on scour and experience of AUR *(8, 9, 10)*, 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 *(3,4,13)* 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, not reported here, shows that scAUR™ and VorGAUR™ products also prevent scouring vortices around bridge piers downstream of bending rivers.

TASK III Flume Tests with Several Smaller Size Sediments at Model Scale

Data on the performance of the scAUR™ fairing and VorGAUR™ VGs were obtained using several smaller size sediments at model scale in the AUR flume to prove the applicability of the designs for fine sediments *(7).* All tests were at a flow speed of 0.66mps when incipient open bed scour of the pea gravel (3.2mm to 6.3mm) was first observed. Melville (14) states that the greatest equilibrium scour depth occurs around a circular pier (width = t) when it is surrounded by uniform sediment at times when the flow velocity equals the critical value, i.e., incipient conditions for open bed scour. Also, live bed scour depth is never larger than incipient scour depth. Melville states: "Recent data by *Sheppard et al.* (13) demonstrate **significant scour depth reductions for increasing**

t/*d50* when t/*d50* > 50. ***Thus, local scour depths at field scale may be significantly reduced from those observed in the laboratory."*** The "t/*d50*" term is the ratio of pier width to median grain diameter. **A value of t/*d50*=50 was used, with a range of sediments from 38.1 to 64.6**.

Three sieved sand or gravel sizes were used to encompass this range for previously reported flow conditions where scour will be the greatest for the AUR t = 76.2mm wide model pier: **Gravel A**: 1.18 to 1.4 mm; **Gravel B:** 1.4 to 1.7mm; **Gravel C**: 1.7 to 2mm. Usually smaller sediment scours before larger pea gravel. **No scour around the scAUR™ model occurred for any of these black slag gravel at speeds when the open bed pea gravel began to scour *(7)* within the y/t = +/- 0.004 measurement uncertainty.**

Task IV.A – Flume Tests of SCAUR™ and VorGAUR™ Concepts for a Larger Class of Abutments

The performance of scAUR™ and VorGAUR™ concepts for wing-wall and spill-through abutments was examined by model scale flume tests at incipient open bed scour flow speeds of 0.66mps (7) and show that scAUR™ and VorGAUR™ prevent the formation of scouring vortices and scour.

Figure 3 shows surface oilflow results for a scAUR™ modified wing-wall abutment with VorGAUR™ vortex generators (VGs)*(7)*. The mixture of yellow artist oil paint and mineral oil flows with the skin friction lines. Yellow streaks are first painted about perpendicular to the flow direction on a black painted surface. The flow causes some oil to be carried downstream in a local flow direction, which can be observed against the black painted surface. **Figure 3 clearly shows that the effects of the scAUR™ with VorGAUR™ are to bring lower velocity flow up from the flume bottom and prevent the scour around the bottom of the abutment.**

Figure 4 shows the deep scour holes for the untreated wing-wall abutment without scAUR™ and VorGAUR™. **With a scAUR™ modified wing-wall abutment with VGs, there is not only no scour around the model base (Figure 5), but there is no open bed scour hole farther downstream of the model around x/L = 2.** This is because the VGs generate counter-rotating vortices which diffuse and reduce the strength of the free-surface generated vortex, which caused the scour hole farther downstream of the model for the untreated case.

