New Omni-directional Scour-Resistant Design for Bridge and Pier Circular Monopiles

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ABSTRACT

Bridge failures over water are likely due to scour, often during floods and peak flow events. Such 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 nature of scouring vortices is discussed and some earlier work using scAUR^{TM} with VorGAUR^{TM} to prevent scouring vortices for nearly unidirectional approach flows at all flow speeds is reviewed. The main purpose of this article is to introduce the new cost-effective omni-directional scour-resistant design for bridge and pier circular monopiles with scAUR^{TM} and new picscAUR^{TM} that prevent scour at all flow speeds. This design has a stacked scAUR^{TM} shaped bottom structure next to the seabed, an inverted picscAUR^{TM} design next, followed by another scAUR^{TM} shaped structure, and finally picscAUR^{TM} ribs on the monopile itself. The scAUR^{TM} surfaces may produce vortices of a scouring sense while the picscAUR^{TM} surfaces produce counter-rotating vortices, resulting in very low flow speeds next to the seabed and nearly no scour.

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, previously used scour countermeasures that do not prevent the scouring vortices, which is the root cause of the local scour, are temporary responses that require many recurring costs (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.

Other than the AUR scAUR^{TM} (streamlined control Against Underwater Rampage) special streamlined fairings that prevent scouring vortices and VorGAUR^{TM} (Vortex Generators Against Underwater Rampage), 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. Thus, 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. 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. Some earlier work using scAUR^{TM} with VorGAUR^{TM} to prevent scouring vortices for nearly unidirectional approach flows at all flow speeds is reviewed.

The main purpose of this article is to introduce the new cost-effective omni-directional scour-resistant design for bridge and pier circular monopiles with scAUR^{TM} and new picscAUR^{TM} that prevent scour at all flow speeds and all flow directions. This design has a stacked axisymmetric scAUR^{TM} shaped bottom structure next to the seabed, an inverted axisymmetric picscAUR^{TM} design next, followed by another axisymmetric scAUR^{TM} shaped structure, and finally axisymmetric picscAUR^{TM} ribs on the circular monopile itself. The scAUR^{TM} surfaces may produce weak vortices of a scouring sense while the picscAUR^{TM} surfaces produce counter-rotating vortices, resulting in very low flow speeds next to the seabed and nearly no scour. The cost of the bridge failures and cost-effective manufacturing and installation of scAUR^{TM} with picscAUR^{TM} designs are briefly discussed.

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 circular monopile by a separating boundary layer. The horseshoe vortex brings higher velocity water downward toward the bed, produces high turbulent shear stress on the bed, triggers the onset of rock and soil scour, and forms a scour hole around the monopile. The leeside wakes deposit the scoured material as shown in the scoured depth contours (Figure 1b). Like in tornadoes, stretching of the horseshoe vortices due to the contraction of the flow on the pier sides 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 flow bed. The 5.79m (19 foot) wide Schoharie Creek pier nose created intense scouring horseshoe vortices (Simpson and Byun, 2019). 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 or ocean bottom.

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 should 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, Flint et al. 2017). Unlike temporary scour countermeasures, the scAUR^{TM} (pronounced like 'scour') fairing designs, discussed below and by Simpson and Byun (2017, 2021), 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.

