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REDUCTION OF BRIDGE PIER SCOUR THROUGH THE USE OF A NOVEL COLLAR DESIGN

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Abstract: Bridge pier scour is the cause of many bridge failures as the pier foundations can become undermined, therefore jeopardizing the structural integrity of the bridge. Due to the potential harm associated with pier scour, numerous prevention methods have been designed and practised which either alter the riverbed around the pier or the shape of the pier itself. However, there is not one method that is easy to install, minimally intrusive, low cost, and maintenance free. The purpose of this study is to present a novel three-dimensional collar as a new scour counter measure alternative. The collar works by containing the horseshoe vortex that forms on the front and sides of the pier and then directs the vortex in the downstream direction away from the critical region around the pier. The erosive vortex behaviour is then unable to touch the riverbed, thus avoiding scour. To guide the collar design process, OpenFOAM (CFD) software was utilized in an iterative manner to provide the flow field behaviour of successive designs. A benefit of this novel collar is that it can be constructed offsite in multiples pieces, transported to the pier location, and simply installed on the pier, making it an easy and minimally intrusive option, while requiring little to no maintenance in the future. The goal of this novel scour counter measure is to provide a new viable solution to the industry which can overcome many of the existing issues.

1 INTRODUCTION

When constructing bridges over rivers or bodies of water, it is ideal to avoid the use of piers positioned within the water; however, this is often unavoidable due to the distances that need to be spanned. In such cases, piers are anchored into the riverbed and protrude out of the water to support the bridge. However, when anchoring into the riverbed, the piers become susceptible to local scour. Scour, which is the reduction in riverbed elevation and in this case, around the base of bridge piers, has proven to be detrimental to the structural integrity of bridges (Chiew 1992). Rapidly or over time, sediment becomes removed within a close proximity to bridge piers, which can lead to the undermining of the pier foundation, ultimately jeopardizing the safety of the bridge (Deng and Cai 2010).

Local scouring occurs because of the presence of a structure interrupting the passing flow. In this case, the structure is a bridge pier which induces flow separation throughout the entire depth as piers always extend out above the water surface. As a result, a portion of the flow is split and redirects itself around the pier causing a local acceleration on either side of the pier. As the faster moving water passes the sides of the pier, alternating vortices, revolving about a vertical axis, are formed and shed off either sides of the pier travelling downstream (Stevens et al. 1991). Due to the orientation of the vortices, sediment along the sides and rear of the pier can be drawn up the low pressure center of the vortices and then deposited a short distance downstream of the pier (Ettema et al. 2006). The remainder of the flow that is obstructed by the pier is drawn downwards to the riverbed due to a pressure gradient. Upon reaching the riverbed, the flow circulates outwards forming a vortex that propagates around the upstream face of the pier and down the sides eventually dissipating downstream into the passing flow (Dey and Raikar 2007). This vortex is known as the horseshoe vortex and is the largest contributing factor in pier scour as sediment is dislodged upstream and along sides of the pier and is transported downstream (Stevens et al. 1991). The combination of both vortex behaviours, but mainly the horseshoe vortex, form the common scour holes present around many bridge piers which can be seen in Figure 1.

Figure 1: Scour hole downstream of a pier at Agassiz Bridge, Fraser River, BC.

