**University of Southern Queensland**
**Faculty of Engineering and Surveying**

# How to Mitigate the Effects of Scour on Bridge Piers Through the Use of Combined Countermeasures

**A dissertation submitted by**

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**Towards the Degree of Bachelor of Engineering (Honours)**
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# Abstract

Construction of a bridge pier in a flow of water will cause a disruption to the flow. Scour around bridge piers arises due to the separation of this water causing erosion of the sediment at the bridge pier and leading to the development of both horseshoe and wake vortices around the pier. The relationship between water and bridge piers in flowing streams creates a three dimensional field of flow. There is an additional pressure head upstream of the pier as the water hits the bridge pier which then curves downwards into the scour hole and a horseshoe vortex is formed. The accumulation of flowing water on the surface pushes back and creates a bow wave. The water also deviates around the pier as it continues its downstream flow and produces a shedding wake vortex. Local scouring occurs due to the action of the horseshoe and wake vortices. Local scour is the immediate change in the bed level surrounding an obstruction due to the restriction or change in the natural flow path. This reduction in the depth of bed level is called scour depth. Scour causes significant structural unpredictability. The bridge foundations are weakened and may eventually cause overall failure of the structure especially when there are floods as the volume and intensity of the moving flow increases so rapidly. Researchers have been trying for quite a long time now to find ways to reduce this scour occurring and thus increase the safety of bridge piers.

Experimentation to understand the scour process and the damage a horseshoe vortex causes is usually conducted in laboratories using straight flumes. Results of some studies noted in this literature review showed that the maximum depth of scour was highly dependent on the amount of time for which the experiment was conducted. It also identified that as the flow rate increased so did the level of erosion. Several engineering designs relating to this topic have been tested over the years and they are becoming more successful with time and research. Bridges are very necessary in our modern world so engineers must study the best ways to install bridge piers to create the least disturbance to natural or man-made waterways in turn reducing erosion around the pier.

This research was developed to understand and consequently aim to reduce scour through the economical design and best use of countermeasures around bridge piers.

The project identified, through a literature review and design analysis, three combined countermeasures for bridge piers. Initially countermeasures were built for testing in the large flume. After preparing the large flume for testing and commencing the control test the large flume unfortunately failed. Due to this misfortune models were then built and tested in the small flume. The results compared the control pier and each separate countermeasure with the amount of erosion which occurred. A control pier for the purpose of this research was a circular pier without any countermeasure. Volumes and dimensions were calculated using a laser scanner (FARO) then further processed and modelled using mining software.  These volumes were used identify the greatest reduction in erosion. These outcomes all showed a decrease in erosion when compared with the control pier but one combined countermeasure in particular, three collars and a plate, showed the greatest reduction but did not totally deny scour.

Results show that an effective reduction in local scour can be achieved through the use of three collars as a combined countermeasure but not totally eliminated.

# Limitations of Use

# Certification of Dissertation

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except were specifically stated.

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Signature

28/10/15

Date

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## Nomenclature

| | | |
|---|---|---|
| $A$ | Cross Sectional area | $m^2$ |
| $b$ | Bridge Pier diameter | $m$ |
| $d$ | Particle diameter | $mm$ |
| $d_{50}$ | Medium size of sediment particle by mass | $mm$ |
| $d_s$ | Scour depth | $m$ |
| $Fr$ | Froude number | $dimensionless$ |
| $g$ | Gravity | $m.s^{-2}$ |
| $k_s$ | Grain roughness of bedding material | $mm$ |
| $P$ | Wetted Perimeter | $m$ |
| $R$ | Hydraulic Radius | $m$ |
| $R_e$ | Reynolds number | $dimensionless$ |
| $S_s$ | Specific gravity of sediment particles | $t.s^{-3}$ |
| $v$ | Velocity | $m/s$ |
| $V_c$ | Velocity at critical depth | $m/s$ |
| $y$ | Depth of flow | $m$ |
| $y_c$ | Critical depth of flow | $m$ |
| $\rho$ | Fluid density | $t.m^{-3}$ |
| $\rho_s$ | Sediment density | $t.m^{-3}$ |
| $\tau$ | Shear stress | $N.m^{-2}$ |
| $\tau_s$ | Critical bedding shear stress | $N.m^{-2}$ |
| $\upsilon$ | Dynamic viscosity of water | $Kg.m^{-1}.s$ |

# 1.0 Introduction

Bridges have been built for a millennium. They provide an essential link over many types of obstructions such as waterways and railways permitting transportation to take the most direct route. Bridge failures due to scour have caused destruction to vital infrastructure resulting in financial stress to both governments and the general public. "Man who overlook water under bridge will find bridge under water" (Neill 1973). This study investigates the effects of scour around bridge piers and assesses potential countermeasures to reduce scour. Scour is the removal of existing sediment because of a change in the velocity of the flow and or restriction in the flow path. This can cause structural integrity of the bridge pier to be undermined resulting in bridge failure. see, e.g., Raudkivi 1986; Dey et al. 1995; Dey and Raikar 2007(Grimaldi 2009a). Scour research is quite extensive however the use of combined countermeasures is limited. This is probably due to each channel being different in size, velocity of flow and sediment size.

This research aimed to investigate, through a literature review of current countermeasures used within the industry, an evaluation and subsequent elimination of these countermeasures. Elimination of these countermeasures was determined by a rating system in which constructability, cost and efficiency were measured. The most suitable countermeasures to be combined for testing were determined through this rating system. Models of the countermeasures were constructed for testing in the small flume at USQ Toowoomba. The efficiency of each combined countermeasure was measured by volume and depth of scour to provide results in which the performance was rated. This performance will be available for industry information.

## 1.1 Objectives

The aim of this research was to investigate the best countermeasure or combined countermeasure to mitigate local scouring and vortex shedding around bridge piers in open channels. A design matrix using a rating system to classify constructability, feasibility and an efficiency factor was employed to identify the most efficient countermeasure. As bridges are necessary for everyday travel this topic is of vital importance to ensure the structural integrity of bridge piers and safety to all who use this infrastructure. Bridges collapse due to the undermining of bridge piers because of the scouring caused by horseshoe and wake vortices.

This research examined the effect of scouring on scale models of bridge piers with countermeasures in a flume. It also examined the best countermeasure to be employed to reduce scour and ensure cohesion of the bedding material around the pier.

Research conducted and literature already published furthered the understanding of the scouring process. Studies completed by others were reviewed so that the strengths and weakness of existing scour mitigation methods could be recognised. By grouping and analysing the strengths and weakness of other designs, a new design could potentially be developed.

This project tested three countermeasures which from analysis within the literature review achieved the highest rating. Testing took place to determine the efficiency of the various combined countermeasures in mitigating the scour depth allowing conclusions to be drawn.

# 2.0 Literature Review

This literature review presents background information and previous understanding within this field of study. Before physically investigating effective methods to reduce scour at bridge piers, it was important to review existing techniques, their efficiencies and weakness. This review investigated local scour and the causes of bridge pier failure. It also provided information about the basics of hydraulic theory relating to open channels offering the reader knowledge to understand the problem at hand. The following points were outlined as part of the literature review:

- General information on scour
- Vortex Shedding
- Sediment Transportation
- Flow Around Piers
- Hydraulic Theory
- Theoretical Checks
- Countermeasures –Pier Attachments, Bed Attachments & Other Devices
- Combined countermeasures
- Conclusion of the literature review

## 2.1 Outline of Scour

In channel flows when an object such as a bridge pier obstructs the flow, scour results. "Scour is defined as the erosion of streambed around an obstruction in a flow field" (Chang,1988). Scour is a process that occurs when there is a rapid and unexpected change in this water flow or an obstruction impedes the flow (Williams 2009). Bridge scour is the removal of sand, soil and pebbles by fast moving water from around the foundations of bridge piers (figure 2.1). The pier impedes the natural flow causing high shear stresses and turbulence which creates horseshoe vortex causing scour to the riverbed. This scour creates a serious threat to bridge piers (Qi 2013).

Scour can occur as contraction scour, local scour or general scour. Contraction scour is when the flow of fluid is reduced either naturally or by human intervention. Local scour is created at the pier simply due to the obstruction being present (Davis 2001). This obstruction causes acceleration to the flow, resulting in vortices created by this restriction. General scour is the lowering of the bedding layer at the obstruction. General scour is often caused by a change in the river flow upstream or may be caused by a manmade barrier. This fluid then flows around the pier and creates a horseshoe vortex (Davis 2001).

Scouring around a bridge pier will reach a maximum where no more bedding material can be eroded from the scour hole. This is called the maximum scour depth and depending on the flow will be reached at different times (eg Days, weeks, Months & years) (Davis 2001). The bedding material also contributes to the rate in which scour occurs. If the bedding material is soft then erosion will occur more quickly.

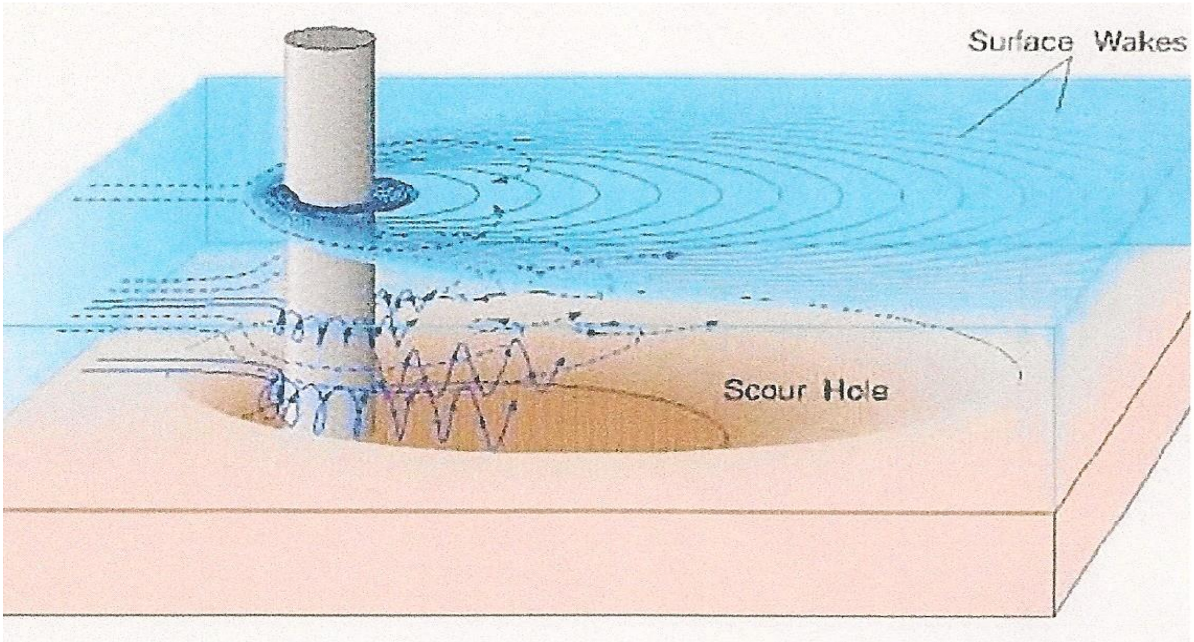



**Figure 2.1 Scour Hole (SSC 2010)**

### 2.1.1 Clear Water Scour

Clear water scour occurs when the fluid does not transport sediment material from the bedding upstream. Clear water scour occurs when the bedding material cannot be carried by the normal flow(Davis 2001).

### 2.1.2 Live Bed Scour

Live bed scour occurs when the bedding material is carried downstream with the flow of the water. Scour holes in live beds are more prevalent during flood occurrences. This is because of the presence of bedding material in the fluid causing shearing to the current bedding layer. When the intensity of the flood decreases the sediment refills the scour hole due to a drop in velocity (Davis 2001).

## 2.2 Vortex shedding

When any water flow is disturbed by a solid object the result downstream is called vortex shedding. The object causes a disruption to the speed and pressure of the water both around the object and downstream (Stoesser 2010). These changes in pressure result in the boundary layer of water separating from the bluff body. Vortices occur in the separated boundary layer of water (Stern 2009). The stream of water disconnects when it impacts on the obstruction causing an unsteady flow downstream.

### 2.2.1 Horseshoe Vortex

"Results show that the shape and size of the pier columns have a significant effect on the spatial and temporal distributions of the bed friction velocity induced by the horseshoe vortex system"(Chang 2013). The horseshoe vortex is created by the flow of water separating at the upstream face of the bridge pier where the initial scour hole has developed. The flow slows down as it approaches the pier hits the upstream face of the pier travels vertically down the pier towards the bedding layer and pier foundation as in figure 2.2 below. This vertical down flow erodes the surface and continues forming the scour hole in a semicircular direction (Masjedi 2010). This then hits the oncoming flow of water to form a horseshoe vortex as seen in the diagram below. The sediment is carried away downstream by the horseshoe vortex (Masjedi 2010).