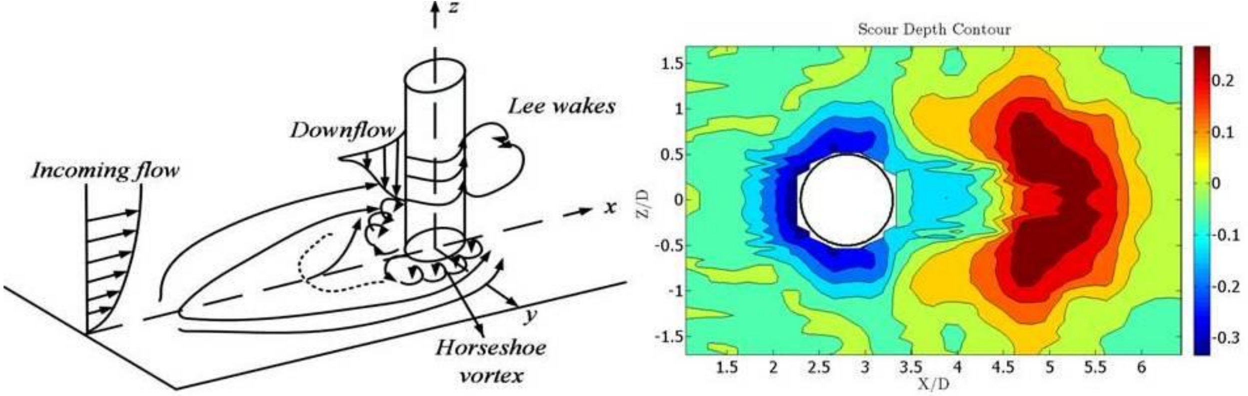

Figure 1. (a, left) The formation of a horseshoe vortex around the bottom of a monopile pier with no scouring-vortex prevention (Wang et al. 2020). (b, right) Measured scour depth contours around a circular cylinder pier (normalized by pier diameter D) after a one-hour 0.65mps surface-water-speed test run (flow left to right) with 2.5mm gravel (Tian et al. 2010).

EARLIER WORK USING scAUR^{TM} WITH VorGAUR^{TM} TO PREVENT SCOURING VORTICES FOR NEARLY UNIDIRECTIONAL APPROACH FLOWS

As discussed in more detail by Simpson (2013) and Simpson and Byun (2017, 2021), 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^{TM} 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 meets this requirement for all water speeds. No one before had used this design feature, thus leading to the patents.

The scAUR^{TM} design fundamentally alters the way the river flows around a pier or abutment. The scAUR^{TM} scouring-vortex-preventing fairing, US Patent No. 8,348,553, and VorGAUR^{TM} 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 or abutment and reduces 3D separation downstream of the bridge pier or abutment with the help of the VorGAUR^{TM} vortical flow separation control. 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^{TM} 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^{TM} and VorGAUR^{TM} 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^{TM} and VorGAUR^{TM} designs also prevent scouring vortices around bridge piers downstream of bending rivers.

Simpson and Byun (2021) discuss the importance of analyzing individual bridge cases using a physics-based approach with a proven turbulence model in a fully three-dimensional Navier-Stokes computational fluid dynamics (CFD) code. The detailed geometry and approach flow situation affect the flow behavior. An example is the case of rock scour under a concrete pier seal in a swirling river flow.

As discussed by Simpson and Byun (2021), there is no situation where scAUR^{TM} and VorGAUR^{TM} designs cost more than current countermeasures. There is no situation where any type of scour is worse with the use of the scAUR^{TM} and VorGAUR^{TM} designs than without them. The more frequent that scouring floods occur, the more cost effective are scAUR^{TM} and VorGAUR^{TM}. Clearly, scAUR^{TM} and VorGAUR^{TM} designs are practical and cost-effective for highway bridges (Simpson and Byun 2017).

Simpson and Byun (2019) discuss the liability costs associated with injuries and the loss of life in bridge failures due to scour. While there may have been some construction deficiencies with the Schoharie Creek Bridge, prior to the bridge collapse 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.

NEW OMNI-DIRECTIONAL SCOUR-RESISTANT DESIGN FOR BRIDGE AND PIER CIRCULAR MONOPILES WITH scAUR^{TM} AND NEW picscAUR^{TM}

The requirement for this design application is that it prevent scour around a circular monopile for any flow approach direction. The axisymmetric design needs to work for tidal applications, coastal storm surges, and tsunami situations. In these cases, strong high speed flows can occur, first in one direction and then the opposite or another direction. Clearly, the VorGAUR^{TM} vortex generators cannot be used since they are effective for only one general direction. What is needed is a design that generates vortices that are counter-rotating to any scouring vortices.

As described above, the scAUR^{TM} shape meets the key upstream streamlined fairing design requirement that the surface shape produces surface pressure gradients that limit the flux of new vorticity at the surface so discrete vortices are not formed. However, as the flow moves around the monopile, it separates. producing a highly turbulent leeside flow (Figure 1a) that can fatigue the bed material and move it downstream, as shown in Figure 1b. A single scAUR^{TM} shaped device like Surface C in Figure 2 raises up away from the bed any vortex that is formed and lowers the surface flow speed and scour. However, it alone would produce some small depth of downstream scour, as tests in the AUR flume have shown. All other devices such as axisymmetric collars and flat plates on the bed produce a horseshoe vortex on the upstream side as well as a more intense leeside separated flow that produces a deep downstream scour hole, as other comparison tests in the AUR flume have shown.