Bridge pier scour has been a popular topic of study for many years due to the potential to harm the public and property. As a result, various different approaches have been taken to address scouring, which can be summarized into four categories: hydraulic, structural, biotechnical, and monitoring counter measures (FHWA 2009). The first, hydraulic counter measures, are intended to address the passing flow or the riverbed surrounding the pier. This can be done by altering the flow near the pier, utilizing sacrificial piles or vanes for example, which helps to deflect the flow and create a region of lower velocity directly upstream of the pier. Another hydraulic approach, being the most common, is to apply armouring around the base of the piers with for example riprap, gabions, or grout filled containers. This method does not alter the flow but rather protects the vulnerable riverbed areas from the erosive forces of the vortices formed around the piers (FHWA 2009). The second counter measure, structural, pertains to addressing the structural aspects of the pier and bridge itself. This can be accomplished by strengthening the portion of the pier that is below the riverbed through extending or underpinning the existing footing. Another approach is to alter the portion of the pier that is above the riverbed by streamlining the shape of the pier, adding structures to the pier such as collars, or cutting holes into the pier, all to reduce the vortex generating factors (FHWA 2009). The third counter measure is biotechnical as it incorporates vegetation such as root wads to perform tasks similar to those of hydraulic or structural counter measures already discussed (FHWA 2009). The last counter measure is monitoring, which does not attempt to directly reduce the scour but instead can give a very informative indication as to the level of erosion that has occurred (FHWA 2009). The four counter measures can be used individually or together, depending on the severity of the situation.

As seen above, there are various types of scour mitigation methods available; however, there are very few that are easy to install, cost effective, minimally intrusive, and low maintenance. One of the most widely used methods is riprap, which is simply larger rocks installed around the base of the pier that protects the sediment from being washed away (Lauchlan and Melville 2001). The problem with this method is that if the riprap is not sized correctly or extreme flooding occurs then some of the rocks can become ejected and transported downstream, reducing the protection around the pier. In addition, upon becoming aware of the dislodged riprap, reinstallation is required to provide the original level of protection necessitating future inspections and maintenance (Lauchlan and Melville 2001). Therefore, there is not one ideal method that can satisfy all of the criteria while guaranteeing protection under extreme flow conditions, which as a result is what motivated the research presented in this paper. There are three main objectives of this paper and they are: 1) to introduce a new, state-of-the-art scour counter measure for cylindrical piers which takes the shape of a collar, 2) to explain the workings of the new collar and its ability to overcome the problems associated with existing scour counter measures, and 3) to perform a numerical modelling flow comparison between a pier with and without the new collar.

2 METHODOLOGY

2.1 Numerical Model

The design of the new pier scour counter measure was guided intensively by the use of a numerical model. The modelling software chosen was the open-source computational fluid dynamics (CFD) software, OpenFOAM v1706, which was used to illustrate the flow behaviour in a channel in the presence of a bridge pier. The solver used within OpenFOAM was *pimpleFoam* operating in *piso* mode which is a transient solver applicable for turbulent, incompressible flows (Hosur et al. 2014). In order to replicate the experimental flow conditions best, the k-omega-SST Delayed Detached Eddy Simulation (DDES) turbulence model was utilized. Detached Eddy Simulation (DES) models switch between Reynolds-Averaged Navier-Stokes (RANS) and Large Eddy Simulation (LES) turbulence models based on the grid size and turbulent length scale for the purpose of reducing the computational cost that is normally associated with LES models. DDES turbulence models improve on the DES models by addressing the issue where the turbulence models switch by shielding the RANS model from the DES model (Gritskevich et al. 2011).

The model domain consisted of a rectangular flume 10m in length, 0.85m in width, and 0.15m in depth, filled entirely with water. A cylindrical pier, 0.09m in diameter by 0.15m tall, was generated used *snappyHexMesh* and situated 1.5m from the outlet. An 8.5m approach was used because, based on a sensitivity analysis, it was found that the flow becomes fully developed after approximately 8m. A flume width of 0.85m was used because when the walls are situated that far apart, they do not interfere with the wake generated by the pier.

In order to achieve the most accurate results while maintaining a reasonable computational cost, two refinement regions were used. First, a level one rectangular refinement, yielding a cell size of 0.004m, was used at the downstream end of the flume stretching 2m upstream by 0.5m across by 0.15m high, therefore encompassing the pier and downstream wake. Then, a level two cylindrical refinement, yielding a cell size of 0.002m, was used around the pier, 0.2m in diameter by 0.06m high, to ensure a high resolution result in the focus area at the base of the pier. In total, this complete mesh yielded a cell count of approximately 5.5 million cells and an average y+ value of 25 at the base of the pier. This mesh was chosen because a sensitivity analysis was performed consisting of six different meshes each possessing an equally finer mesh and the velocities at specified locations, for this chosen level of refinement, no longer changed in the focus region and remained constant for finer meshes.