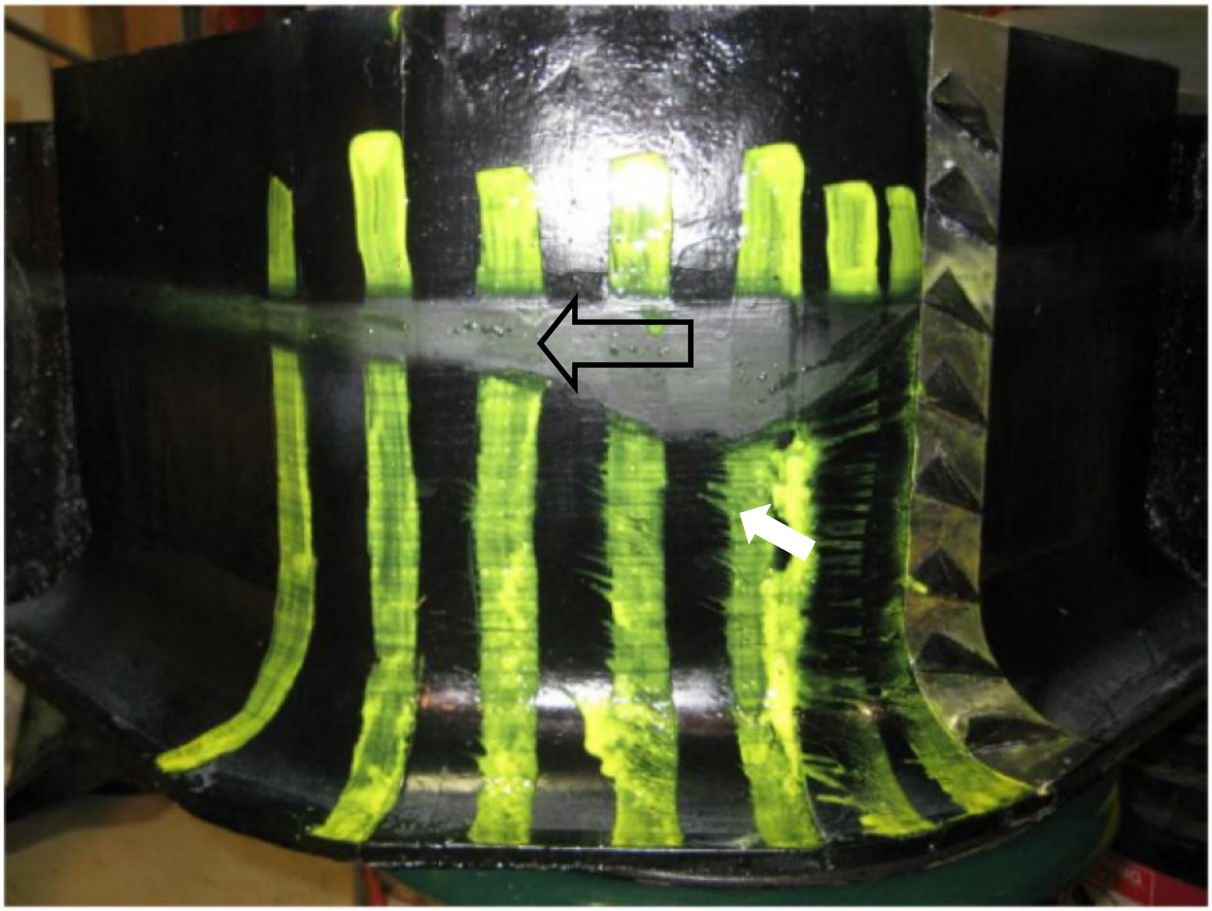

Figure 3. Surface oilflow results for the modified wing-wall abutment model with VGs. Flow from right to left. The upward streaks show that scAUR™ and VorGAUR™ products cause the flow to move up the abutment. The gray region is produced by a mixture of the oilflow material and waterborne substances at the free surface.