Figure 2 shows a new omni-directional scour-resistant design for bridge and pier circular monopiles with scAUR^{TM} and new picscAUR^{TM} design, which is also protected by US Patent 9,453,319. In Figures 2 and 3, when the upstream clockwise vortical flow approaches the structure, the highest speed flow below 2H is at the uppermost location, as shown by the flow velocity profile in Figure 3. As the flow moves over the properly spaced axisymmetric angle stainless steel (SS) roughness on Surface B, momentum and kinetic energy are greatly reduced, and counter-clockwise vorticity in a trapped eddy or vortex is formed between the angle (SS) ribs as shown in Figure 3. Shamloo and Pirzadeh (2015) and Kadivar et al. (2021) review and show the rotational flow pattern of a trapped eddy between the rib roughness elements. Simpson (1973) pointed out the effect of a trapped eddy on the flow. Also, the counter-clockwise direction of the trapped eddy was verified by the direction of colored thread tufts mounted on Surface B between the ribs when the model shown in Figure 4 was in a flow. The vortical flow trapped between the angle pieces is forced around the side of the pile due to the spanwise pressure gradient. These vortices are stronger and are of the opposite sense to the vortices formed by the Surfaces A and C, which have the sense of scouring vortices.

Above Surface A on the upstream side of the monopile, a strong downflow occurs, as suggested in Figure 1a. Using the picscAUR^{TM} design features, as the flow moves downward over the properly spaced axisymmetric angle steel roughness on the monopile above Surface A (Figures 3 and 4), momentum and kinetic energy are greatly reduced, and counter-clockwise vorticity is formed, just like on Surface B. This vortical flow is trapped between the angle pieces and is forced around the side of the pile. This vorticity is of the opposite sense to the vortices formed by the Surfaces A and C, which have the sense of scouring vortices.

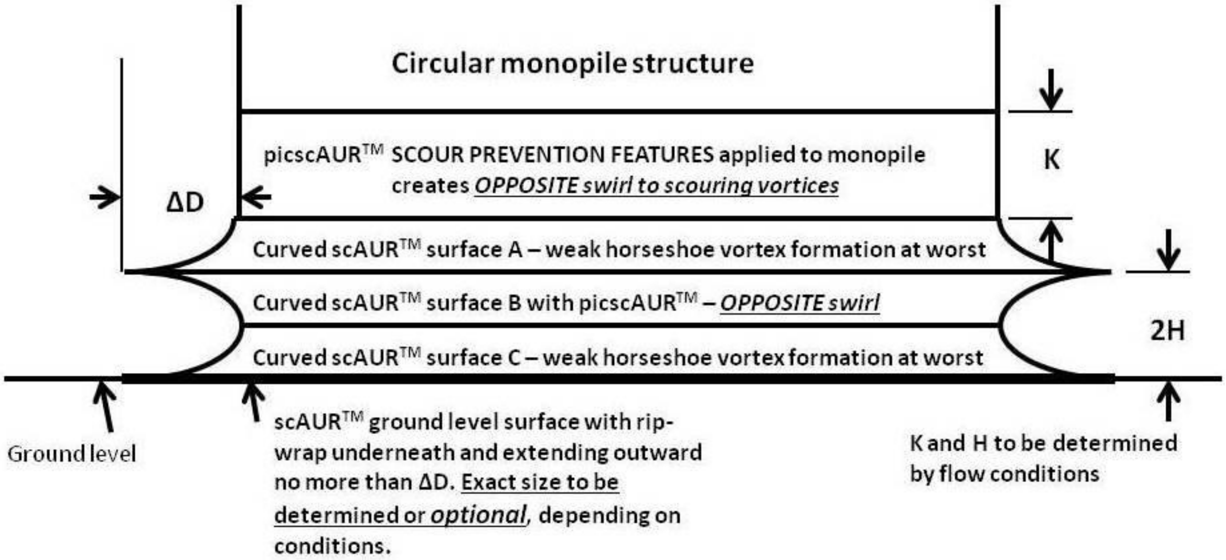

Figure 2. Axisymmetric scAUR^{TM} with picscAUR^{TM} scour prevention features for a monopile, 2nd edition.