The inlet velocity condition used was *turbulentInlet,* as it consists of a constant inflow which was set to 0.335m/s but also includes a turbulent fluctuation which was set to ten percent of the inflow velocity. The pier and the bottom of the flume were given a *noSlip* condition, while the walls were given a *slip* condition to ensure the walls had as little impact on the passing flow as possible. The top of the flume, which was filled to the surface with water, utilized a *symmetryPlane* to reduce the influence of the top boundary on the flow behaviour especially around the pier. Wall functions were used for the pier and bottom of the flume specifically employing the nutkWallFunction and the nutkRoughWallFunction, respectively. The rough wall function was used only for the bottom of the flume because it allows for the bed roughness to be specified, which in this case was 0.001m. To ensure the most efficient computational time, *adjustTimeStep* was turned on such that it adjusted the time step to maintain a maximum courant number of 0.8. In order to calibrate and further validate the results obtained from the numerical model, preliminary experimental tests were performed in a laboratory setting.

2.2 Experimental Setup

The experimental tests were conducted within a straight rectangular flume possessing a length of 30m, a width of 1.5m, and a depth of 0.5m, located in the University of Ottawa's Civil Engineering Hydraulic Laboratory. The focus area was a 4m long section located 3m from the downstream end of the flume. This section possessed a rigid concrete floor surfaced with sieved 0.001m sand affixed to the concrete surface in a uniform layer. The purpose of using a fixed floor was to replicate the conditions within the numerical model since OpenFOAM is not equipped with sediment modelling capabilities. In the center of the 4m long focus area of the flume, a cylindrical acrylic pier with a diameter of 0.09m was installed to the floor vertically. The tests were run under constant flow conditions where the depth was set to 0.15m and the velocity was maintained at 0.36m/s at a height of 0.07m above the bottom. To measure the velocity, an acoustic Doppler velocimeter (ADV) was used. The values used for both experimental and numerical tests were based off of a 1:30 Froude scale.

2.3 Model Validation

In order to validate the numerical model, velocity profiles of the flow were taken in the laboratory flume using the ADV at three locations: 0.72m upstream of the pier where the flow is fully developed yet undisturbed by the pier, 0.14m upstream of the pier at the beginning of the stagnation region, and 0.75m downstream of the pier in the turbulent wake. The velocity profiles consist of a series of point measurements taken 0.05m apart in the vertical direction. A comparison between the velocity profiles obtained numerically and experimentally at the three locations can be seen in Figure 2. At all three locations the numerical model matched the experimental results respectively well indicating a high level of trust in the numerical results. The downstream location possesses error bars, representing the standard deviation, that are substantially larger than the other two locations due to the turbulence induced by the bridge pier.