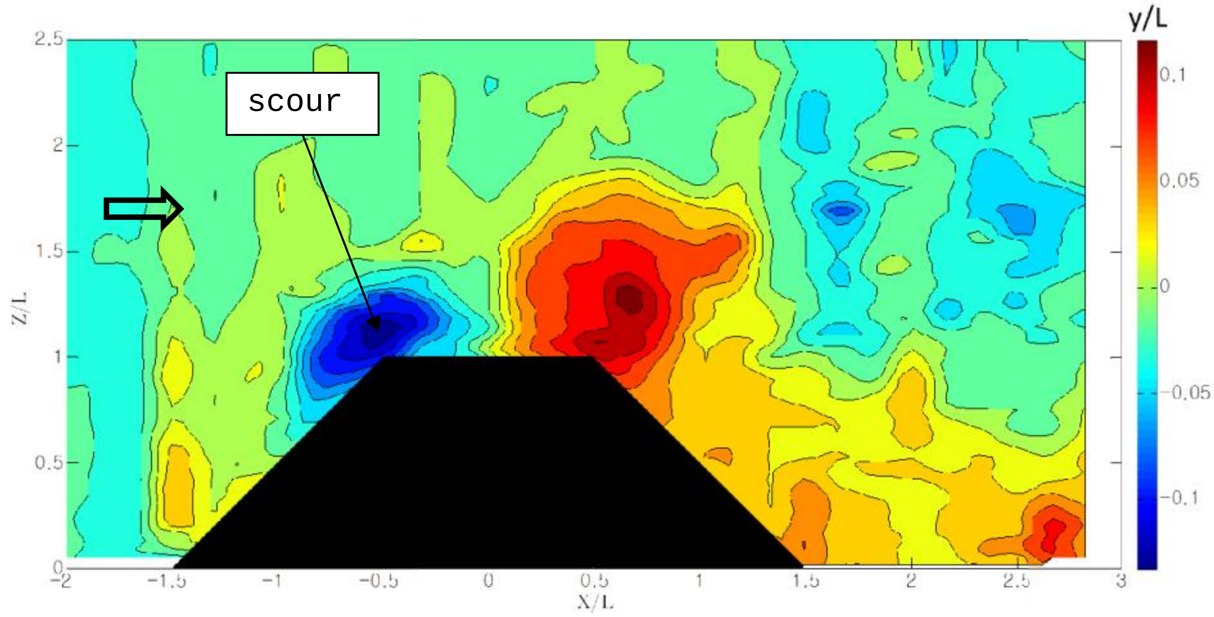

Figure 4. Bed level change contours after and before flow around the wing-wall abutment model with length L = 159mm into the flow <u>without</u> scAUR™ and VorGAUR™ products *(7)*.

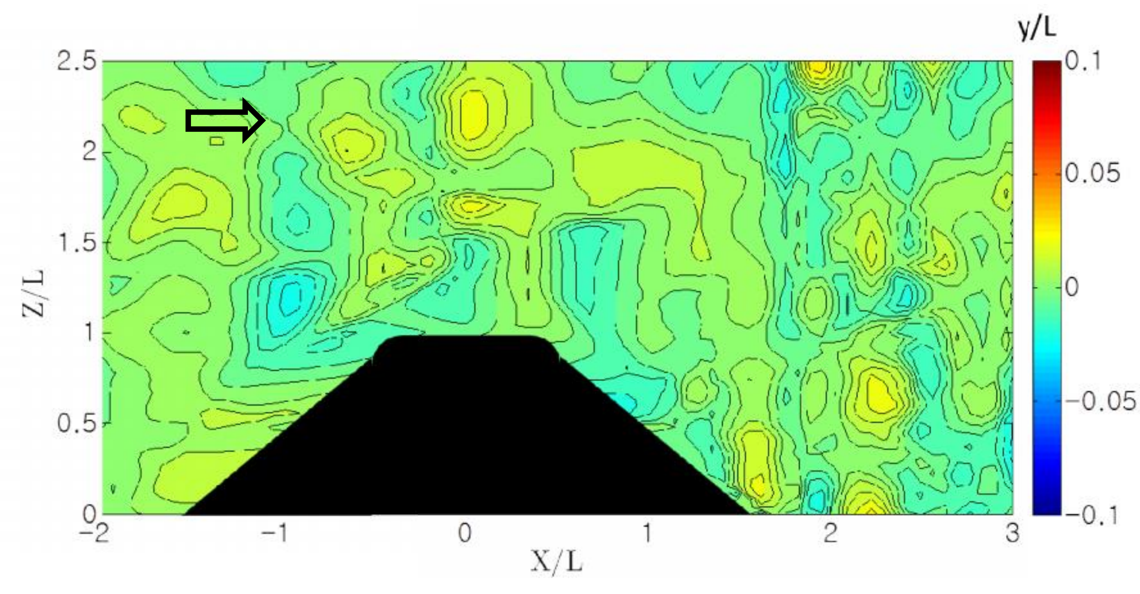

Figure 5. Bed level change contours after and before flow around the scAUR™ modified wing-wall model with VorGAUR™ VGs. No scour observed at any location.

Flow and scour depth results are given for flume tests without and with scAUR™ modified spill-through abutment with VorGAUR™ VGs under the same 0.66mps flow (7). The surface oilflow (Figure 6) clearly shows that the scAUR™ and VorGAUR™ products bring lower velocity flow up from the flume bottom and prevent scour around the bottom of the abutment. Figure 7 shows the deep scour holes for the untreated spill-through abutment (7). Figure 8 shows no scour around the upstream contraction and near the base of the modified spill-through abutment due to the fairing. Although there is still a very minor scour at the downstream of the model, its max depth (-0.02L) is much lower than that for an untreated abutment. **The open bed scour due to the free surface vortex has been prevented.**