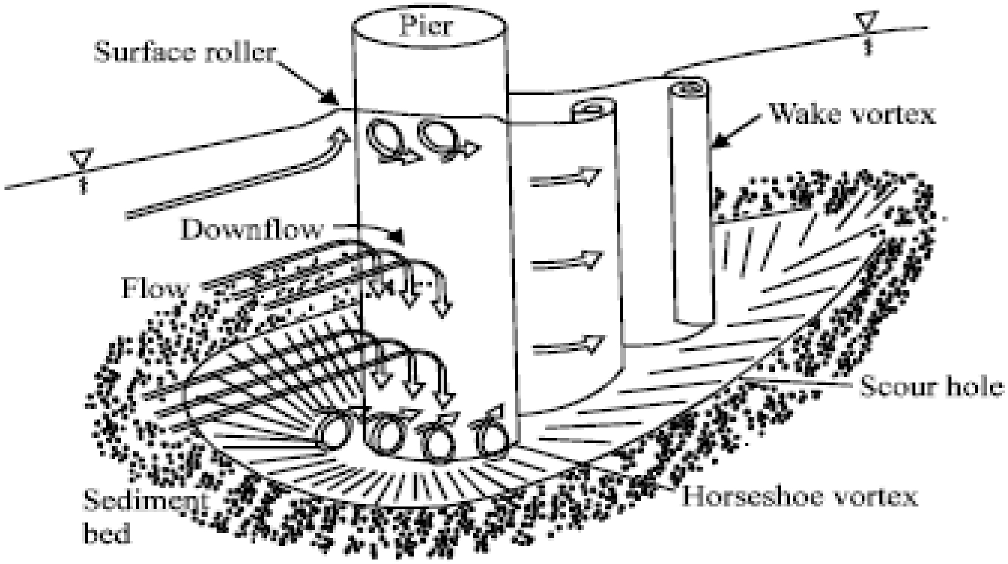



**Figure 2.2 Horseshoe and Wake Vortices (Masjedi 2010)**

### 2.2.2 Wake Vortex

Wake vortices form behind a bridge pier and affect the downstream flow pattern (Younis 2006). This phenomenon is caused by the separation of flow around the bridge pier (figure 2.2 above). Melville (1975) wrote, "each of the concentrated vortices acts with its low pressure center as a vacuum cleaner" (Melville 1975). Wake vortices only cause problems with scour when piers are shielded by riprap or other countermeasures upstream of the bridge pier (Stevens 1991). This effect of scour causes little concern compared to the effect of horseshoe vortices. When the bridge pier is large in diameter the effect of the horseshoe vortices is negligible, but once again the wake vortices cause scour downstream (Stevens 1991).

## 2.3 Sediment transportation

Sand, soil, rocks and other solid debris are transported when the flow of water is increased and or disturbed due to bluff bodies. This results in a natural reduction of soil matter around the bluff body and creates an increase of soil matter further downstream (SSC 2010).

## 2.4 Flow around piers and how piers affect flow

The flow around bridge piers will be turbulent for scour and vortex shedding. This turbulent flow is the most critical condition that will affect the structural integrity of the bridge if not controlled through innovative design. The flow in front of the pier is moving in a downwards direction as it hits the pier as seen below.

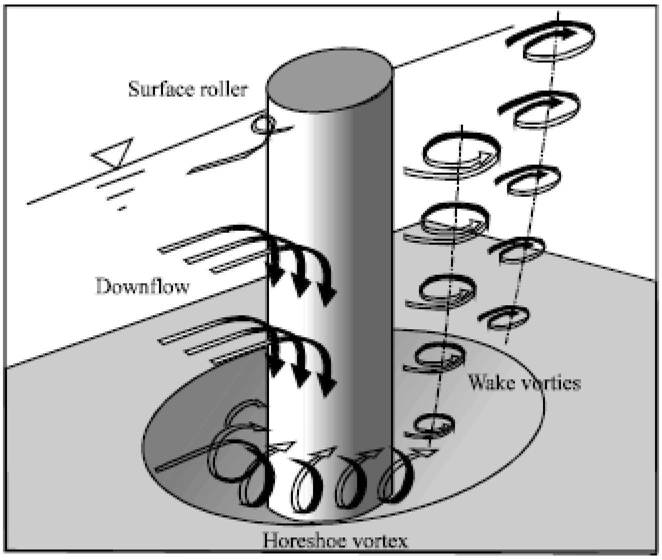



**Figure 2.3 Flow around piers (Esfandi 2010)**

The speed of the water pushes the vortex around the pier as seen in the above figure 2.3 as horseshoe and wake vortices. To try and combat the effect of the horseshoe vortex the use of larger materials such as large rocks can be used to secure the bedding material. Another option to limit the creation of horseshoe vortices is to use a collar around the bridge pier thus abating the downwards flow of water (Esfandi 2010).

## 2.5 Hydraulic theory

An open channel can be defined by one surface of water being bound by atmospheric pressure and free flowing. Open channels can either be constructed or formed by a natural occurrence. Examples of open channels are rivers and streams. A channel can be classified into prismatic or non-prismatic channel. Prismatic channels contain features which remain constant and are usually associated with manmade structures. Non-prismatic channels are categorized by fluctuating features which do not remain constant (Unitec 2011). These are commonly identified with natural channels.

## 2.5.1 Flow Classifications and Flow Regimes.

### 2.5.2 Steady and Unsteady Flows

Steady flow is defined as one with flow properties that do not change with time. Unsteady flow is classified by flow properties that change with time. This unsteady flow may contain surges. An example of when unsteady flow occurs is during a flood.

### 2.5.3 Uniform and Non-uniform Flows

Uniform flow occurs when velocity and depth of the channel does not change with distance. Steady uniform flows transpire in long channels where there are no extra entries or exit points and where the water mass remains constant due to the uniform slope. This steady uniform flow is the result of the balanced condition where the energy loss due to friction is the same as the potential energy created from the decline of the slope. The flow depth under this condition is known as normal depth. Steady non-uniform flow fluctuates when the conditions vary with distance but not with time (Unitec 2011). The mean velocity will change with distance and not with time.

### 2.5.4 Flow classification

There are three classifications of flow. They are Laminar, Transitional and Turbulent flows. Laminar flows occur when the fluid is moving slowly in smooth parallel layers (streamline flow). Turbulent flow is when the fluid travels at speed where flows are erratic. This type of flow is often associated with flooding conditions. It is also most evident around structures due to the disturbance in flow path. Turbulent flows are unpredictable due to the changing velocities and direction, making analysis difficult. The turbulent motion of water moves in a vortex motion. Transitional flow occurs as a mix between turbulent and laminar flows (Richards 2010). Transitional flows are obvious when unsteadiness starts to be evident within the flow (figure 2.4).

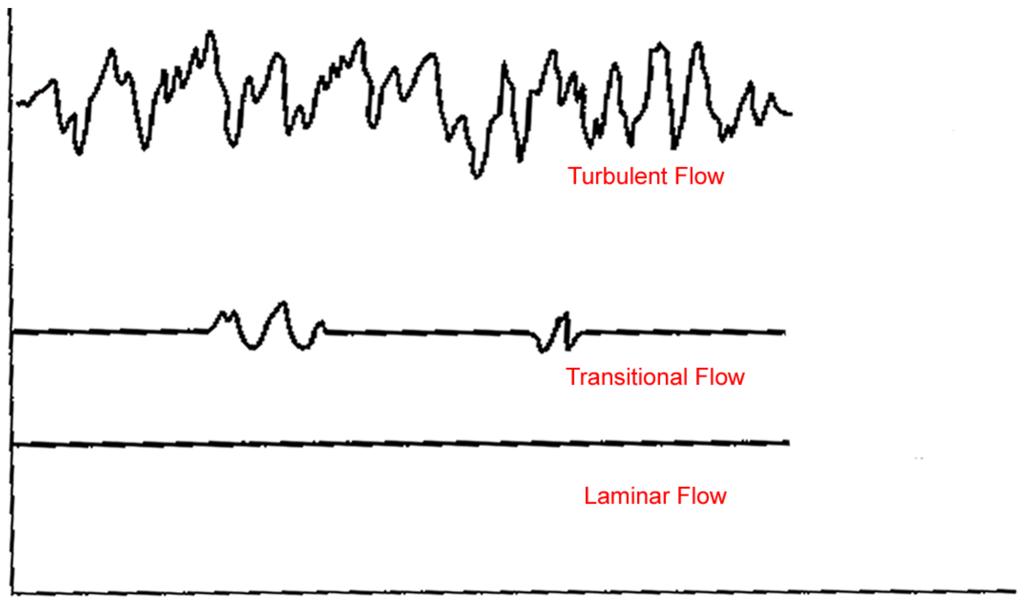



**Figure 2.4 Flow Charts (Sydney 2005)**

### 2.5.5 Reynold's Number

Reynold's number (Re) is the numerical method to determine the flow condition within a channel. The equation is a ratio of the momentum forces to viscous forces (Chadwick 2013). The equation is dimensionless.

$$Re_{Channel} = \frac{\rho RV}{v} \qquad (2.1)$$

$Where,$
$\rho = density$
$R = Hydraulic\ Radius$
$V = Velocity$
$v = Viscosity$

The hydraulic radius is a function of the area over the wetted perimeter.

Table 1 below outlines the open channel Reynolds number for the different flows.

**Table 1 Open Channel Reynolds Number**

| Flow Classification | Re Channels |
|---|---|
| Laminar Flow | Re<500 |
| Transitional Flow | 500< Re <2000 |
| Turbulent Flow | 2000 < Re |

### 2.5.6 Velocity Disturbance across an Open Channel

Friction created along the boundaries of an open channel will cause the measured velocity to fluctuate. The velocity also varies due to the secondary currents which rebound off the boundaries of the channel (Unitec 2011). Figure 2.5 depicts the change in velocity in an open channel. The atmospheric pressure contributes to the variance. The maximum velocity is found to be just below the surface.

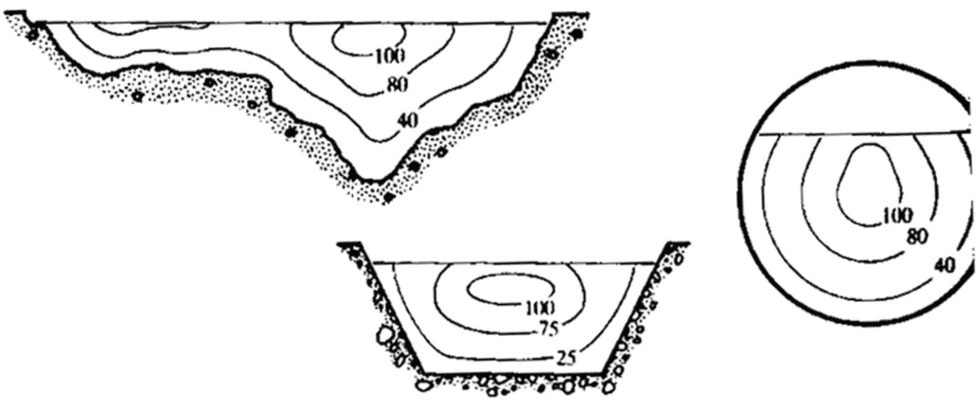



**Figure 2.5 Velocity disturbance across an open channel (Sierra 2009)**

### 2.5.7 Froude Number

Froude number (Fr) is a dimensionless parameter that describes the type of flow within an open channel (Nalluri 2009). The Froude number is proportional between gravitational and inert forces.

$$Fr = \frac{V}{\sqrt{gy}} \qquad \text{Eq. (2.2)}$$

$Where,$
$V = Velocity$
$y = Hydraulic\ mean\ depth$
$g = Acceleration\ due\ to\ gravity$

### 2.5.8 Flow Separation

The real fluid flow around a non-streamlined shape (eg. cylindrical pier) is only symmetrical before the obstruction in the upstream flow. As fluid passes the downstream face of the obstruction the streamlines start to diverge (figure 2.6). Maximum constriction occurs at the Y Axis line between the boundary layer and the upstream face (Chadwick 2013). As the fluid passes the midway point the flow decreases in intensity. The streamlined flow disappears and strong eddies appear causing energy loss. The fluid in the boundary layer is travelling slower than fluid in the stream. At this point negative velocities occur in the inner part of the boundary layer as seen in figure 2.6. There is a distinct line where the body of the flow is separated into negative and positive velocity showing flow separation.