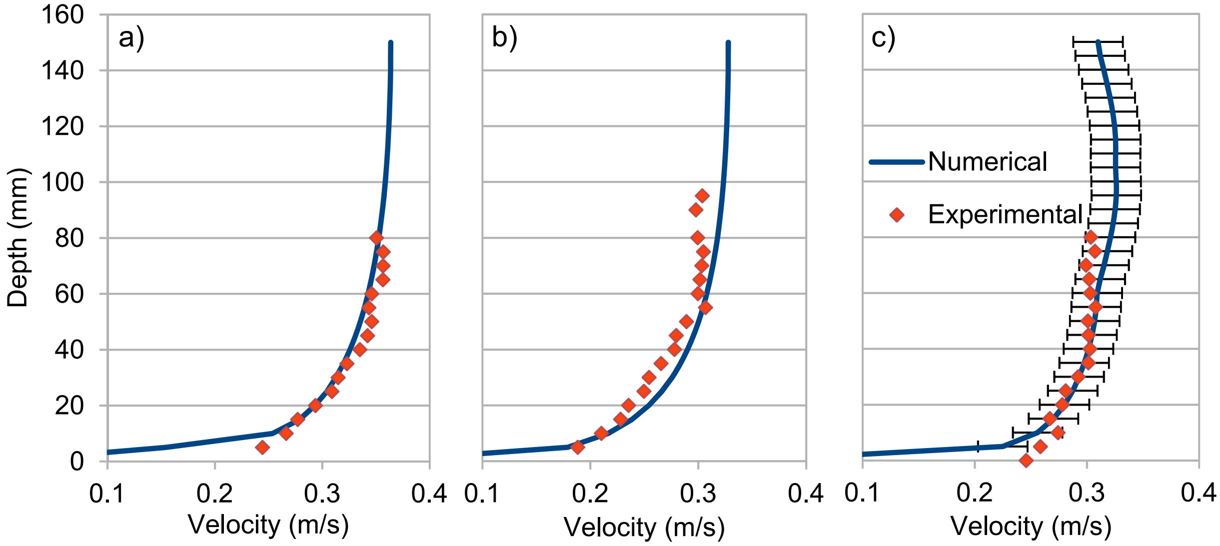

Figure 2: Velocity profile comparison. (a) 0.72m upstream of pier; (b) 0.14m upstream of pier; and (c) 0.75m downstream of pier.

3 SCOUR COUNTER MEASURE DESIGN

It is known that the largest contributor to pier scour is the horseshoe vortex and then to a lesser degree, the wake vortices (Stevens et al. 1991). Therefore, if the goal is to reduce scour then the horseshoe vortex must be addressed. The approach taken with this new counter measure was to harness the horseshoe vortex rather than trying to interrupt or impede its very powerful forces. In doing so, the objective was to disallow the horseshoe vortex from contacting the riverbed by containing it within a structure. This structure was formed into the shape of a circular collar which mounts around the pier and rests on the riverbed. The only similarity between this design and existing pier scour prevention collars is that both revolve around the pier, otherwise the differences are significant. Specifically, as the flow approaches the upstream face of the pier and is drawn downwards to the riverbed, this new collar design allows the flow of water to enter into a rounded cavity within the collar where it can circulate forming the common horseshoe vortex and propagate around the upstream face of the pier as it naturally would. This occurs within the collar cavity until it passes the sides of the pier, then the circulating flow is directed out of the rear of the collar and the energy is dissipated downstream. This can be seen in Figure 3 as the new collar design, more formally known as collar prototype number one, is presented. The main concern is to protect the immediate vicinity around the base of the pier especially on the upstream side and transfer the turbulent flow downstream away from the pier where it cannot harm the stability of the pier foundation.

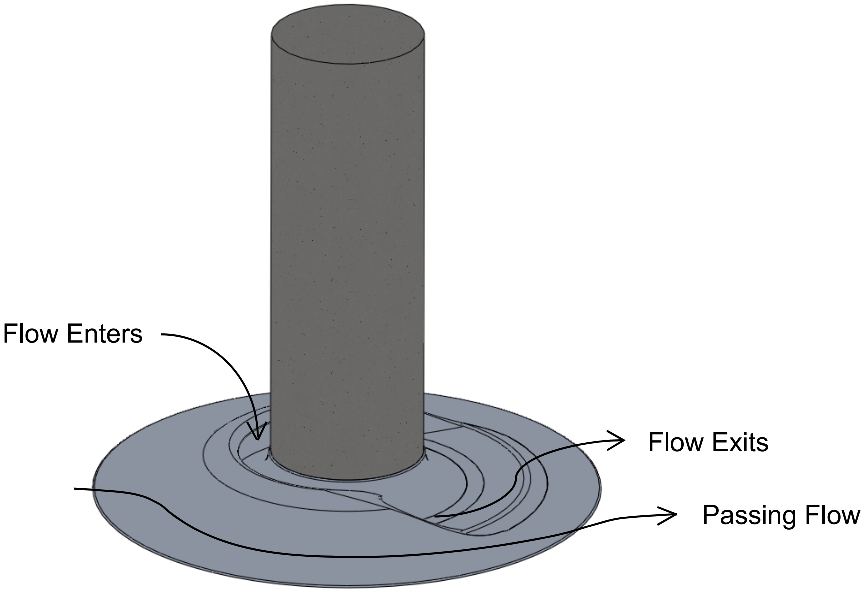

Figure 3: New counter measure design (collar prototype number one).