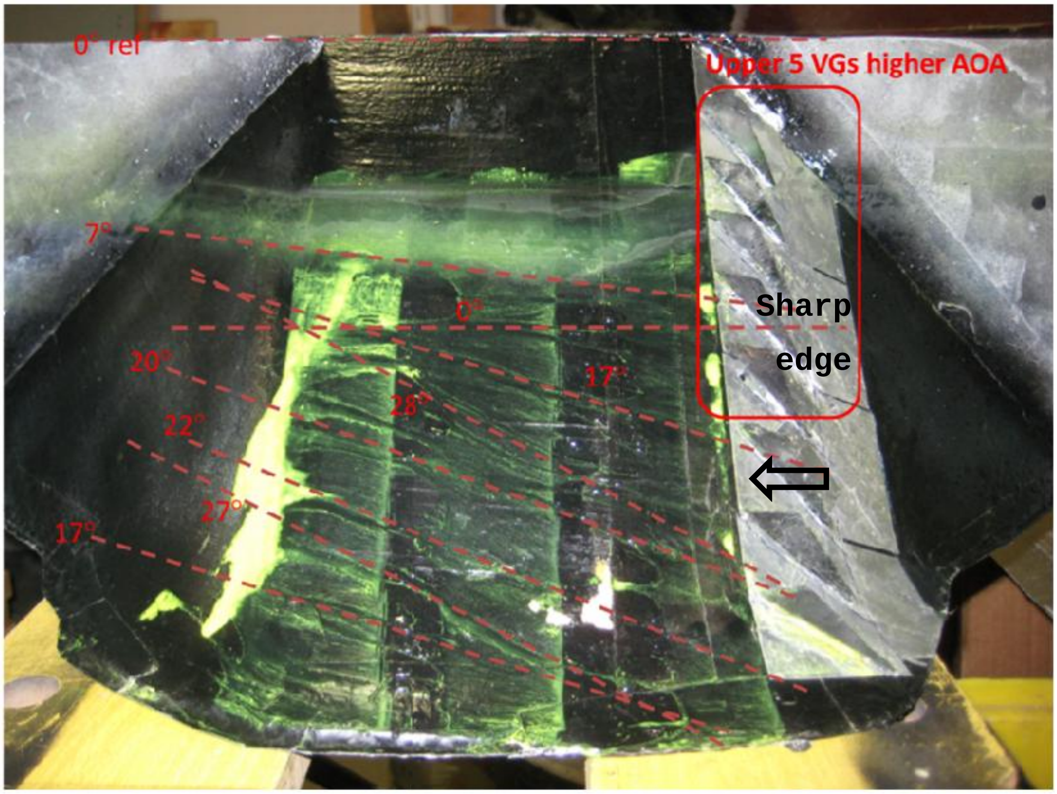

Figure 6. Surface oilflow results for modified sharp-edge spill-through abutment model with 8 VGs. Note that scAUR™ and VorGAUR™ cause the flow to move up the abutment as it moves downstream, bringing low speed fluid from the bottom of the river and preventing scour. The gray region is produced by a mixture of the oilflow material and waterborne substances at the free surface *(7)*.

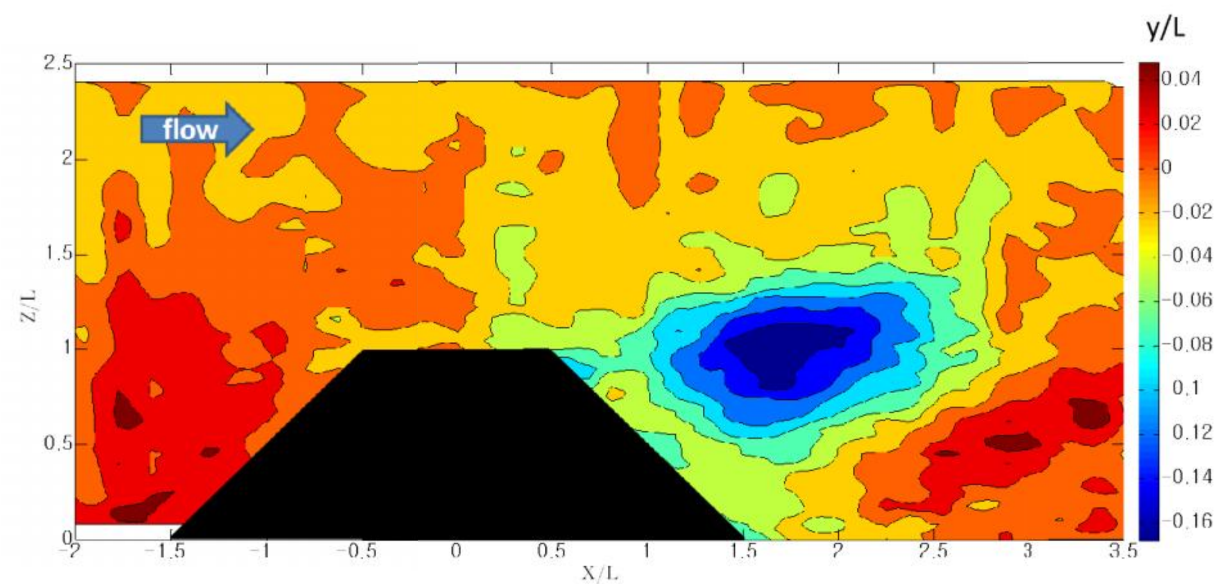

Figure 7. Bed level change contours after and before flow around the untreated spill-through model (L= 159mm). Note the dark blue scour hole.