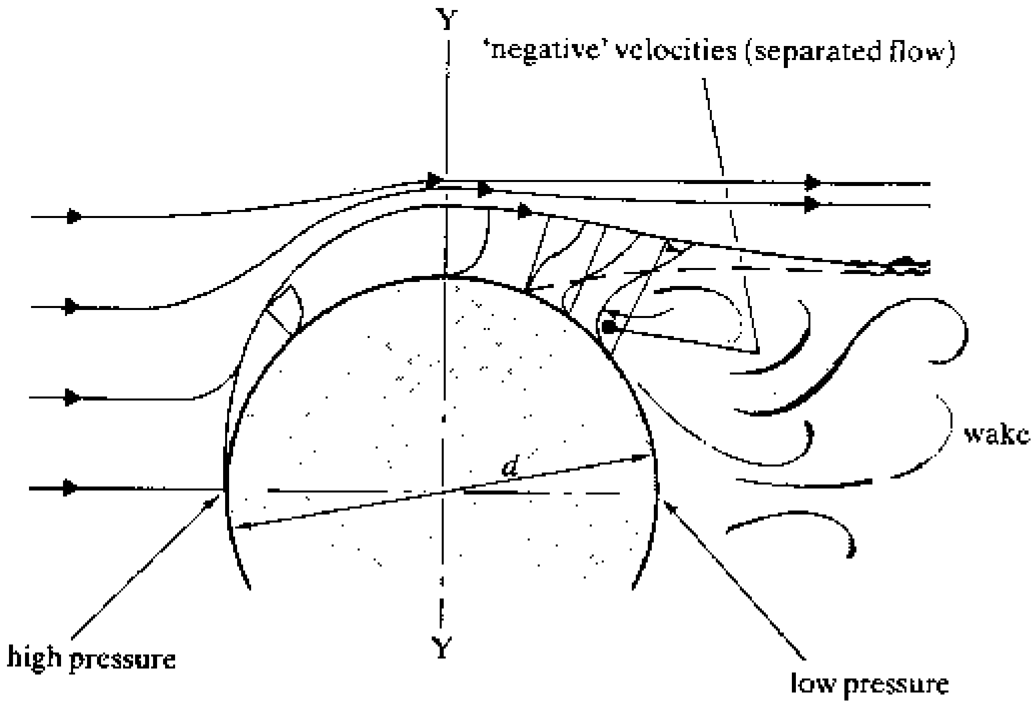



**Figure 2.6 Flow Separation (Chadwick 2013)**

## 2.6 Theoretical Checks

### 2.6.1 Critical Mean Velocity

Before any practical testing is carried out, flow conditions within the large flume must be considered. This is to ensure that the critical mean velocity is checked so the threshold for sediment transportation is reached. This is calculated using Neill's Equation (Administration 1993):

Neill's equation

$$Vc = 1.41\sqrt{(s_s - 1)gd_{50}}\left(\frac{y}{d_{50}}\right)^{\frac{1}{6}} \quad \text{Eq. (2.3)}$$

Where,
Ss = Specific gravity of sediment particles
y= flow depth (m)
$d_{50}$ = Median size of bed material (m)
g = Acceleration due to gravity

### 2.6.2 Pier Scour depth

The formula below has been developed to predict the maximum scour depth around a bridge pier (Administration 1993). It can be used for both cases of scour either live bed or clear bed scour conditions.

$$\frac{y_s}{y_1} = 2.0\, k_1 k_2 k_3 \left[\frac{a}{y_1}\right]^{0.65} {Fr_1}^{0.43} \qquad \text{Eq. (2.4)}$$

Where,
L = Pier Length (m)
a = Pier width (m)
$Fr_1$ = Froude Number directly upstream of the pier
$V_1$ = Mean velocity of flow upstream of the pier
g = Acceleration of gravity
$k_1$= Correction for pier nose shape
$k_2$=Correction for the angle of attacked of flow
$k_3$=Correction factor for bed condition
$y_1$ = Depth upstream
$y_s$ = Depth of Scour

### 2.6.3 Sediment Size

The theoretical check of the size of the sediment to the diameter of the bridge pier will be checked. This is to ensure independence between sediment size and bridge pier diameter.

$$\frac{b}{d_{50}} > 50 \qquad \text{Eq. (2.5)}$$

If this equation is greater than 50 then there is no relationship between sediment size and scour depth (Ettema 1980).

## 2.7 Countermeasures Review

Studies have identified two principal countermeasure categories used to minimize scour around bridge piers (Tafarojnoruz 2010)

- Flow altering
- Bed armouring

### 2.7.1 Flow altering measures

Flow altering measures are designed to reduce the strength of the downflow and the horseshoe vortex, the primary instigators of scour (Tafarojnoruz et al., 2010). “using flow altering devices, the shear stresses on the riverbed, in vicinity of the pier, are reduced by altering the flow pattern around a pier which in turn reduces the scour depth” (Mubeen 2013).

Tafarojnoruz, Gaudio and Dey (2010) grouped flow-altering techniques into the following four categories:

1. Pier Slots
2. Pier attachments
3. Bed attachments
4. Other devices

### 2.7.2 Pier Slots

Slots allow approaching water to pass through the pier (Tafarojnoruz 2010). Reduced resistance created by the more direct path, weakens the horseshoe vortex and strength of the downflow. Openings may be created in the pier itself or by gaps between several smaller piers acting to support a single area. Both techniques work to reduce resistance to the waters flow and subsequent scour. Scour reduction efficiencies for techniques investigated by Tafarojnoruz *et al.* (2010) were around 35% to 39% (Tafarojnoruz 2010).

Pier slots reduce the friction area of the pier allowing water to flow through minimizing the downflow that will reach the bedding surface (Mubeen 2013). This method is an indirect method that allows less contraction pressure to occur as the natural flow is more freely dispersed. The slot design is critical. If the slot is placed too high then the ability to divert the downflow to the bed is minimal (Chiew 1992). When the slot is below the surface, the water passing through acts as a jetstream and erodes the bed downstream of the pier. Debris is a major concern as the slot can very easily be filled making this countermeasure unproductive (Mubeen 2013). Regular maintenance is required to ensure that blockage doesn't occur making this option an expensive exercise. Placing a slot into a pier is also a strength concern as structural capacity is reduced. The placement of the slot is critical to structural integrity and thus requires considerable calculations before implementation (Mubeen 2013).

## 2.8 Pier attachments

Pier attachments include threading, collars or horizontal plates and pier-attached plates (Tafarojnoruz 2010).

### 2.8.1 Threading

Threading involves wrapping cable around the pier from top to bottom so that the cable is sloping downwards. Scour reduction efficiency is directly proportionate to the amount of cable installed. Efficiency increases as more cable is applied and the slope of the cable reduced (Tafarojnoruz 2010). Dey et al. (2006) suggested that the best configuration is a triple thread with a thread angle of fifteen degrees (Dey 2006; Tafarojnoruz 2012). Results using threading show minimal changes to scour reduction when compared to a bridge pier with no countermeasure. The results obtained from studies showed that similar scour shapes developed. Threading reduces the downflow pressure by acting as a frictional component against the downward flow (Tafarojnoruz 2012). Threading has been utilised to lessen the downward flow which contributes to the development of horseshoe vortices. This method is inexpensive and easy to apply.

### 2.8.2 Collars and horizontal plates

Collars are attached to the bridge pier and are used to deflect the flow of water (Melville 1999). Several studies have been conducted to determine the best position for placement and size of the collar. Installing a collar impacts directly on the downflow reducing both scour depth and the rate of scour (Mubeen 2013). Collars encompass the whole pier, whereas a plate is usually only attached to the front of the pier.

Collars and or horizontal plates are placed at or just below the original bed level to deny scour continuing beyond the depth of the collar or plate (Tafarojnoruz 2010). When the collar width was increased and it was placed below the bed level the reduction of scour depth increased considerably. The size of particles in the sediment also affected the performance of the collar (Gogus 2010).

Plates are generally positioned on the upstream side of the pier whereas collars are circular disks that surround the pier (Tafarojnoruz 2010). The plates/collars width controls the scour reduction efficiency; however size is dictated by practicality. Plates help alleviate the downflow at the face of the pier from forming a horseshoe vortex. Studies by Kumar (1999) showed that a larger scour hole formed at the upstream face of the pier when using a smaller diameter of collar at a greater height rather than using a larger diameter of collar at a lower height (Kumar 1999).

Experiments have also been conducted using a rectangular and a circular collar. Results showed scour decreased using either collar but a rectangular collar was superior decreasing scour depth by 79%. This same experiment also showed that the greatest reduction in scour depth was gained by placing the collar under the river bed (Jahangirzadeh 2014).

### 2.8.3 Pier Attached Plates

Plates (vanes) are placed on the pier at an angle to divert the downflow away from the bed level. By diverting the downflow away from the bed, the horseshoe vortex is denied. Scour depth reduction efficiency was recorded as high as 90% in good conditions (Tafarojnoruz 2010). The angle investigated by Tafarojnoruz *et al.* (2010) was 45 º. Plates sloping upward were more efficient.

## 2.9 Bed attachments

Bed attachments include sacrificial piles, vanes, bed sills, surface guide panels and sleeve and collared sleeve. Bed armouring utilizes physical barriers to negate scour (Tafarojnoruz 2010).

### 2.9.1 Sacrificial piles

Sacrificial piles, as the name suggests, are piles positioned in front of the bridge pier as a barrier/deterrent of heavy flows. They consist of a group of piles upstream of the bridge pier which causes a smaller velocity of wake which in turn reduces any horseshoe vortex immediately upstream of the pier and consequently a reduction in scour depth. The efficiency of sacrificial piles is dictated by the configuration, size and number of piles used (Tafarojnoruz 2010). Recent research concluded that the effectiveness of sacrificial piles as a scour countermeasure is also dependent on the velocity flow angle and the flow intensity (Melville 1999). Studies determined scour volume reduction efficiency between 40% and 50% (Tafarojnoruz 2010).

Sacrificial piles are said to be ineffective as scour countermeasures in live-bed conditions. The only time sacrificial piles are effective is when the flow is straight and the intensity of the flow is negligible (Mubeen 2013).

### 2.9.2 Sacrificial sheet piles

Sacrificial sheet piles are another countermeasure employed to reduce scour at bridge piers. The sheet piles are joined and positioned in a way that the join forms a peak in the direction of the oncoming flow. This method diverts the flow from the pier reducing the velocity of flow impacting the pier. The highest scour reduction was 47% (Tafarojnoruz 2010).

### 2.9.3 Vanes

Vanes are blades situated before the pier to alter the flow velocity, direction and distribution (Tafarojnoruz 2010). Vane efficiency is determined by the vanes height, orientation in relation to flow, length and the lateral distance between each (Tafarojnoruz 2010). Rock vanes are placed at an angle so the tip of the vane is immersed even during times of low flows in the channel or stream. Vanes, by aligning the flow of water can effectively move the scour away from the bridge support and into the centre of the channel. Vanes are an economical method of reducing scour when the bridge and waterway are only small (Johnson 2001). When the bridge is a single span, options to reduce scour such as riprap and bed armouring may interrupt the flow of the water and cause contraction scour so the use of vanes has proven effective (Johnson 2001). Scour reduction efficiency according to studies reviewed was 30% to 50% (Tafarojnoruz 2010). Two vanes placed opposite to each other at a short distance away from the front of the pier proved more effective than a single vane (Kells 2008; Tafarojnoruz 2012).

### 2.9.4 Surface guide panels

Panels are positioned in a similar orientation and location as the sacrificial sheet piles only the panels are not set into the bed of the waterway directly. The panels are anchored into the bed to allow water to pass underneath the panel. This forces the water downwards, causing erosion directly beneath the panel. The erosion creates a bowl in the bed level. The end of the bowl then acts as a jump, pushing the water upwards as it approaches the pier. This reduces the downflow at the pier and scour intensity. Reduced downflow correlates to weakened horseshoe vortex (Tafarojnoruz 2010).

### 2.9.5 Sleeve and collared sleeve

A sleeve is a cylindrical steel container used to contain the horseshoe vortex (Tafarojnoruz 2010). The container has a solid base. The horseshoe vortex occurs inside the sleeve and the base and sides of the sleeve deny scour. Sleeve only methods have demonstrated failure to deny scour around the outside of the sleeve (Tafarojnoruz 2010). To improve the sleeve capability, a collar is placed around the sleeve. The collar denies scour outside the sleeve while the sleeve contains the primary horseshoe vortex/scour potential.

### 2.9.6 Bed Sills

Grimaldi et al (2009), conducted experiments which concluded that placing a bed sill a short distance downstream of the pier decreased the size and depth of the scour hole (Grimaldi 2009b). It was noted, if the distance between the bed sill and pier was less, the efficiency of this countermeasure increased. This countermeasure does not come into effect immediately. The scour behind the pier must develop sufficiently before the bed sill starts to counteract the scour process (Grimaldi 2009b). The best positioning of the bed sill as stated by Grimaldi et al (2009a), suggested that the bed sill should be adjacent to the downstream face of a circular pier (Tafarojnoruz 2012). The bed sill acts as a barrier against the removal of sediment and therefore an increased scour hole. In a recent study the buildup of debris at the face of the bed sill caused a greater scour depth meaning this countermeasure can be detrimental to the reduction of scour (Tafarojnoruz 2012).

## 2.10 Other Devices

Other devices noted by Tafarojnoruz *et al* (2010) include suction and modifying the pier shape. The use of riprap is also a method of preventing scour build up around bridge piers.

### 2.10.1 Suction applied to pier

Holes are drilled through the lower part of the pier and water is suctioned through the pier using pumps. This method showed positive scour reduction outcomes but did contribute to minor scour downstream (Tafarojnoruz 2010).

### 2.10.2 Modifying pier shape

Pier shape can change the strength of the downflow and the horseshoe vortex (Tafarojnoruz 2010). Sharp-nosed piers can reduce the downflow and weaken the horseshoe vortex provided the flow direction matches the orientation of the sharp nose. If the flow direction changes and meets the flat faces of the pier, scour intensity increases dramatically (Tafarojnoruz 2010). If a blunt nose pier is implemented there will be no variation in scour intensity with flow direction changes. Industry professionals support this predictability and blunt nosed piers are used most frequently.

The shape of the bridge pier greatly influences the amount of scour. A cylindrical shape was the most common but a round nosed pier, a sharp nosed pier or a girder design are all now well-known shapes for pier design (Figure 2.7). If the shape is sharp nosed or rectangular the flow must align with the pier face for scour to be reduced. If there is even a small change in flow a cylindrical pier is safer to be used as scour will increase with the other pier shapes (Lauchlan 1999). Figure 2.7 below shows the most commonly used shapes for bridge pier design as per the Queensland Main Roads and Transport Manual (2013).