The remainder of the flow that does not enter into the collar cavity passes over the outer surface. The outer surface was designed in such a way that it slopes down to the riverbed, then curves outwards reaching a thin edge in an asymptotic fashion. This thin flat edge was incorporated to allow the passing flow to step smoothly onto and off of the collar generating as little turbulence as possible, therefore reducing the chances of scour occurring beneath the collar. In addition, the outer diameter of the collar was designed to be 3.3 times the pier diameter because the optimal size for reducing scour is approximately 3 times the pier diameter but in order to accommodate the inner cavity while maintaining the correct outer shape, a slightly larger diameter was required (Kumar et al. 1999). Therefore, any residual turbulence generated by the presence of the pier or raised collar region will not be able to contact the riverbed in the critical region around the pier because it is shielded by the large diameter collar. Lastly, the gradual change in slope was then utilized to gently transition the flow that does not enter the collar cavity to bypass over the collar and around the pier with the goal of minimizing any additional vortices that may form as a result of the collar's presence.

4 RESULTS

The numerical model was utilized throughout the design process as a tool to guide the changes made necessary to achieve a successful design. Specifically, stream tracers were used, as one of the main goals was to entirely contain the horseshoe vortex while using the smallest cavity possible for the purpose of reducing the influence on the passing flow. This took a series of trial and error iterations of analysing the stream tracers to obtain the correct diameter of the inner cavity and the correct outer slope. The shape was deemed successful and the design iterations were seized when the entire horseshoe vortex occurred inside the collar cavity and the redirected flow that did not enter the cavity remained on top of the collar's edge for the entire upstream half of the collar. Initial designs possessed a slope that was too steep which caused the flow that did not enter the cavity to be separated forming a secondary vortex immediately upstream of the collar on top of the riverbed. As a result, this would induce greater amounts of scour counteracting the purpose of the collar.

In Figure 4, a time-averaged comparison is presented showing the flow behaviour around a standard cylindrical pier and the same pier with collar prototype number one. Figure 4(a), which shows the pier without the collar, illustrates the standard flow behaviour where the flow separates in the presence of the pier causing a majority to be redirected around the sides of the pier but also a large portion to be drawn down to the riverbed. In the stagnation region immediately upstream of the pier, almost all of the streamlines approaching the pier are drawn downwards to some degree in the z-direction; however, only the streamlines in approximately the bottom one-third of the water depth are drawn all the way down to the riverbed. This portion of the flow that does reach the riverbed, redirects itself into a circular path, propagating around the upstream face of the pier forming the famous horseshoe vortex. Meanwhile, the remainder of the flow that does not become drawn all the way down to the riverbed redirects itself around the sides of pier but increases in velocity while doing so. The combination of the horseshoe vortex and the increased velocity around the sides of the pier, especially at the base, is what causes the sediment in that region to be dislodged and transported downstream.