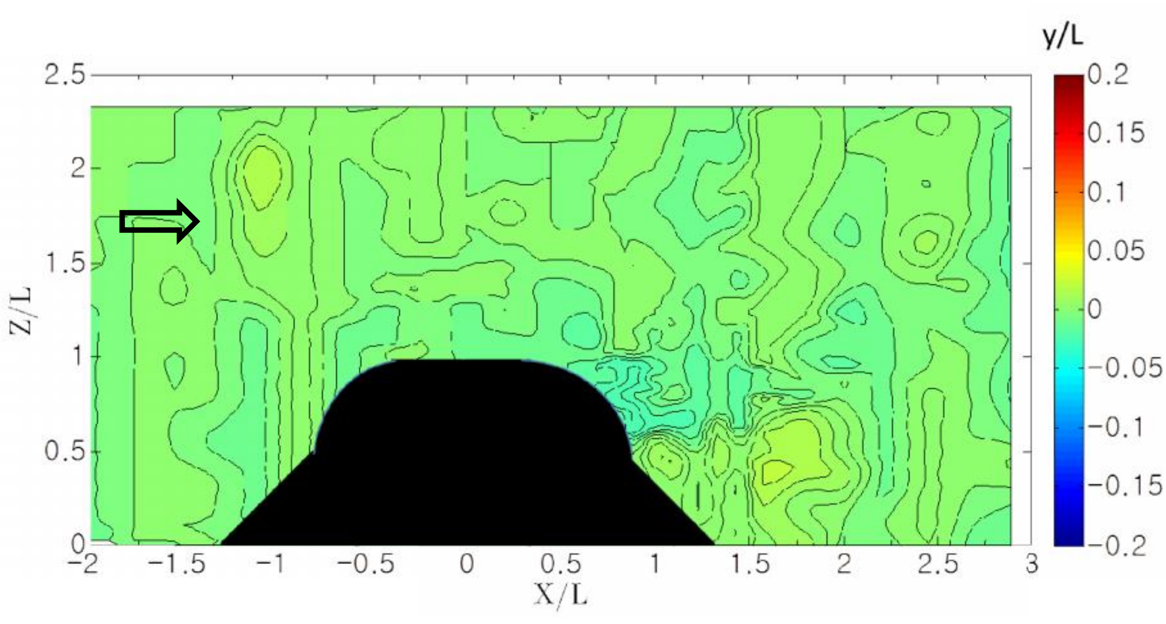

Figure 8. Bed level change contours after and before flow around the scAUR™ modified sharp-edge spill-through model with VorGAUR™ VGs (L = 229mm).

TASK IV.B – Flume Tests of Foundations Exposed by Open Bed Scour

Aspects of the scAUR™ and VorGAUR™ design features have been expanded for use around the foundation (AUR Provisional Patent) in order to further protect the foundation from the effects of contraction scour, long term degradation scour, settlement and differential settlement of footers, undermining of the concrete scAUR™ segments, and effects of variable surrounding bed levels. As all AUR flume studies have shown (7), under these conditions scour of the open bed material occurs at a lower river speed before scour of the material around the base of the scAUR™ fairing occurs.

This means is that scour of the river bed away from the scAUR™ protected pier or abutment occurs first and that the river bed level will be lower away from the pier or abutment. If a pier or abutment foundation is exposed, it will still have a higher immediate surrounding river bed level than farther away. Even so, one would like to further arrest scour around the foundation to prevent high speed open bed scour from encroaching on the river bed material next to the foundation.

Second, if the front of the foundation of a pier or abutment is exposed to approach flows, then a foundation horseshoe or scouring vortex is formed at the front which will cause local scour around the pier or abutment. This suggests that a curved-top ramp be mounted in front of the foundation that prevents the formation of this foundation horseshoe vortex.

Based on these facts, flume tests were conducted with 3 foundation leading edge ramp configurations: (1) an exposed rectangular foundation with no front ramp protection, (2) an upstream curved-top foundation ramp with trapezoidal span-wise edges to produce a stream-wise vortex to bring open bed materials toward the foundation, and (3) a curved-top upstream foundation ramp with straight span-wise edges. Gravel A was used around the foundation since it was the smallest gravel tested in this project in Task III.