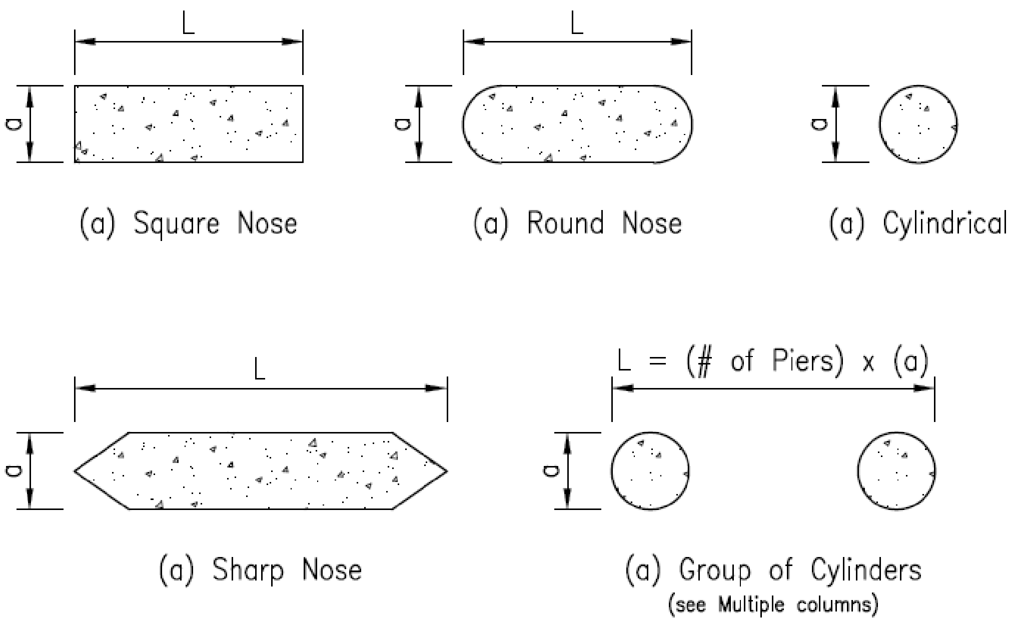



**Figure 2.7 Varying pier shapes (Roads 2013)**

### 2.10.3 Riprap

Riprap is the most commonly used method for reducing the effect of scour around a bridge pier (Mubeen 2013). This method is both efficient and cost effective. Riprap stones are commonly used to stop horseshoe vortex where the downflow from the pier face is prevented from eroding the bedding due to the armoring in place. Failure can follow using riprap stones, most likely evident during flood events where the sediment within the water moves the riprap stones (live bed condition) further downstream (Lauchlan 2001). Under live-bed conditions the riprap moves downstream defeating the original placement of the riprap layer. Placing the riprap layer below a sediment bed was identified as a possible solution by Chiew and Lim (Chiew et al., 2000).

Failure may also occur in clear water conditions where the stones are not large enough to withstand the shear stress caused from the downflow from the front of the pier (Lauchlan 2001). Riprap stones vary in size and thus voids are created due to the uneven shapes which allow the flow to erode the bed layer below. This can cause subsidence of the riprap layer (Lauchlan 2001).

## 2.11 Combination of countermeasures

Tafarojnoruz *et al* (2010) explored the efficiency of combinations and found that the practicality of employing some of these combinations was difficult or required very specific conditions to improve efficiency. The following combinations were tested and improvements though sometimes small were noted:

- Submerged vanes and a bed sill
- Sacrificial piles and a collar
- Sacrificial piles and a slot
- Slot and collar
- Multiple collars
- Bed sill and collar
- Slot and bed sill

Gaudio (2012) suggests that a higher reduction in scour is achieved through a combination of mitigating techniques. Chiew (1992) noted that in clear water conditions a combination of slot and collar eliminated scour around the bridge pier. Parker et al (1998). In live-bed conditions the combination of permeable sheet piles with riprap reduced scour by up to 91% (Gaudio 2012). This article also concludes that an incorrect combination of countermeasures can be less effective than a single countermeasure (Gaudio 2012). The results obtained from this current project could prove very helpful in mitigation techniques for future use.

### 2.11.1 Submerged vanes and a bed sill

These countermeasures used singly in previous research only showed reductions of below 20% so were not considered effective. This configuration positioned two vanes submerged upstream of the pier to catch sediment between them and prevent the scour hole growing. A bed sill was placed downstream to avoid any build up to the back of the pier. Testing with this combination only saw an eight percent greater reduction than if a single bed sill had been used (Gaudio 2012).

### 2.11.2 Combination of sacrificial piles and a collar

Sacrificial piles in combination with a collar can help alleviate the scour depth because the scour which occurs at the base of the sacrificial pile deposits this scour into the scour hole around the pier. This method reduces the equilibrium and the rate of scour at the pier (Gaudio 2012). In this combination the collar's usual performance to reduce scour at the pier face didn't transpire. The results showed an undermining upstream of the collar at the face of the pier (Gaudio 2012). This mitigating combination only reduced the effect of scour marginally more than the individual mechanisms and is therefore not a recommended solution.

### 2.11.3 Combination of Sacrificial piles and a Slot

The insertion of a slot into a pier reduces the force of the water lessening the horseshoe vortex created and results in a reduction of scour depth. The sacrificial piers again reduce scour at the pier by depositing crosswise sediment into the pier scour holes.  The performance of this combined method was minor in relation to the performance of each single countermeasure(Gaudio 2012).

### 2.11.4 Combination of a slot and collar

Studies have also taken place to include a collar and slot (Mubeen 2013). This combination of a slot combined with a collar proved greater efficiency than just the individual slot or collar but the slot created scour downstream at the rear of the pier and the outflow from the slot can also affect the structure of wake vortices and diverge them further down the watercourse (Gaudio 2012).

Experiments conducted by Chiew (1992) showed that if a slot was cut into the pier at a quarter of the diameter of the pier at bed level and a collar placed around the pier then scour could be eliminated Chiew (1992) (Moncada 2009).

### 2.11.5 Multiple collars

Garg et al. (2005) experimented with various sizes of collars around a bridge pier. Studies showed that a collar three times the diameter of the pier and placed at bed level reduced scour to zero.  Due to concern of normal degradation of the riverbed Garg et al. (2005), experimented using three collars one and a half times the diameter of the pier.  This reduced the scour by 83%. Concern arose with this first experiment where the collar was three times greater than the pier diameter as it could prohibit any traffic beneath the bridge (Garg et al. 2005).

### 2.11.6 Bed Sill and Collar

This combination varies in its effectiveness.   The sill helps prevent the grooves that appear under the collar and cause the scour hole around the pier.  The difference is noted to be dependent upon the placing of the bed sill in relation to the pier and also the width of the bed sill (Gaudio 2012).

### 2.11.7 Slot and bed sill

A slot reduces scour by decreasing the strength of the down flow, therefore limits the horseshoe and wake vortices. The important design aspects of the slot to enable scour reduction are the slot width, length, sinking depth and the skew angle (Grimaldi 2009a). The bed sill reduces the extent of the vortices at the rear of the bridge pier. Scour will still occur to some degree as far as the bed sill is located. The best option for placement of the bed sill was found to be adjacent to the bridge pier. As a combined countermeasure the performance proved to be an effective combination (Grimaldi 2009a).

## 2.12 Conclusion of Literature Review

This literature review provided the basis of an understanding of various countermeasures used within the hydraulic industry to reduce scour around bridge piers. The literature provided information on previous results stating both the efficiencies and failures of various countermeasures. Further reading offered evidence of combined countermeasures mostly proving to be more effective in the reduction of scour. Dependent upon the way the countermeasures were combined, a greater reduction in scour generally occurred, but at times a combination provided lower effectiveness, compared to an individual performance. By using the literature review the studies of individual and combined countermeasures suggests the following recommendations.

The performance of pier slots was shown to be an effective countermeasure but costly to maintain. Collars and plates were reviewed as a good countermeasure in reducing the scour depth. The reduction in the downflow at the face of the pier was one of the main advantages and collars and or plates were one of the highly recommended countermeasures previously tested. Pier attached plates also presented positively from the literature review. Vanes are another suggestion recommended from the literature mainly due to their cost efficiency and performance. Two vanes mirroring each other at a 45 º angle to the flow proved to be effective. The literature showed riprap to be an effective countermeasure also, but only in limited situations. Bed sills are noted to mainly be effective in combinations and are primarily limited to small channels due to cost.

From the literature above combinations in the optimum configuration were commonly found to perform better. From these readings slot and collars and/or multiple collars used in the right combination appear to be very effective. The literature also suggests that the most effective groupings are dependent on the channel conditions.

From the analysis matrix, the combination of vane and plate could prove to be an effective combined countermeasure therefore testing was performed using this permutation. Both inward and outward facing vanes combined with a plate were chosen to determine the optimum measure for the reduction of erosion. Multiple collars have already been discussed in the literature review but were shown to be effective in the implementation of this combined countermeasure and were therefore also selected to be tested against a control pier.

To provide a performance indicator as to which combined countermeasures would offer the greatest efficiency, the volume of erosion would be measured and compared. The greatest reduction in erosion using the chosen combined countermeasures when compared to the control pier would be recommended for implementation.

# 3.0 Design Analysis

## 3.1 Elimination of Countermeasures and Choosing a Design

To choose combined countermeasures, elimination through a design matrix rating system was used. The ratings were measured using a scale of 1 to 5 with five being the most suitable. A countermeasure was rated on the basis of three criteria. Constructability was judged on how easily the model could be built and implemented at the site. It was also necessary to rate each model on the basis of ease of construction. In practice if a pier is already constructed trying to cut a slot into this pier would not be suitable. However placing a vane in front of an already constructed pier would be possible. Cost was assessed on the affordability of the countermeasure in terms of construction, material cost, maintenance costs and the life expectancy of the countermeasure. Efficiency was the final criteria assessed. Efficiency was based on previous results obtained from the literature review.

**Table 2 Rating System**

| Point value | Construction | Cost | Efficiency |
|---|---|---|---|
| 1 | Hard to construct | Very expensive, materials difficult to source, labour intensive to build | Inefficient except in limited cases, |
| 2 | Not as difficult to construct | Expensive to construct and maintain | Limited change in scale |
| 3 | Moderately difficult to construct | Moderately expensive | Moderately efficient |
| 4 | Easy to construct | Reasonably cost effective | Efficient in some situations |
| 5 | Very easy to construct | Very cost effective | Very efficient in most situations |

## 3.2 Design Matrix – Evaluation of strength and weakness

The aim of the tables shown below was to rate and then by process of elimination establish the most effective and efficient pier, bed attachment, and or pier attachment to provide the outcomes to be tested. Further evaluation then determined the combinations of countermeasures which were tested. The information below was taken from the literature review above and grouped accordingly. Using the information in Table 3 allowed for the creation of further tables (Tables 4 – 7) to pinpoint the most effective pier and combined countermeasures.

**Table 3 Advantages & Disadvantages of countermeasures**

| | **Strength** | **Weakness** | **Evaluation/summary** |
|---|---|---|---|
| **Pier Shape**<br>• **Blunt Nosed** | Used to create greater structural integrity | No variation in scour intensity with flow direction changes | |
| • **Sharp Nosed** | Weakens the horseshoe vortex provided the flow direction matches the orientation of the sharp nose | If the flow direction changes and meets the flat faces of the pier, scour intensity increases dramatically | This design would be recommended when the flow direction is the same as the orientation of the sharp nosed pier. |

| | | | |
|---|---|---|---|
| • **Circular** | Direction of flow doesn't matter with this design. | Without pier or bed attachments scour holes are formed. | This design is used when the direction of flow is unknown or too unpredictable. Good for majority of scenarios |
| • **Pier Slot** | Reduces downwards flow weakening the horseshoe vortex | Debris is often caught in the slot making it less effective and reduction of scour is dependent on the positioning of the slot. | This countermeasure will be tested as part of this research with one or more other countermeasures. The pier slot size and location must be taken into account to ensure structural stability. |
| **Bed Attachments**<br>• **Sacrificial piles** | Reduces horseshoe vortex immediately upstream of the pier and therefore a reduction in scour depth. | Efficiency of sacrificial piles is dictated by the configuration, size and number of piles used and is also dependent on the velocity flow angle and flow intensity. Ineffective as a countermeasure in live- bed conditions. The only time sacrificial piles are effective is when the flow is straight. | This method is good for clear water scour but not effective in live bed conditions. |

| | | | |
|---|---|---|---|
| • **Sacrificial sheet piles** | Reduces the velocity of the flow. Good in flood conditions | Scour can occur locally at the sheets. Difficult to construct and rust is a concern. | Studies suggest the usage with riprap protection. Good combination in reducing high scour conditions |
| • **Vanes** | Blades situated before the pier to alter the flow velocity, direction and distribution of the water. Very economical. | Two vanes are more effective than one. | Other studies showed positioning, including angular positioning of vanes was found to be difficult. |
| • **Surface panels** | Reduces downflow at the pier and scour intensity and correlates to a weakened horseshoe vortex. | Creates a bowl at the site of the sheet causing the water to be pushed upwards towards the pier. | Not the best option from literature reviewed. |
| • **Sleeve and collared sleeve** | This causes the horseshoe vortex to occur inside the sleeve and scour is denied by the base and sides of the sleeve. The collar negates scour outside the sleeve. | Incorrect positioning of the sleeve can lead to greater scour | Position of this countermeasure under live bed conditions can cause issues. |