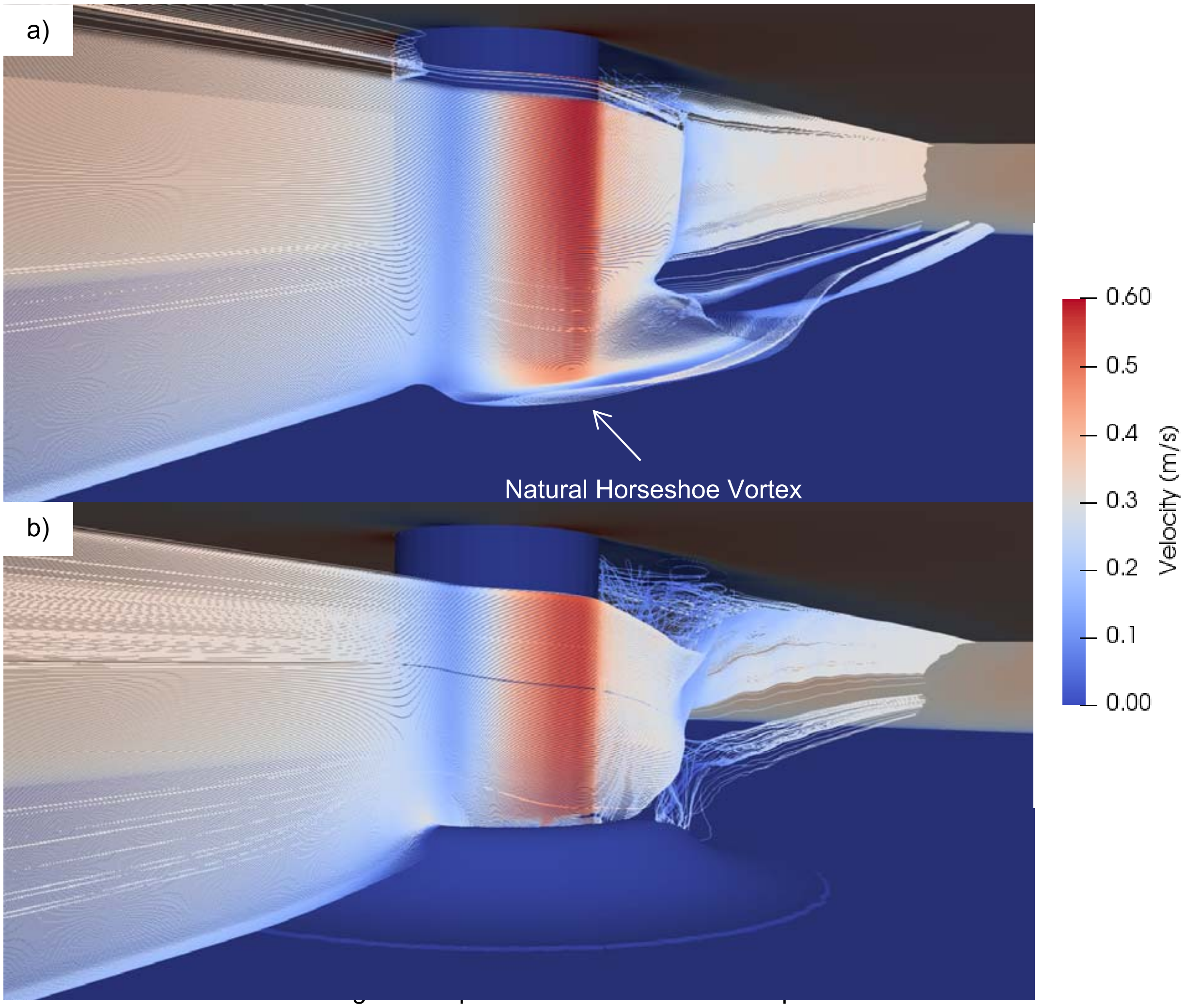

Figure 4(b) shows the flow behaviour as a result of adding the new collar. The streamlines approach the pier and separate in the same manner as when the collar is not present but any of the streamlines that are drawn down to the riverbed enter directly into the collar cavity, circulate within, and then exit out the rear without being interrupted. Due to the collar presence, both scour causing mechanisms, seen when the collar is not installed, are addressed. Firstly, the entire horseshoe vortex no longer contacts the riverbed because it occurs inside of the collar cavity. While secondly, the high velocity flow along the sides of the pier also can no longer induce higher shear stress on the riverbed as the collar protects the entire critical region around the pier. In addition, since the critical region is protected, wake vortices that are naturally generated and shed off of the sides and rear of the pier are not able to scour around the base as it is protected by the collar.