Flume tests for scour depth were made for these 3 cases with a 12.7mm high foundation elevation with or without a leading edge ramp *(7).* These tests were done under the same conditions and flume geometry as the cases for Task III with a flow speed of 0.66mps at which the open bed pea gravel begins to be carried downstream. As shown in Figure 9, the model foundation is 12.7mm above the surrounding gravel A bed level.

Without a ramp, as expected, the scour occurred at the front corners of the model due to the front foundation horseshoe vortex. There is gravel accumulation along the pier side near the location of VGs on the scAUR™ fairing on the pier, which is caused by the horseshoe vortices and downstream upflow generated by the VGs.

Although the second case is for the 12.7mm high foundation with a curved-top ramp with trapezoidal sides, scour occurs at the front corner of the ramp and more gravel accumulates along the pier side around the VGs *(7).* There is a gravel mound at the downstream model edge. Therefore, this trapezoidal-sided front ramp is not effective to reduce or prevent the scour.

For the 12.7mm high elevation foundation with a curved-top straight-sided ramp, the front scour and the scour hole and mound next to the foundation along the side are negligible within scour depth measurement uncertainties. The scour hole along the pier side is away from the pier foundation several piers foundation heights and the gravel accumulate on the pier side downstream of the VG. Results for a 19mm high foundation produced very similar results *(7)*. **In summary, all of these foundation tests show that a leading edge straight-sided curved top ramp prevents scour around a foundation when there is open**

bed scour.

Figure 9. Gravel level after flume test for 12.7mm high elevation with a 12.7mm high straight-sided curved leading edge ramp.

<u>TASK VI. Tests of Full-Scale scAUR™ and VorGAUR™ Prototype in the University Of Iowa Institute of Hydraulic Research (IIHR) Flume.</u>

Full-scale pier model scour tests were conducted during 2013 in the University of Iowa Institute of Hydraulic Research (IIHR) 3.05m wide Environmental Flow Facility, which is described at the website: http://www.iihr.uiowa.edu/research/instrumentation-and-technology/environmental-flow-facility/. Previously measured inflow velocity profiles by IIHR validated the high quality of flow in this flume, which increased confidence that high quality and unquestionable scour data would be obtained. The full-scale model was attached to the flume floor.

Two test gravel sediment sizes (specific gravity = 3) were used during each test. With only a trace amount below 3.2mm, by weight about 63% of the smaller sediment gravel was between 3.2mm and 6.3mm and 37% was between 6.3mm and 9.5mm. The larger test gravel, which filled most of the flume bed, was between 9.5mm and 16mm. A 88.9mm outside diameter vertical circular cylinder model was located downstream of the scAUR™ model about 0.46m from a flume side wall and 0.46m from the end of the gravel bed and tested with the larger gravel at the same time as each of the several configurations of the scAUR™ full-scale model to show that the flow conditions cause scour with the cylinder. Test runs continued until after the cylinder scour reached equilibrium conditions with no further observed scour. With the larger gravel, the equilibrium scour hole was 76mm deep in front of the cylinder and extended 89mm upstream with a span-wise width of 0.28m.

Measurements were obtained for the scour depth around the base of the model after the flume was drained using photos of laser sheet surface locations (5), surface oilflows over the model to determine the local surface flow direction, and some pitot tube flow velocity data in front of and around the model. Five full-scale model configurations were tested with the larger and smaller gravel on opposite sides of the model: Configuration A, full-scale 10.16m long 1.42m wide scAUR™ model with 6 VorGAUR™ vortex generators with three 2.44m side sections on each side, as shown in Figure 10, flush with the gravel bed top; Configuration B, same as Configuration A, but with 8 VorGAUR™ vortex generators; Configuration C, same as B, but with the straight-sided leading edge curved-top ramp like in Figure 9 above and the model 76mm above the surrounding gravel bed; Configuration D, full-scale scAUR™ with 8 VorGAUR™ vortex generators with only one side section on each side and flush with the gravel bed; Configuration E, full-scale scAUR™ nose and tail sections with 4 nose section VorGAUR™ vortex generators with no side sections.

Configuration A was tested to examine the full-scale flow and scour behavior for a pier width to length ratio similar to candidate scour-critical bridges. Another vortex generator was added for Configuration B to try to move more flow upward near the model end. Because the curved-top leading edge ramp was useful in preventing scour around foundations exposed by open-bed scour in the AUR small model flume studies (Task IV.B above), Configuration C was tested. Configuration D was selected to examine the effect of pier width to length ratio on scour for cases where multiple circular piers in a row could be surrounded by one scAUR™ fairing. Configuration E examines scour for the case where a scAUR™ fairing is around one nearly circular pier.