| | | | |
|---|---|---|---|
| • **Bed sill** | Reduction in velocity and resultant scour reduction occurs at the pier due to the sills influence. Best configuration is when the bed sill is adjacent to the back of the pier. | Buildup of debris can occur at the face of the bed sill rendering this countermeasure ineffective. Scour still occurs downstream of the pier. This countermeasure must span across the width of the streambed and therefore can be expensive. | Scour will still occur at the rear of the pier but the extent of scour will be restricted by the sill. Debris can also be of concern with this countermeasure. |
| • **Riprap** | Most commonly used, efficient and effective**.** Prevents horseshoe vortex. | In event of floods riprap is moved downstream and defeats the purpose. It can cause shear failure when the downwards pressure is too great causing subsidence of the riprap layer once again defeating its purpose. | Riprap stones are most commonly used and are an inexpensive method of mitigating scour. However are not suitable for small streams. |
| **Pier Attachments**<br>• **Threading** | Inexpensive but reasonably ineffective. Reduces the downward velocity and therefore less horseshoe | Threading shows minimal change to scour reduction when compared to a bridge pier with no countermeasure. | This method is inexpensive but ineffective. |

| | | | |
|---|---|---|---|
| | vortices | | |
| • **Collars or Horizontal plates** | Collars reduce both scour depth and the rate of scour. Plates are generally positioned on the upstream side of the pier whereas collars are circular disks that surround the pier.The greatest reduction in scour was found when the collar was placed under the river bed. Plates/collars width controls the scour reduction efficiency. Using a rectangular collar was superior to a circular collar decreasing scour depth by 79% | Using a small collar placed at the wrong height can actually increase the size of the scour hole. Vibration can be of concern when using a large collar. It is also difficult to install a large plate. | Using multiple collars provides safety with concern to the lowering of the natural bed level. Multiple plates reduce the effects of horse vortices. Using a single collar at a diameter three times of the pier size can see a reduction in scour up to 100%. |

| | | | |
|---|---|---|---|
| • **Pier attached plates** | Plates (vanes) placed on the pier at an angle divert the downflow away from the bed level negating the formation of a horseshoe vortex. Scour depth reduction was recorded as high as 90%. The angle investigated was 45 °. Plates sloping upward were more efficient. | Debris buildup on the plates can be an issue with this countermeasure | This method may be tested as a suitable countermeasure. |

The table below provides a recommendation for most effective and efficient design of pier and various countermeasures based on results using a rating system of 0 to 5 (with five being the most effective and efficient refer to Table 2).

### 3.2.1 Shape of the pier

**Table 4 Shapes of piers**

| **Countermeasure & Design** | **Constructability** | **Cost** | **Efficiency** | **Overall Rating** |
|---|---|---|---|---|
| **Blunt Nose** | Requires more detailed form work – 3 points | 3 points – More material and construction detail required than circular | 4 points if the direction of the flow is the same orientation as the pier. | **10 points** |
| **Sharp Nose** | Requires more detailed form work - 3 points | 3 points – More material and Construction detail required than Circular | 4 points if the direction of the flow is the same orientation as the pier. | **10 points** |
| **Circular** | Easiest to construct – 5 points | 5 points – least amount of material in designs chosen | 5 points as the direction of flow is not important | **15 points** |
| **Slot** | Requires greatest amount of form work – 2 points | 2 points – Requires more time and detail to construct | 5 points - height and direction of slot is crucial. Excellent countermeasure in reducing the downflow pressures. | **8 points** |

From the information in the table above the circular pier was chosen to be the most effective.  The direction of flow in the channel is irrelevant with this shape and therefore would permit the greatest amount of variation to size of channel, velocity of flow and live bed conditions available when building a pier in any open water channel.

**Selection: Circular pier as highlighted**

### 3.2.2 Bed attachments

**Table 5 Bed Attachments**

| Countermeasure & Design | Constructability | Cost | Efficiency | Overall Rating |
|---|---|---|---|---|
| **Sacrificial piles** | 5 points – easy to build | 3 points – dependent on how many, their size and height. | 2 points – only effective in clear water conditions. | **10 Points** |
| **Sacrificial sheet piles** | 2 points - difficult to construct and implement. | 2 points - rust easily so therefore not cost efficient. | 4 points – good in flood condition with aid of riprap stones. The singular | **8 Points** |

| | | | | |
|---|---|---|---|---|
| | | | efficiency is not as effective. Scour can occur locally. | |
| **Vanes** | 4 points – with the positions of the vanes being crucial | 5 points - cheap to implement | 4 points – depends on the flow direction and the placement of the vane in relation to the flow direction | **13 points** |
| **Surface panels** | 2 points – difficult to place and anchor | 3 points – inexpensive to construct but expensive to implement | 2 points – creates bowls at the base of the panel and not very effective | **7 points** |
| **Sleeve and collared sleeve** | 3 points – moderately difficult to construct | 3 points –this measure is reasonably expensive if the sleeve is included | 3 points – can easily get clogged with debris and incorrect positioning can cause greater scour. | **9 points** |
| **Bed sill** | 4 points – easy to construct | 2 points – expensive to construct due to countermeasure spanning | 2 points – Scour will occur to a certain degree before countermeasure is | **8 points** |

| | | | | |
|---|---|---|---|---|
| | | across entire channel | effective. Can also get clogged with debris | |
| **Riprap** | 5 points – easy to construct and implement | 5 points – cheap and cost effective method | 3 points – mainly suitable for small channels. Not good in flood conditions | **13 points** |

Bed attachments are a countermeasure that could be constructed in a channel at any given time. Sacrificial piles and riprap were the easiest to construct as shown in Table 5 above however sacrificial piles are only effective in clear bed conditions so were ruled out as ineffective for most river and channel situations. Riprap, vanes and bed sills were the next easiest to construct. Riprap is efficient and easy to construct however is limited in its efficiency as it is only suitable for small channels and not good in flood situations. This investigation aimed to establish countermeasures which will withstand flood situations as this is one of the most common reasons for bridge failure so riprap was ruled out as a combined countermeasure to be tested. From the rating system shown in Table 5 vanes received the highest rating and would therefore be suggested as suitable for bed attachments. From the above information vanes will be combined with another countermeasure and tested as part of this study.

**Selection:** Vanes as highlighted

### 3.2.3 Pier Attachments

**Table 6 Pier Attachments**

| **Countermeasure & Design** | **Constructability** | **Cost** | **Efficiency** | **Overall Rating** |
|---|---|---|---|---|
| **Threading** | 5 points –easy to construct | 5 points – Cheap countermeasure to implement | 1 point – ineffective countermeasure to reduce scour. | **11 points** |
| **Collars or Horizontal plates** | 4 points – reasonably simple to construct | 4 points – can be expensive depending on the number of collars and thickness of material | 5 Points –placement is crucial but when positioned at correct height and or spacing very effective | **13 points** |
| **Pier attached plates** | 4 points – reasonably easy to construct. Positioning is crucial | 4 point – reasonably cheap to implement | 5 points – can be really effective if positioned at the right angle | **13 points** |

Once again using Table 6 above collars and/or horizontal plates appear to be the most effective.  Both of these countermeasures will be tested as part of a combination.

**Selection:** Collars or pier attached plates as highlighted

### 3.2.4 Combined Countermeasures

**Table 7 Combined Countermeasures**

| Countermeasure & Design | Constructability | Cost | Efficiency | Overall Rating |
|---|---|---|---|---|
| **Submerged vanes and a bed sill** | 2 points – time consuming to construct | 2 points - This combination would be expensive to construct as the bed sill itself is expensive. | 1 point – as using the vanes actually caused larger scour holes downstream of the pier with the combination of bed sill | **5 points** |
| **Sacrificial piles and a collar** | 4 Points – construction is fairly easily with the | 3 points – as a combination this would be | 1 point – did not improve scour compared to just a | **8 points** |

| | | | | |
|---|---|---|---|---|
| | position of the collar being the most crucial and hardest part of construction | a reasonably expensive process. | collar. | |
| **Sacrificial piles and a slot** | 3 points – Construct is quite difficult especially creating the slot | 3 points – constructing a slot is time consuming and labour intensive. | 1 point – no improve using a combination | **7 points** |
| **Slot and collar** | 3 points – construction of this combination is moderately difficult | 3 points – slots are expensive to construct | 4 points – Debris can block the slot rendering this countermeasure ineffective. However this combination is highly effective in clear water. | **10 points** |
| **Multiple collars** | 4 points – construction and position of the collars are paramount | 4 points – depending on the diameter of the collar this is a reasonably efficient and cost effective | 5 points – The efficiency of this countermeasure is very functional in reducing scour | **13 Points** |

| | | | | |
|---|---|---|---|---|
| | | method | | |
| **Bed sill and collar** | 3 points – Bed sill is time consuming and labour intensive. | 3 points – the bed sill would be expensive to construct depending on the width of the channel. | 2 points – Fairly ineffective as a combined combination compared to individual performances | **8 points** |
| **Slot and bed sill** | 3 points – Construction of both countermeasure reasonably difficult and time consuming | 3 points – dependent on the width of the channel the bed sill can be expensive to construct. The slot construction is expensive | 3 points – the slot can get blocked by debris rendering this countermeasure ineffective. | **9 points** |

From Table 7 above which was information taken from the literature review multiple collars was deemed to be the most efficient and effective. Other combinations were not as efficient either in their cost or constructability so multiple collars was chosen to be tested. Three rectangular collars was deemed to be effective as it allowed varying situations to occur within the channel and could still reduce the volume of scour.

**Selection:** Multiple collars as highlighted

To present another option for testing the highest rating of pier attachment was combined with the highest rating of bed attachment to provide a combined countermeasure to be tested.

**Selection:** Vanes with a pier attached plate

## 3.3 Design Matrix Summary and Chosen Design with Countermeasures

From the rating process established above the following conclusions were drawn:

This research eliminated designs through a logical process in which merit points were given based on constructability, feasibility (cost) and the efficiency of the design to reduce scour. From journal articles reviewed, individual efficiency of a single countermeasure in reducing the effects of scour was noted to be at best 50%. In stating this, the performance of some combined countermeasures proved less efficient than a single countermeasure. However some combinations achieved much higher efficiency.

The circular pier was chosen to be the most effective. The direction of flow in the channel is irrelevant with this shape. The bed attachment of a vane was chosen due to efficient reduction in scour noted in the literature review. The pier attachment showed both a collar and pier attached plate to be the most effective method to reduce scour. Reviewing the combinations presented in the above matrix provided the information that multiple collars were also an optimum choice.

The testing conducted included using the highest rated bed attachment combined with the highest rated pier attachment to try and achieve the greatest reduction in scour.

These combinations were:

- Vanes placed upstream of the pier face with vane pointing inwards towards pier with pier attached plate
- Vanes placed upstream of the pier face with vane pointing outwards from the pier with pier attached plate
- Three Rectangular Collars