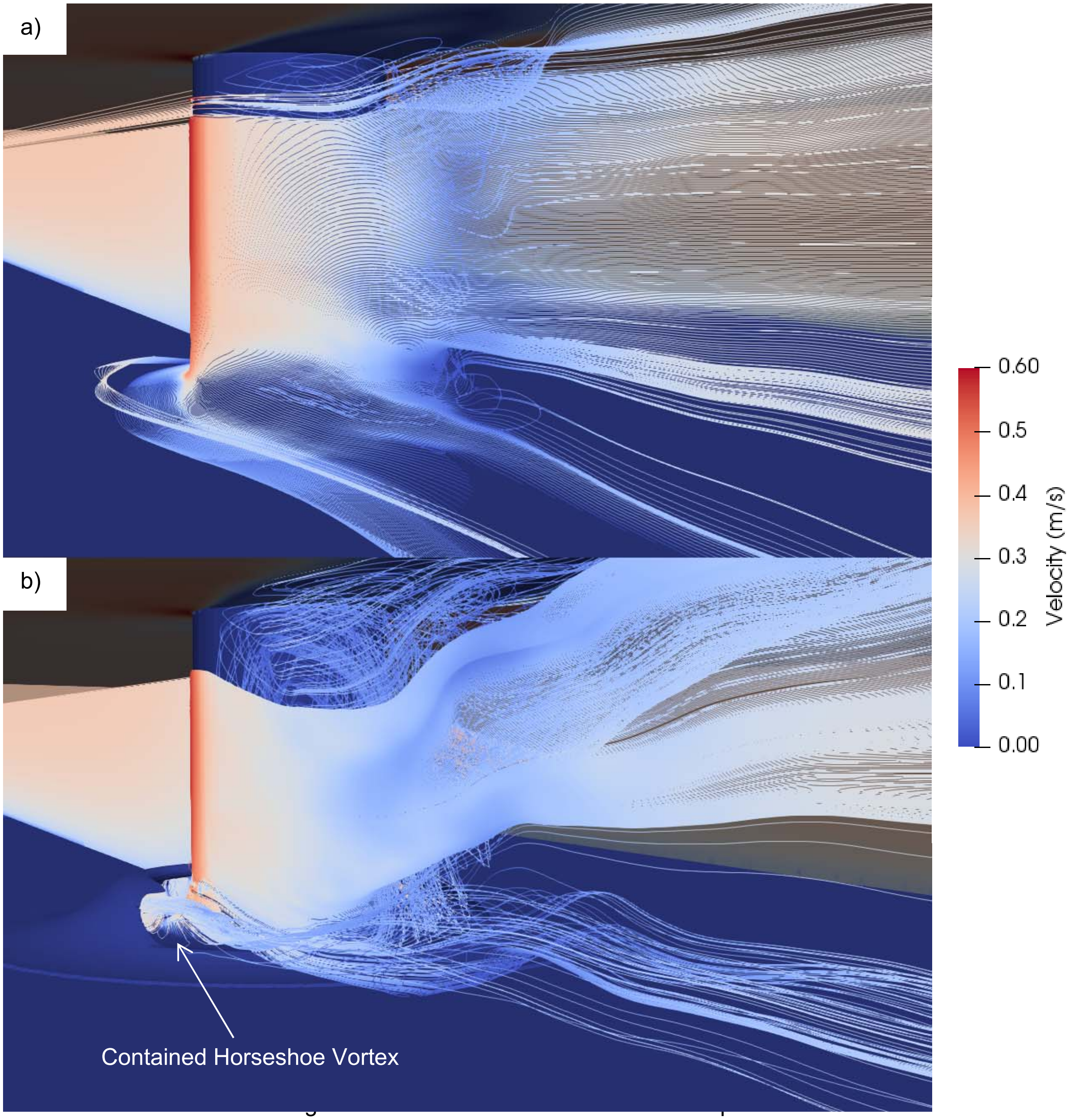

Figure 5 is another comparison at a different angle, looking upstream, of the time-averaged flow behaviour around a pier with and without the collar. When the collar is not present, as seen in Figure 5(a), the horseshoe vortex extends further out from the pier and naturally contacts a large area of riverbed. However, when the collar is installed, the vortex is contained in a more compact manner close to the pier, allowing the remaining flow that is passing by to smoothly traverse over the collar and around the sides of the pier. The benefit to such collar over other counter measures is that the location and size of the horseshoe vortex is stationary and known despite varying flow conditions because it is confined to the predetermined shape of the collar. Figure 5(b) confirms that the horseshoe vortex does actually occur inside the collar cavity because the stream tracers demonstrate the circulating motion within. Once the vortex passes the sides of the pier, it exits out the rear of the collar in an upward direction off of a spoiler. This helps lessen the contact between the exiting vortex and the riverbed, even though there is little harm in small amounts of scour occurring downstream of the pier outside of the critical region.

5 DISCUSSION

Collar prototype number one overcomes the installation issue faced with many other counter measures because it can be constructed offsite in a specific facility. In doing so, the quality of the final product and the accuracy of the shape will be significantly better because there is access to more equipment in a weather controlled environment. To further simplify the installation, the collar will be constructed in pieces at the offsite location and transported to the pier site in smaller manageable sections. Upon arriving to the pier site, these sections will be bolted together around the pier and rested directly on the riverbed. It is crucial that when the collar is installed there is as small of a gap between the collar and pier as possible because the downward flow upstream of the pier will otherwise pass through the gap and erode underneath. This method of construction and installation is minimally intrusive as the pier does not need to be altered and no excavation of the existing riverbed is required, which ultimately results in less of an impact on the surrounding environment.

Another positive aspect of collar prototype number one is the lack of maintenance required. Once the collar is installed on the pier, for the remainder of the collar’s life there is no foreseeable maintenance that is needed since increased flow will not harm the collar. If a large quantity of sediment is transported from upstream and enters into the collar cavity, due to the high velocity that occurs within the horseshoe vortex, the sediment will be washed out and sent downstream. Any stones or debris that are too large to be flushed out will be blocked from entering through the use of a screen affixed to the top of the cavity opening.