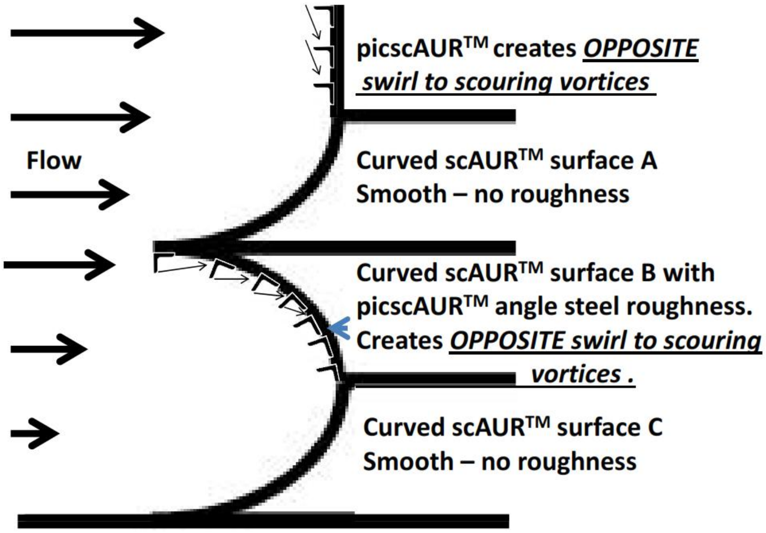

Figure 3. Closeup view of one picscAUR^{TM} design for axisymmetric scAUR^{TM} with picscAUR^{TM} scour prevention features, 2nd edition. The angle steel roughness extends entirely around the monopile in this axisymmetric design.

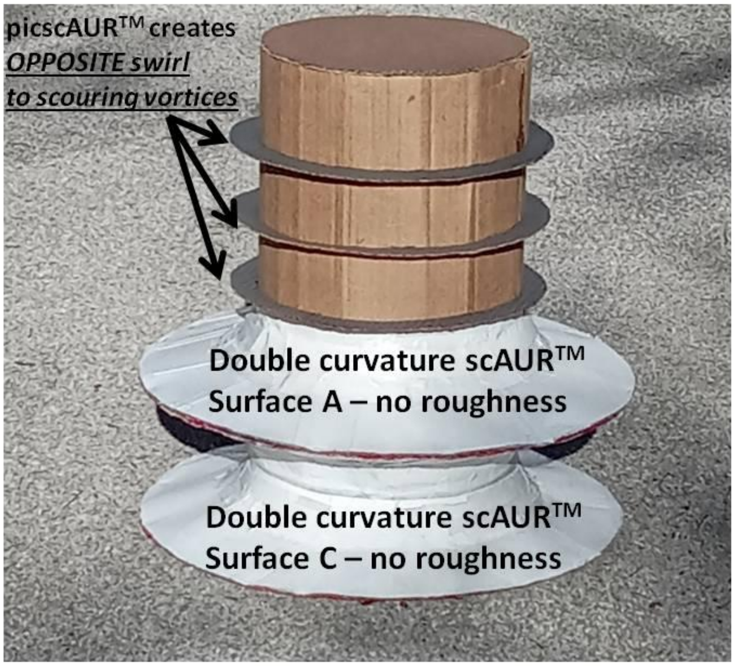

Figure 4. Pile test model (0.3048m or 1 foot diameter) for axisymmetric scAUR™ with picscAUR™ scour prevention features, 2nd edition, on a gravel bed. Double curvature scAUR™ surface B with picscAUR™ angle stainless steel roughness is below Surface A and above Surface C.

The performance of several small water flume models provided data (Simpson and Byun 2022) used to assess the performance of this new scAUR™ and picscAUR™ design. With estimates of horseshoe vortex strengths required to move various-sized test gravel (Simpson 2013), one was able to develop the counter-rotating vortex strengths required from picscAUR™ surface B and the picscAUR™ surface above Surface A (Figure 2) that can nullify the effects of scouring vortices produced on surfaces A and C (Simpson and Byun 2022).