# 4. Methodology

## 4.1 Introduction

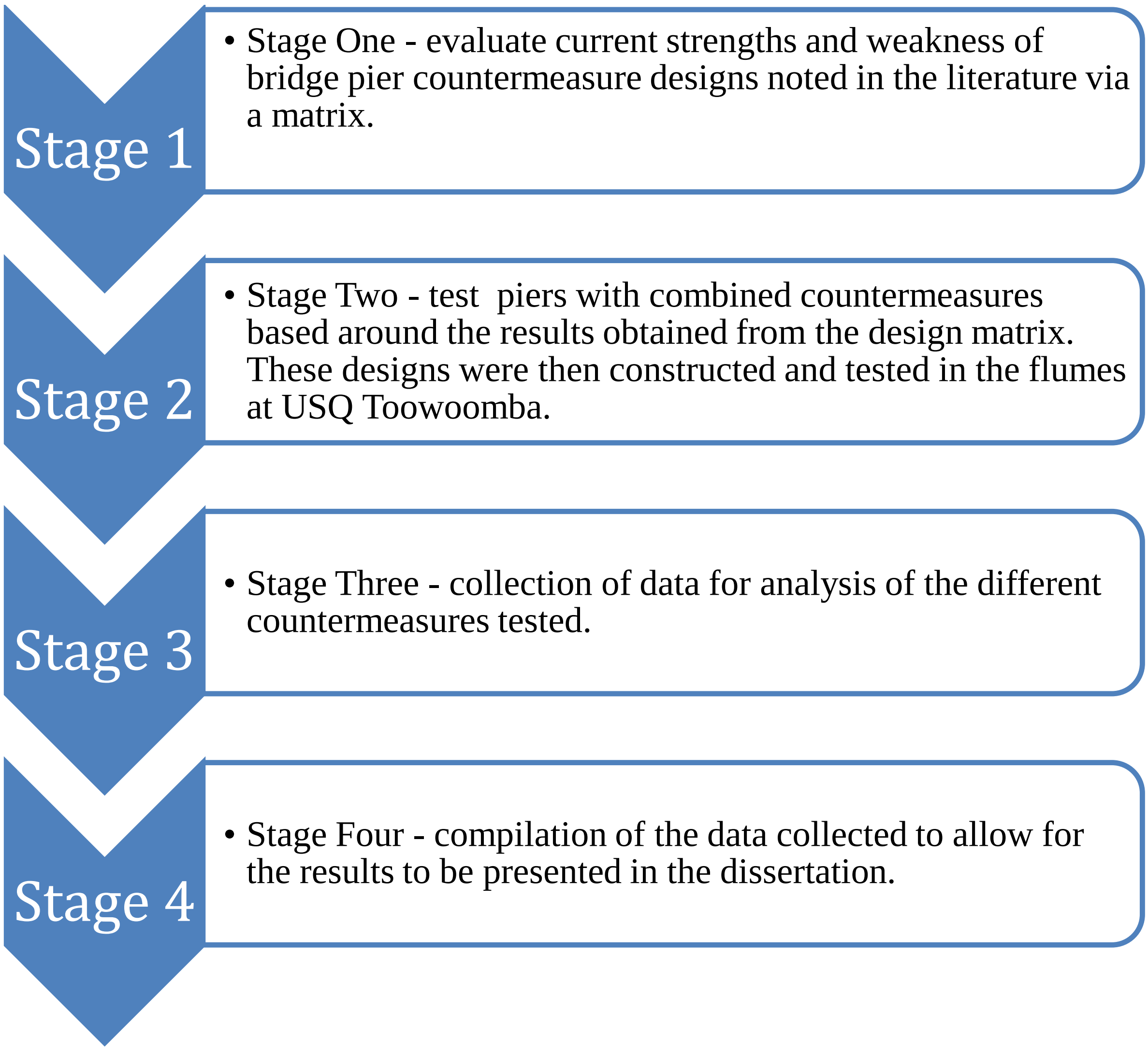
The aim of this project was to establish any minor improvement which may result from research conducted into ways to alleviate scour holes around bridge piers. “Predicting the maximum depth, area, and volume of the scour hole around a pier is important in order to design the pier foundations, avoiding pier and bridge failure” (Grimaldi 2009b). The majority of the literature review above confirmed that combinations prove to be a more efficient technique than a single countermeasure. This research used two or more combinations to determine a better outcome from countermeasures against scour around bridge piers.

Data collection for this experiment was conducted in both the large and small flumes at USQ in Toowoomba. Combined countermeasures were tested in a hydraulic flume to assess their efficiency. Non-cohesive material was used to form the bedding.

The original intention of this research was to use the large flume. However after completing preparation of the flume and testing the control model for 45 minutes the pump ceased working and repair of the pump was outside the time constants available for this research. Due to this equipment failure the alternative of the small flume became the only method of testing.

The research and results gathered from the testing undertaken are presented in this dissertation. It offers recommendations of combined countermeasures to mitigate the effects of local scouring.

The stages below formed the basis of testing:




## 4.2 Experimental Process and Setup –Large Flume

### 4.2.1 Large Flume

The large flume which is 20m long, 2m wide and 0.9m depth was used to carry out testing of combined countermeasures against scouring of a bridge pier. This flume is located at USQ Toowoomba. Positioning of the bridge pier model in the correct location (centred) of the flume to minimise the flow effects of the side walls was vital. In these conditions examination of volume of erosion for each design was to be the focus of the experiment. The base material of the flume was silty clay and river washed sand was used around the pier to observe changes in scour depth. A timber weir controlled the depth of water downstream and a gate valve controlled the upstream flow depth. Figure 4.1 below shows the flume used for testing prior to weeds being removed.

**Figure 4.1 Large Flume at University of Southern Queensland**

**Figure 4.2 Control valve**

The discharge was controlled by a valve at the start of the flume (Figure 4.2). Figure 4.3 below details in L/s the discharge:


**Figure 4.3. Discharge Gauge L/s**

This gauge showed the discharge of the fluid. A new electrical pump was installed and tests were carried out to determine its capacity.

### 4.2.2 Construction of Model Piers and Countermeasures

These models were built at the University of Southern Queensland Faculty of Engineering and Surveying. The piers were built using plastic pipe with a diameter of 225mm and were a length of 800mm. The plastic pipe was filled with concrete to help stabilize each model once plates or collars were attached.

The first test used a cylindrical pier to generate a standard for testing (Figure 4.4). This pier was built in the same way as described above. Testing was revised based on the variations shown during this initial trial.

In the second test a slot was cut out of the pipe to allow the plate to be slotted into position. This plate was the same width as the pier and extruded 0.5D from the face of the pier in a rectangular shape.  The dimension of this plate was width of 225mm and length from the face of 112.5mm (the overall length to allow for the cantilever of this plate was 225mm). For construction of the vanes a sheet of plastic was cut at an angle of 45 degrees. This sheet was approximately a 100mm in length (Figure 4.8).  A concrete base of 75mm was formed for this vane which was then placed in the wet concrete.  The vanes were to be placed at a 45 degree angle inwards towards the pier in this first test approximately 200mm away from the face of the pier (Figure 4.6).

In the third test the same procedure was to be carried out with the only alteration being the positioning of the vanes. In this test the vanes were to be placed outward at a 45 degree angle at the same distance away from the pier (Figure 4.5).

In the final combination of countermeasures to be tested, three rectangular collars attached to a circular pier were positioned as above in the centre of the flume. Collars were a length of 1.5D of the pier with the aim to reduce scour. The pier was constructed using a 225mm pipe in which collars were inserted at varying levels. The collar was situated below the surface at a depth of D/6 with the next collar being positioned at the surface and the final collar at a height of D/6 above the bedding material (Figure 4.9 & 4.10).  Once the collars were connected to the pipe shell the centre was filled with concrete for support.

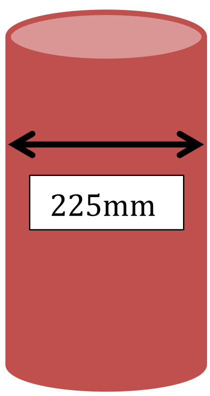



**Figure 4.4 Test one no countermeasure – Control Test**

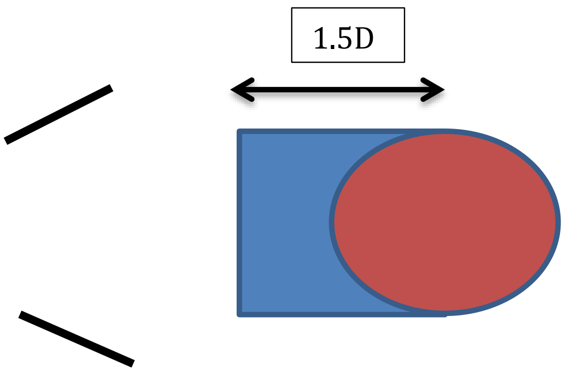



Figure 4.5 Test Two Outward Vanes

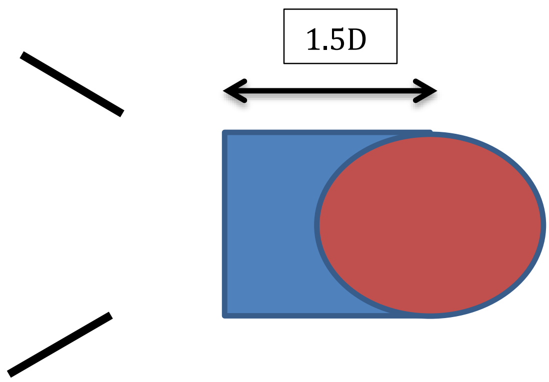



Figure 4.6 Test Three Inward Vanes

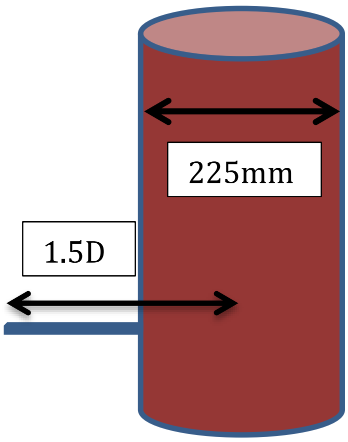



Figure 4.7 Cross sectional View Pier with plate

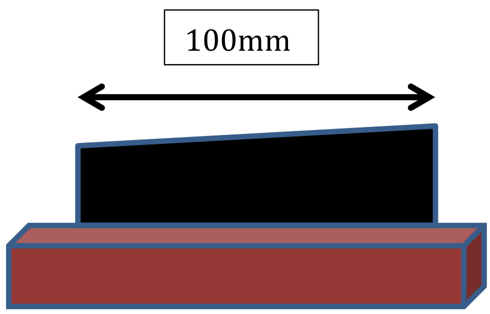



Figure 4.8 Cross sectional View Vane

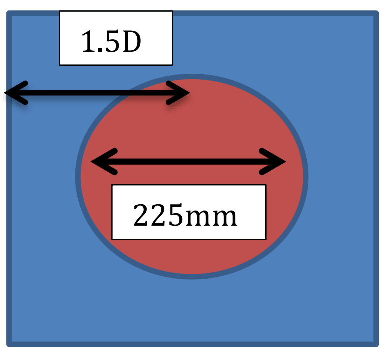



Figure 4.9 Multiple Collars top sectional View

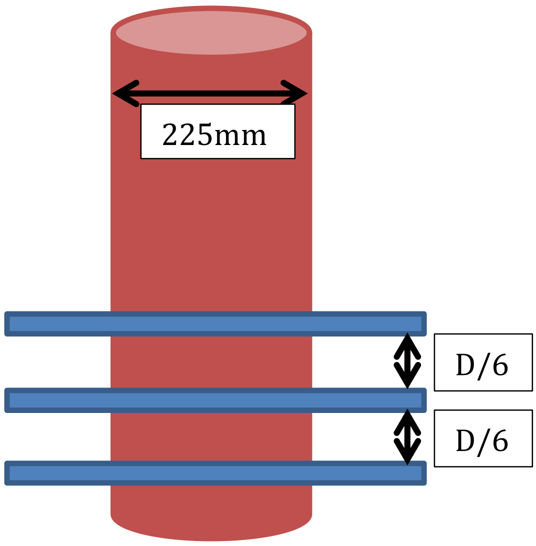



Figure 4.10 Cross sectional View -Multiple Collars

### 4.2.3 Bedding Material –Sand

The Standard used as a control for the size of bedding material is AS1141.11.1-2009 (Incorporating Amendment No 1). The methodology used was a sieving process in which particle size was determined. A table was necessary to show particle size and identify a median particle grain size for bedding material. A water absorption and density of particles test was conducted in accordance with AS 1141.5 "Method for sampling and testing aggregates". This identified the apparent particle density of the bedding material allowing for the theoretical check using Neil's Equation [Eq. (2.3)].

The particle size distribution analysis was performed to determine the way in which the material would perform in situ. The grading of a sediment material was chosen on the basis of being cohesionless allowing for optimum test conditions in which scour was likely to occur.

This sieve analysis allowed for the grading of the bedding material and the calculation of the $d_{50}$ (median particle size). Five different samples of sand were tested to allow for a choice of sand with the least cohesion. The samples were tabulated showing the sieve size, mass retained and mass passing through.

**Table 8 - Sieve Analysis –Test One**

**Sample one – Garden City Landscape Centre – Coarse Sand**

| **Sieve Size (mm)** | Self-Weight of Aperture (g) | Mass Retained including weight of Aperture (g) | Mass Retained (g) | Mass Passing (g) | Cumulative Mass Retained (g) | Percentage Retained (%) | Percentage Passing (%) |
|---|---|---|---|---|---|---|---|
| **4.75** | 410.7 | 412.3 | 1.6 | 798.4 | 1.6 | 0.2 | 99.8 |
| **3.35** | 462.8 | 485.2 | 22.4 | 776 | 24 | 3 | 97 |
| **2.36** | 399.2 | 467.2 | 68 | 708 | 92 | 11.5 | 88.5 |
| **2.00** | 441.3 | 498.5 | 57.2 | 650.8 | 149.2 | 18.65 | 81.35 |
| **1.18** | 399.4 | 730.2 | 330.8 | 320 | 480 | 60 | 40 |
| **0.600** | 430 | 659.7 | 229.7 | 90.3 | 709.7 | 88.71 | 11.29 |
| **0.500** | 341.6 | 366.5 | 24.9 | 65.4 | 734.6 | 91.83 | 8.18 |
| **0.425** | 331 | 345.3 | 14.3 | 51.1 | 748.9 | 93.61 | 6.39 |
| **0.3** | 316.1 | 344.4 | 28.3 | 22.8 | 777.2 | 97.15 | 2.85 |
| **0.25** | 320.1 | 331 | 10.9 | 11.9 | 788.1 | 98.51 | 1.49 |
| **0.15** | 269 | 279.2 | 10.2 | 1.7 | 798.3 | 99.79 | 0.2125 |
| **0.075** | 253.4 | 254.8 | 1.4 | 0.3 | 799.7 | 99.96 | 0.0375 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **0.052** | 254 | 254.1 | 0.1 | 0.2 | 799.8 | 99.98 | 0.025 |
| **pan** | 517.8 | 518 | 0.2 | 0.000 | 800 | 100 | 0 |
| Total Weight of Sample | | | 800 grams | | | | |