The small and large gravel bed sections are flush with the edge of the model for all configurations, except Configuration C when the model is elevated 76mm above the bed to simulate a foundation exposed by open bed scour. The flume test section water level was 0.91m above the test bed and the near-free-surface flow speed was about 0.76mps for all Configurations, since “open-bed” scour of the smaller gravel was observed at this speed.

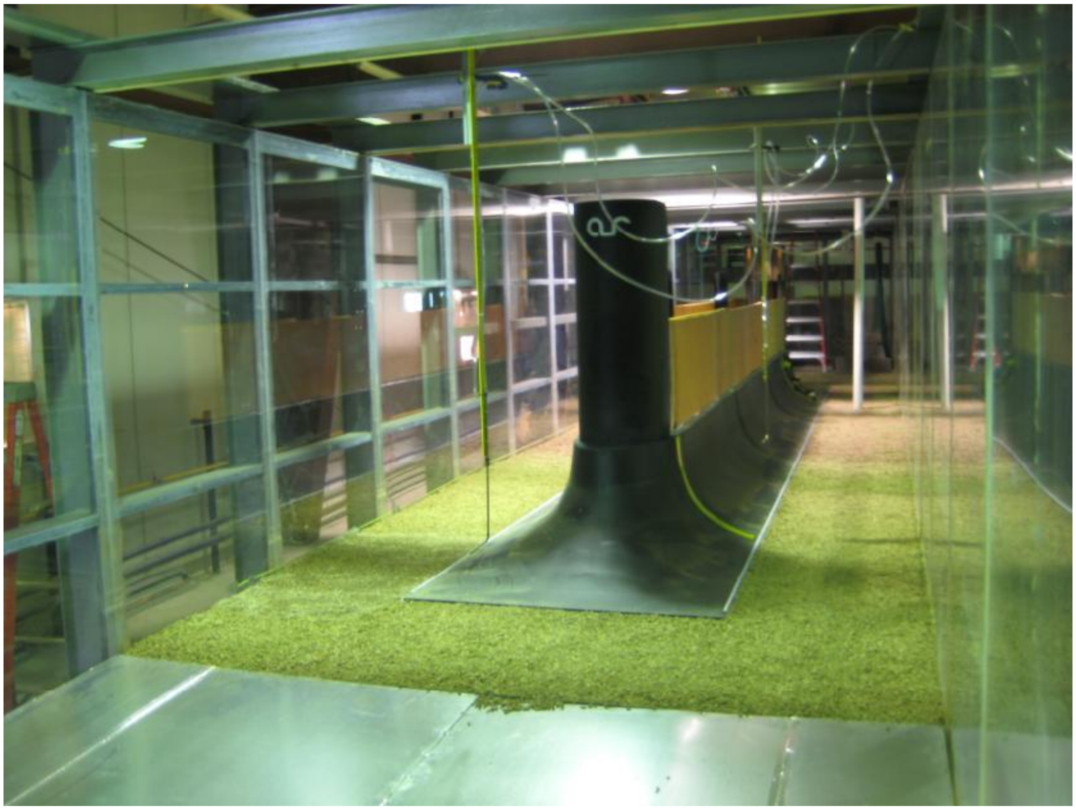

Figure 10. Photo from upstream of the AUR full-scale 10.16m long 1.42m wide scAUR™ with VorGAUR™ vortex generators model in the IIHR Environmental Flume Facility with three 2.44m side sections on each side for Configurations A and B. Small and large gravel on opposite sides are flush with the edge of the model.

In summary of these tests, the full-scale model tests confirmed that there was no scour around the front and sides for each Configuration with either the smaller or larger gravel, as was also observed at model scale. Only a small amount of scour of the smaller gravel was observed downstream, which was due to full-scale model width to flume width (0.15 to 1/3) flow blockage effects, which were comparable to flow blockage results for the 1/7 size models in the AUR flume (7).

TASK VII. Cost-effective Manufacturing and Installation of scAUR™ and VorGAUR™ Products

Before this project, AUR performed a cost benefit analysis of scAUR™ with VorGAUR™ as compared to current scour countermeasures *(7).* 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 *(7).*

There is no situation where scAUR™ and VorGAUR™ products cost more than current countermeasures. 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 (7).

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 (7).