The strength of a trapped vortex or eddy formed on the upstream side is approximately the upstream approach speed at the edge of the rib times the rib spacing (Shamloo and Pirzadeh 2015). Each of the vortices moves around the monopile between adjacent ribs, driven by the pressure gradient with some viscous drag on the ribs and the surface B. Using a combination of a finite element method and integral momentum and continuity equations, the strength of the downstream Rankine combined vortex that emerges from its adjacent ribs can be calculated (Simpson and Byun 2022). Using principals of vortex dynamics (Robertson 1965), the net near-surface flow velocities from all of the shed vortices can be calculated.

Because relatively strong strength counter-rotating vortices can be produced by the rib roughness on the picscAUR™ surfaces, from the calculations above the net bed surface velocity is about 10% or less than that produced by the horseshoe vortex when there is only the monopile, for all approach flow speeds. Since the scouring forces on the bed material vary with the **square** of the local near-bed velocity, this means that the scouring surface force is less than 1/100 of that for a monopile alone. For test flows with only Surface A around the monopile, there was downstream movement of 2.5mm gravel. For test flows under the same conditions but with the model in Figure 4, there was no movement of the 2.5mm gravel.

COST OF THE BRIDGE FAILURES AND COST-EFFECTIVE MANUFACTURING AND INSTALLATION OF scAUR^{TM} with picscAUR^{TM} DESIGNS

Following the cost-comparison methodology as reviewed by Simpson and Byun (2021), the costs and benefits associated with the scAUR^{TM} with picscAUR^{TM} scour-protection designs for monopiles were compared to some current scour protection methods. Currently, a practice is to install monopiles for bridges and piers very deeply into the bed for tidal or expected storm surge areas to guarantee fixity. Peterson (2023) reports that 0.762m (30 inches) and 1.372m (54 inches) diameter concrete piles were driven up to 42.68m (140 feet) into the bottom of the Pamlico Sound for a new bridge since there was about a 15.85m (52 foot) scour depth for the previous bridge.

The cost for one stainless steel (SS) scAUR^{TM} with picscAUR^{TM} unit varies with the size squared. Its corrosion resistance gives it a lifetime of 100 years even in seawater environments, using a proper thickness, construction methods, and type of SS. For a 0.3048m (one foot) diameter pile, as shown in Figure 4, the cost is less than several thousand US dollars. For retrofits. these units can be prefabricated onshore and installed on the ocean bed by divers, limiting the labor time required. For new piles, a unit may be installed as the pile is driven into the bed. While the scAUR^{TM} with picscAUR^{TM} design may not prevent all scour, especially for fine sandy soils, it is effective for a riprap covered bed. It is clearly less costly than very deep piles. At bare minimum, the scAUR^{TM} with picscAUR^{TM} design is cost-effective for much more confidence that the pile will not lose fixity. 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, 2019, 2021).

CONCLUSIONS

Many bridges over water around the world are susceptible to scour of supporting rocks and soil during peak flow events such as floods, tidal events, coastal storm surges, and tsunami situations. Here a new omni-directional scour-resistant design for bridge and pier circular monopiles with scAUR^{TM} and a new picscAUR^{TM} design was presented for all flow speeds. It meets the design requirement that it prevent scour around a circular monopile for any time-varying flow approach direction. In these cases, strong high speed flows can occur, first in one direction and then the opposite or another direction. Because relatively strong strength counter-rotating vortices can be produced by the rib roughness on the picscAUR^{TM} surfaces, the net water bottom bed surface velocity is about 10% or less than that produced by the horseshoe vortex when there is only the monopile. Since the scouring forces on the bed material vary with the **square** of the local near-bed velocity, this means that the scouring surface force for this scAUR^{TM} and new picscAUR^{TM} design is less than 1/100 of that for a monopile alone.

The costs associated with the fabrication and installation of the scAUR^{TM} with picscAUR^{TM} design are very favorable compared with other traditional scour protection methods. The installed cost for a seawater resistant stainless steel (SS) scAUR^{TM} with picscAUR^{TM} unit varies with the size squared. This approach is clearly less costly than using very deep piles. At bare minimum, the scAUR^{TM} with picscAUR^{TM} design is cost-effective for much more confidence that the pile will not lose fixity. Current temporary countermeasures are much more expensive when the present value of future expenses is considered, especially regarding liability costs associated with failures. Bridge owners receiving US federal funds are no longer prohibited from using patented or proprietary products in designs.

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