**Table 9 - Sieve Analysis –Test Two**

**Sample Two – Superior Sand Gravel – Coarse sand**

| **Sieve Size (mm)** | Self-Weight of Aperture (g) | Mass Retained including weight of Aperture (g) | Mass Retained (g) | Mass Passing (g) | Cumulative Mass Retained (g) | Percentage Retained (%) | Percentage Passing (%) |
|---|---|---|---|---|---|---|---|
| **4.75** | 410.6 | 425.7 | 15.5 | 784.5 | 15.5 | 1.94 | 98.06 |
| **3.35** | 463 | 483.5 | 20.5 | 764 | 36 | 4.5 | 95.50 |
| **2.36** | 399.4 | 442.1 | 42.7 | 721.3 | 78.7 | 9.84 | 90.16 |
| **2.00** | 441.9 | 469.7 | 27.8 | 693.5 | 106.5 | 13.31 | 86.69 |
| **1.18** | 399.5 | 512.7 | 113.2 | 580.3 | 219.7 | 27.46 | 72.54 |
| **0.600** | 429.9 | 648.9 | 219 | 361.3 | 438.7 | 54.84 | 45.16 |
| **0.500** | 341.7 | 421.1 | 79.4 | 281.9 | 518.1 | 64.76 | 35.24 |
| **0.425** | 331.1 | 375.5 | 44.4 | 237.5 | 562.5 | 70.31 | 29.69 |
| **0.3** | 316.1 | 429.8 | 113.7 | 123.8 | 676.2 | 84.53 | 15.48 |
| **0.25** | 319.6 | 368.3 | 48.7 | 75.1 | 724.9 | 90.61 | 9.39 |
| **0.15** | 268.7 | 333.0 | 64.3 | 10.8 | 789.2 | 98.65 | 1.35 |
| **0.075** | 253.4 | 263 | 9.6 | 1.2 | 798.8 | 99.85 | 0.15 |
| **0.052** | 254 | 254.6 | 0.6 | 0.6 | 799.4 | 99.93 | 0.07 |
| **pan** | 518 | 518.6 | 0.6 | 0.000 | 800 | 100 | 0.00 |
| Total Weight of Sample | | | 800 grams | | | | |

**Table 10 - Sieve Analysis –Test 3**

**Sample Three – D and D Sand & Gravel – Jacobs Well**

| **Sieve Size (mm)** | Self-Weight of Aperture (g) | Mass Retained including weight of Aperture (g) | Mass Retained (g) | Mass Passing (g) | Cumulative Mass Retained (g) | Percentage Retained (%) | Percentage Passing (%) |
|---|---|---|---|---|---|---|---|
| **4.75** | 618.2 | 618.6 | 0.4 | 631.3 | 0.4 | 0.06 | 99.94 |
| **3.35** | 462.9 | 465.9 | 3 | 628.3 | 3.4 | 0.54 | 99.46 |
| **2.36** | 400.9 | 403.5 | 2.6 | 625.7 | 6 | 0.95 | 99.05 |
| **2** | 442.2 | 442.8 | 0.6 | 625.1 | 6.6 | 1.04 | 98.96 |
| **1.18** | 438.7 | 442.5 | 3.8 | 621.3 | 10.4 | 1.65 | 98.35 |
| **0.6** | 429.9 | 508.1 | 78.2 | 543.1 | 88.6 | 14.03 | 85.97 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **0.5** | 341.9 | 424.1 | 82.2 | 460.9 | 170.8 | 27.04 | 72.96 |
| **0.425** | 331.6 | 417.3 | 85.7 | 375.2 | 256.5 | 40.60 | 59.40 |
| **0.3** | 316.9 | 459.7 | 142.8 | 232.4 | 399.3 | 63.21 | 36.79 |
| **0.25** | 319.1 | 453.2 | 134.1 | 98.3 | 533.4 | 84.44 | 15.56 |
| **0.15** | 268.8 | 361.4 | 92.6 | 5.7 | 626 | 99.10 | 0.90 |
| **0.075** | 283.7 | 289 | 5.3 | 0.4 | 631.3 | 99.94 | 0.06 |
| **0.052** | 254.1 | 254.3 | 0.2 | 0.2 | 631.5 | 99.97 | 0.03 |
| **pan** | 379.3 | 379.5 | 0.2 | 0 | 631.7 | 100.00 | 0.00 |
| Total Weight of Sample | | | 631.7 grams | | | | |

**Table 11 - Sieve Analysis –Test 4**

**Sample Four – D and D Sand & Gravel – Medium Sand**

| **Sieve Size (mm)** | Self-Weight of Aperture (g) | Mass Retained including weight of Aperture (g) | Mass Retained (g) | Mass Passing (g) | Cumulative Mass Retained (g) | Percentage Retained (%) | Percentage Passing (%) |
|---|---|---|---|---|---|---|---|
| **4.75** | 618 | 618.3 | 0.3 | 675 | 0.3 | 0.04 | 99.96 |
| **3.35** | 462.6 | 464.3 | 1.7 | 673.3 | 2 | 0.30 | 99.70 |
| **2.36** | 400.6 | 406.2 | 5.6 | 667.7 | 7.6 | 1.13 | 98.87 |
| **2** | 442 | 447.5 | 5.5 | 662.2 | 13.1 | 1.94 | 98.06 |
| **1.18** | 438.7 | 480.5 | 41.8 | 620.4 | 54.9 | 8.13 | 91.87 |
| **0.6** | 430.1 | 658 | 227.9 | 392.5 | 282.8 | 41.88 | 58.12 |
| **0.5** | 341.7 | 462.7 | 121 | 271.5 | 403.8 | 59.80 | 40.20 |
| **0.425** | 331.4 | 407 | 75.6 | 195.9 | 479.4 | 70.99 | 29.01 |
| **0.3** | 316.2 | 403.6 | 87.4 | 108.5 | 566.8 | 83.93 | 16.07 |
| **0.25** | 318.7 | 364.2 | 45.5 | 63 | 612.3 | 90.67 | 9.33 |
| **0.15** | 268.7 | 313.9 | 45.2 | 17.8 | 657.5 | 97.36 | 2.64 |
| **0.075** | 283.6 | 298.2 | 14.6 | 3.2 | 672.1 | 99.53 | 0.47 |
| **0.052** | 254.1 | 255.9 | 1.8 | 1.4 | 673.9 | 99.79 | 0.21 |
| **pan** | 379.3 | 380.7 | 1.4 | 0 | 675.3 | 100.00 | 0.00 |
| Total Weight of Sample | | | 675.3 grams | | | | |

**Table 12 - Sieve Analysis -Test 5**

**Sample Five– D and D Sand & Gravel – Rav Bourne White**

| **Sieve Size (mm)** | Self-Weight of Aperture (g) | Mass Retained including weight of Aperture (g) | Mass Retained (g) | Mass Passing (g) | Cumulative Mass Retained (g) | Percentage Retained (%) | Percentage Passing (%) |
|---|---|---|---|---|---|---|---|
| 4.75 | 617.8 | 619.6 | 1.8 | 692.5 | 1.8 | 0.26 | 99.74 |
| 3.35 | 462.5 | 462.8 | 0.3 | 692.2 | 2.1 | 0.30 | 99.70 |
| 2.36 | 400.6 | 400.9 | 0.3 | 691.9 | 2.4 | 0.35 | 99.65 |
| 2 | 442 | 443.3 | 1.3 | 690.6 | 3.7 | 0.53 | 99.47 |
| 1.18 | 438.6 | 455.7 | 37.7 | 652.9 | 41.4 | 5.96 | 94.04 |
| 0.6 | 429.7 | 558.7 | 129 | 523.9 | 170.4 | 24.54 | 75.46 |
| 0.5 | 341.5 | 432.9 | 91.4 | 432.5 | 261.8 | 37.71 | 62.29 |
| 0.425 | 331.2 | 419.5 | 88.3 | 344.2 | 350.1 | 50.42 | 49.58 |
| 0.3 | 316 | 453 | 137 | 207.2 | 487.1 | 70.16 | 29.84 |
| 0.25 | 318.3 | 399.9 | 81.6 | 125.6 | 568.7 | 81.91 | 18.09 |
| 0.15 | 268.5 | 366.3 | 97.8 | 27.8 | 666.5 | 96.00 | 4.00 |
| 0.075 | 283.3 | 309.1 | 25.8 | 2 | 692.3 | 99.71 | 0.29 |
| 0.052 | 253.9 | 255.3 | 1.4 | 0.6 | 693.7 | 99.91 | 0.09 |
| pan | 379.1 | 379.7 | 0.6 | 0 | 694.3 | 100.00 | 0.00 |
| Total Weight of Sample | | | 694.3 grams | | | | |

The above tabulated data has been graphed below on a log scale to show the particle distribution of each sample (Figure 4.11).

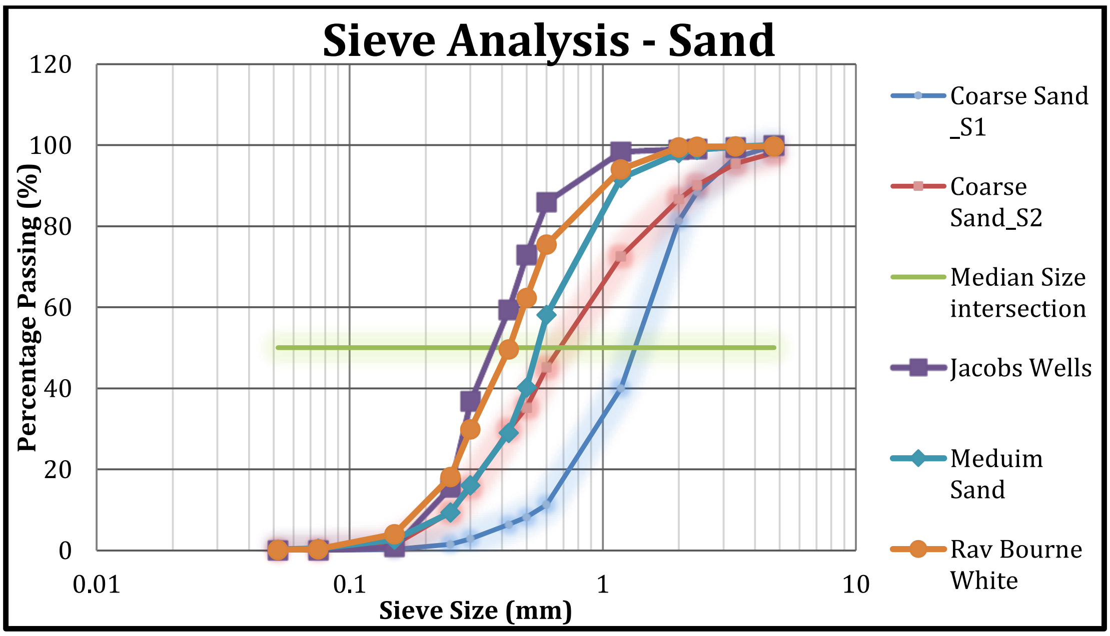



**Figure 4.11 Sieve Analysis**

The median size grain ($\boldsymbol{d_{50}}$) has been tabulated below for each sample.

**Table 13 - Sieve Analysis – Median size grain distribution $d_{50}$**

| Median size grain distribution $d_{50}$ | |
|---|---|
| **Sample 1** | 1.36mm |
| **Sample 2** | 0.59mm |
| **Sample 3** | 0.38mm |
| **Sample 4** | 0.41mm |
| **Sample 5** | 0.54mm |

From this analysis the bedding material chosen for testing was Jacob's Well (Sample 3) which showed the greatest rise on the graph. This sharper rise compared to other samples indicated a lesser amount of cohesion. The lesser amount of cohesion meant greater scour would occur during testing at a lower velocity. Sediment transportation would also occur at a lower velocity.

The table below was completed for Jacob's Well showing the apparent particle density, dry particle density and water absorption in accordance with AS 1141.5 "Method for sampling and testing aggregates".

**Table 14 - Sieve Analysis- Jacob's Well Density**

| Sample Three – Jacobs Well | |
|---|---|
| Apparent particle density | 1.4432 t/m³ |
| Dry Particle density | 1.3612 t/m³ |
| Water Absorption | 5.68% |

### 4.2.4 Excavation of Flume

Initial clearing of the weeds and levelling of the ground within the flume began. Further excavation of bedding material at a distance 8m from the inlet and a depth of 0.300m for a width and length of 2m was dug to provide depth to assimilate conditions for a foundation and support for the pier as per figure 4.12. Once the pier placement was established the area was filled with Jacob's Well sand.

**Figure 4.12 Excavation of Flume showing area of interest dug at 0.300m below flume bedding level**

## 4.3 Testing method – Large Flume

Boards were placed in slots in the sides of the flume (figure 4.13) to capture the water so that the depth required for testing was achieved. The excavation of the centre of the flume to a measurement of 2m x 2m x.0.3m was then completed. Once the control pier was in place washed river sand was filled in this area to the same height as the bed level of the flume. The pier was then anchored and tied provide stability and ensure that the model did not move during testing.

**Figure 4.13 Flume showing control pier in positon, sand filled and slot for boards to water control depth**

The valve (figure 4.14) was then slowly released to allow the flow of water into the flume until the required depth of 250mm was achieved. The control valve was opened slowly to ensure a steady flow without any surges.