Retrofit to an Existing Bridge

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 (7). 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 (7).**

New construction

In the case with new construction, essentially the difference between the way cast-in-place bridge piers and abutments are constructed currently without the scAUR™ products and in the future with the scAUR™ products is that scAUR™ steel forms for the concrete are used *(7).* All standard currently used concrete construction methods and tools can be used. During the bridge design phases, the bridge pier or abutment foundation or footer top surface width and length would need to be large enough to accommodate the location of the scAUR™ concrete fairing on top. Rebar needed for the scAUR™ would be included in the foundation during its construction. Stainless steel rebar for welding to the stainless steel vortex generators mounting plates on the surface need to be used for specific locations. **Clearly, since the new construction cost is about 1/3 of retrofit costs, the best time to include the scAUR™ fairing on piers is during new construction (7).**

CONCLUSIONS

Local scour of bridge piers and abutments is a common cause of highway bridge failures. All currently used countermeasures are temporary and do not prevent the root cause of local scour – discrete large-scaled vortices formed by separations on underwater structures. Using the knowledge of how to prevent the formation of discrete vortices, prior to this NCHRP-IDEA project, AUR developed, proved using model-scale tests, and patented new local-scouring-vortex-prevention products that are practical cost-effective long-term permanent solutions to the bridge pier and abutment local scour problem. In this current NCHRP Project, further computational work on the effect of pier size or scale and model flume tests for other sediments, other abutment designs, and for open bed scour conditions showed that the products prevent scouring vortices and scour. Full-scale prototypes were successfully tested and cost-effective manufacturing and installation plans were developed. **The present value cost of these products over the life of a bridge are an order of magnitude cheaper than current scour countermeasures.** Plans for installation of a prototype version on a scour-critical bridge in Virginia are underway.

Acknowledgments

The scAUR™ and VorGAUR™ were developed first with IR&D funding from AUR, Inc. The new work here was partially supported as Project NCHRP-162 from the NCHRP-IDEA program. The authors appreciate the endorsements and involvement from New Hampshire, Texas, and Virginia DOTs for the NCHRP program.

References

1. Lagasse, P., Zevenbergen, L., Schall, J., and Clopper, P., *Bridge Scour and Stream Instability Countermeasures.* FHWA Technical Report Hydraulic Engineering Circular (HEC)-23,

2001.

2. Briaud, Jean-Louis, *Monitoring Scour Critical Bridges*, NCHRP Synthesis 396, 2006.

3. Ettema, R., Yoon, Byungman, Nakato, Tatsuaki and Muste, Marian, *A review of scour conditions and scour-estimation difficulties for bridge abutments*, ***KSCE Journal of Civil Engineering***, Volume 8, Number 6, Pages 643-65, 2004.

4. Sheppard, D.M., Demir, H., and Melville, B., *Scour at Wide Piers and Long Skewed Piers*, NCHRP-Report 682, 2011.

5. Tian, Q.Q., Simpson, R.L., and Lowe, K.T., *A laser-based optical approach for measuring scour depth around hydraulic structures,* 5^{th} International Conference on Scour and Erosion, ASCE, San Francisco, Nov. 7-11, 2010.

6. Barkdoll, B.D., Ettema, R., and B. W. Melville, *Countermeasures to Protect Bridge Abutments from Scour*, NCHRP Report 587, 2007.

7. Simpson, R. L., *Unabridged Report on Full-Scale Prototype Testing and Manufacturing and Installation Plans for New Scour-Vortex-Prevention scAUR*^{TM} *and VorGAUR*^{TM} *Products for a Representative Scour-critical Bridge,* AUR, Inc., Internal Report NCHRP-162, July 2013.

8. Simpson, R.L. *Turbulent Boundary Layer Separation*, ***Annual Review of Fluid Mechanics***, Vol. 21, pp.205-234, 1989.

9. Simpson, R.L., *Aspects of Turbulent Boundary Layer Separation*, ***Progress in Aerospace Sciences***, Vol.32, pp.457 – 521, 1996.

10. Simpson, R. L., *Junction Flows,* ***Annual Review of Fluid Mechanics,*** Vol. 33, pp. 415-443, 2001.

11. Durbin, P.A. and Petterson Reif, B.A., ***Statistical Theory and Modeling for Turbulent Flows***, Wiley, 2001.

12. Simpson, R.L., “Some Observations on the Structure and

Modeling of 3-D Turbulent Boundary Layers and Separated Flow,” ***Invited Plenary Lecture, Turbulent Shear Flow Phenomena-4,*** Williamsburg, Va, June 27-29, 2005.

13. Sheppard, D.M., Odeh,M., Glasser,T., “Large Scale Clear-Water Local Pier Scour Experiments,” ***J. Hydraulic Eng***., ASCE, Vol. 130, pp. 957 -063, 2004.

14. Melville, B., “The Physics of Local Scour at Bridge Piers,” ***4th International Conference on Scour and Erosion***, Tokyo, Japan, 2008.