To further confirm the versatility and robustness of the design, experimental tests are underway in the laboratory. Numerous other existing scour counter measures, in addition to collar prototype number one, are being examined for comparison purposes under varying flow conditions.

The research presented in this paper possesses some limitations which are mainly attributed to the fact that the collar design is still in its infancy stage. The first limitation is that the collar was made for cylindrical piers only. The intention was to validate the design concept on cylindrical piers due to simplicity, then following validation adapt it for different shaped piers such as square, rectangular, and elongated. Once the shape has been adapted, a solution will then be available for bridge piers of every shape. The second limitation is that the collar was designed for unidirectional flow only, while it is understood that some locations where piers are present experience tides or flows that change direction. The goal is to eventually adjust the design in such a way to accommodate flood and ebb tides but the current focus is on perfecting unidirectional flow. The third limitation is that the physical construction and material of the actual full-size collar has yet to be determined as a thorough investigation into these areas still needs to be performed. The final limitation is that the collar was tested under only one flow velocity and that is due to the high computational cost associated with numerical modelling. However, upon achieving satisfactory results from the experimental tests for this collar design, additional velocities will be investigated to fully evaluate the collar’s capabilities.

6 CONCLUSION

Bridge pier scour has been an issue for many years and a significant amount of time and money has been invested into researching the topic. Many counter measures have been designed; however, there is not one solution that is ideal. The introduction of a new state-of-the-art three-dimensional collar looks to overcome issues existing in the previous scour counter measures by being easy to install, minimally intrusive, maintenance free, and low cost. The newly proposed design works by containing the horseshoe vortex that occurs on the upstream face and sides of the pier within a collar structure that prevents it from contacting the riverbed. As a result, the erosive forces associated with the horseshoe vortex occur within the inner collar cavity and scour is avoided. Therefore, this novel design has the potential to change the way bridge pier scour is currently being addressed and will significantly improve the safety of bridges.

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