**Figure 4.14 Flume Control Valve slowly opening showing water flow**

This intial test was conducted purely to understand and test the capacity of the newly installed pump.  Water was realeased slowly into the flume to reduce the effect of surges on the bedding layer.  After increasing the discharge the pump ceased working approximately 30mins later. As a result testing stopped  and the only results obtained are soon below. Figure 4.15 provides a panoramic view of water being pumped from the dam into the flume, flowing out over the weir and continuing around returning to the dam. Further testing in the large flume was unable to be completed within time constraints and testing was therefore moved to the small flume.

**Figure 4.15 Panoramic view of water flowing from dam into flume and returning to dam**

## 4.4 Experimental Process and Setup – Small Flume

Due to the malfunctioning of the pump in the large flume testing was moved to the small flume.   The same bedding material as analyzed above was adopted.  The models were also scaled down, however the construction method was different, and this has been explained further below.

### 4.4.1 Small Flume

The small flume is 3.8m long, 0.615m wide with a maximum depth of 0.120m and located in the Hydraulic Lab at USQ Toowoomba. A floating floor was constructed from marine ply at a depth of 0.030m. This was constructed to ensure the approach flow from the inlet was as uniform as possible prior to reaching the bedding material. This approach flooring was 1.8m in length with the bedding material 1.4m in length and the last part of the floating floor continued to the end of the flume where a sediment trap collected the moving particles. Baffles were also placed at the inlet of the flume to help control the flow from the pump. The baffles were introduced to provide a more uniform flow prior to fluid hitting the bedding material. This however was ineffective so a fly screen mesh was added to the face of the baffles to achieve a uniform flow (figure 4.16).

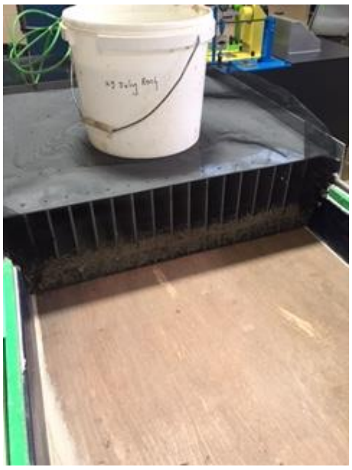


**Figure 4.16 Baffles and Fly Screen Mesh for Laminar Flow**

The bridge pier was centred in the flume using a metre ruler and another straight edge to give a 90 ° angle in which the pier could be positioned as illustrated below. Positioning of the bridge pier model in the correct location (centred) was vital to minimise the flow effects of the side walls (figure 4.17).


**Figure 4.17 Positioning of Pier**

In these conditions the examination of scour for each design was the focus of the experiment. The base material of the flume was Jacob's Well sand which was used around the pier to observe changes in scour depth.

A weir controlled the depth of water downstream and a gate valve controlled the upstream flow depth. The flow of the flume was measured through a flow meter which reports velocities from the pump in litres per minute (figure 4.18). The holding tank at the end of the flume required extra water due to its poor holding capacity. A ruler was placed in the holding tank to ensure the height of water was at a consistent depth to maintain a constant flow for each experiment.

**Figure 4.18 ManuFlo Gauge**

### 4.4.2 Construction of Model Piers and Countermeasures

Models were built at the University of Southern Queensland. The control pier was built using plastic pipe with a diameter of 68mm and a length of 180mm in total. The plastic pipe was then filled with concrete to help stabilize this model. The first test used a cylindrical pier to generate a standard for testing (figure 4.19). This test then became the control and subsequent tests were conducted using the same parameters.

The countermeasure models were constructed out of plastic using a 3D printer. The designs were created through Tinkercad. The first design using a countermeasure created a pier with a plate extruding 0.25D from the face of the pier in a rectangular shape. The dimensions in total of this plate were a width of 68mm and length of 34mm at the same height as the sand (30mm).

For construction of the vanes a 3D printer was once again used for fabrication. The vanes were positioned at an angle of 45 º to the pier. Theses vanes were 70mm in height (figure 4.20 & 4.21). The vanes were placed at a 45 ºangle inwards towards the pier in the first test at 100mm away from the face of the pier (figure 4.21).

In the next test the same procedure was carried out with the only alteration being the positioning of the vanes. In this test the vanes were placed outwards at a 45 ºangle and the same distance away from the pier (figure 4.20).

In the final combination of countermeasures tested, three rectangular collars were attached to a circular pier and positioned in the centre of the flume. Collars were a length of 1.5D of the pier with the aim to reduce scour. The pier was constructed using the 3D printer where collars were inserted at varying levels. The first collar was situated below the bed surface at a depth of D/6 with the next collar being positioned at the bedding surface and the final collar at a height of D/6 above the bedding material (figure 4.24). The pipe shell was then filled with concrete to provide support. All models have been painted with a bitumen membrane to ensure a consistent frictional surface for each pier. This was also completed to model a more industrial finish.

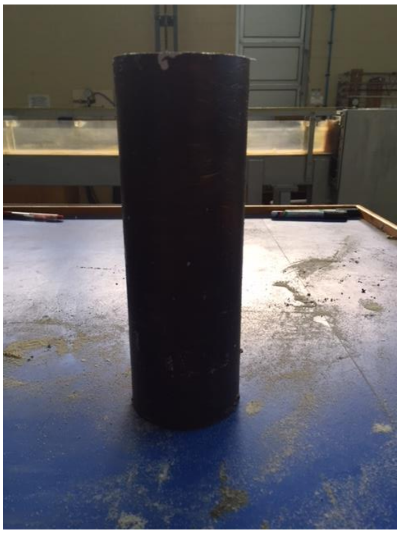


**Figure 4.19 Test one no countermeasure – Control Test**

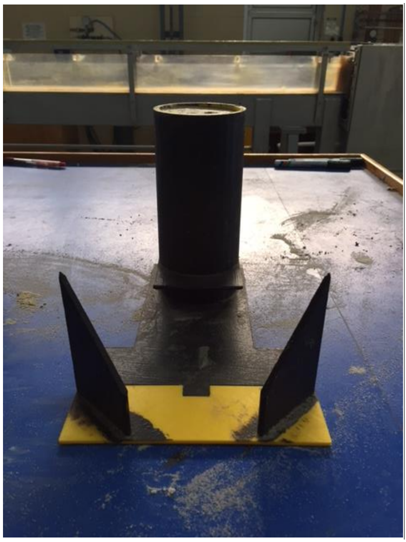


**Figure 4.20 Test Two Outward Vanes**

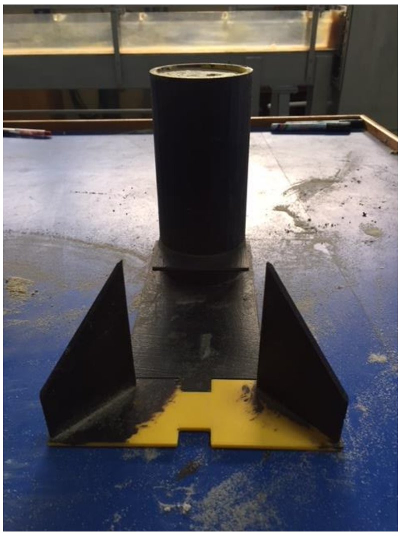


**Figure 4.21 Test Three Inward Vanes**

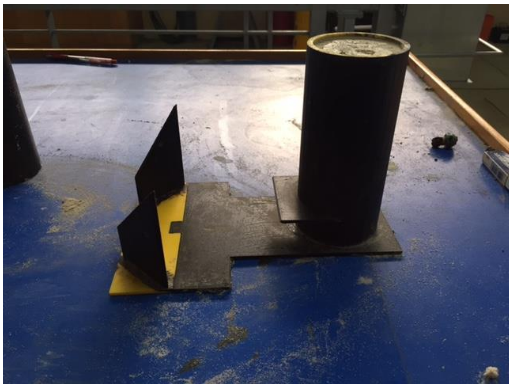


**Figure 4.22 Cross sectional View Outward Vanes with Pier attached plate**

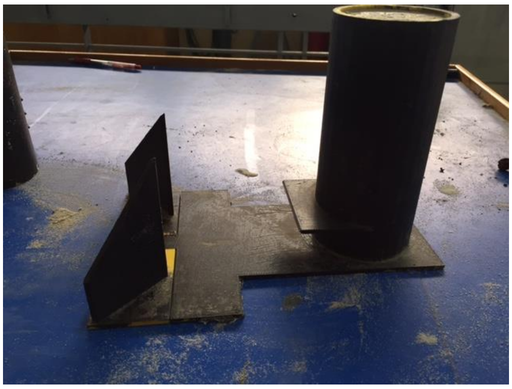


**Figure 4.23 Cross sectional View Inward Vanes with Pier attached plate**

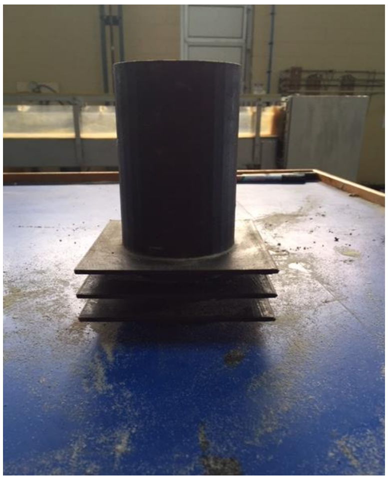


**Figure 4.24 Cross sectional View -Multiple Collars**

### 4.4.3 Installation of floating floor and bedding material

The small flume required a floating floor constructed from marine ply to provide containment of the bedding material. This was also built to provide a run of clear flow before hitting the bedding material.  The first section of the flume prior to the start of the bedding sand was 1.8m long. Bedding sand of 0.258m3 was then placed in the flume and a further section of floating floor was constructed at the end of the pier at a length of 0.600m. The bedding sand section measured 1.4m in length.

## 4.5 Theoretical Calculations

### 4.5.1 Flow Conditions

Steady flow was achieved by passing water through baffles and aluminum fly screen situated at the beginning of the flume. A depth of 70mm was established to allow for testing of the countermeasures. The testing was completed with a discharge of 500Litres/min ($8.33 \times 10^{-3} m^3/s$).With the gate valve open at this discharge the velocity was approximately 0.194m/s. The Reynold's number was then calculated to ensure flow around the pier was turbulent.

$$Re_{Channel} = \frac{\rho RV}{v} \qquad \text{(Eq 2.1)}$$

$$Hydraulic\ Radius\ R = \frac{A}{P} = \frac{by}{b + 2y}$$

$$Hydraulic\ Radius\ R = \frac{0.615m \times 0.070m}{0.615m + 2 \times 0.070m}$$

$$R = 0.057m$$

$$Re_{Channel} = \frac{pRV}{v}$$

$$Re_{Channel} = \frac{0.057m \times 0.194m/s}{1 \times 10^{-6}} = 1.1058 \times 10^4$$

$$\therefore Turbulent\ Conditions$$

Scour occurs in turbulent conditions caused by the obstruction of the pier.

The Froude Number was calculated next to determine the flow regime of the channel.

$$Fr = \frac{V}{\sqrt{gy}} \qquad \text{(Eq.2.2)}$$

$$Fr = \frac{0.194m/s}{\sqrt{\frac{9.81m}{s^2} \times 0.070m}}$$

$$Fr = 0.234 \quad \therefore Subcritical\ Flow$$

### 4.5.2 Sediment Size

The theoretical check of the size of the sediment to the diameter of the bridge pier was completed. This was to ensure independence between sediment size and bridge pier diameter. If this equation was greater than 50 then there would be no relationship between sediment size and scour depth.

$$\frac{b}{d_{50}} > 50 \qquad \text{Eq. (2.5)}$$

$$\frac{68mm}{0.38mm} = 178.95 > 50$$

$$\therefore Scour\ depth\ is\ independent\ of\ sediment\ size$$

### 4.5.3 Critical Mean Velocity

As per the literature review the critical mean velocity was calculated to ensure particle transportation occurred. This was calculated using Neill's Equation:

Where,
Specific gravity of sediment particles (Ss) =1.4432 t/m$^3$,
y= flow depth (m) = 0.070m (Test depth)
$d_{50}$ = Median size of bed material (m) =0.36mm

$$Vc = 1.41\sqrt{(s_s - 1)gd_{50}} \left(\frac{y}{d_{50}}\right)^{\frac{1}{6}} \qquad \text{Eq. (2.3)}$$

$$Vc = 1.41\sqrt{(1.4432\ \mathrm{t/m^3} - 1) \times 9.81 m/s^2 \times 0.00036m}\ \left(\frac{0.070m}{0.00036m}\right)^{\frac{1}{6}}$$

$$Vc = 0.137 m/s$$

The table below was calculated to show the different critical mean velocity (Vc) at various heights within the small flume.

**Table 15 Jacob's Well – Critical Mean Velocity**

| Jacob's Well | | | |
|---|---|---|---|
| **Critical Mean Velocity Vc (m/s)** | Y Depth | Q(m3/s) | Litres minute |
| **0.119** | 0.03 | 0.00219 | 131.40 |
| **0.137** | 0.07 | 0.00589 | 353.12 |
| **0.143** | 0.09 | 0.00790 | 473.43 |

### 4.5.4 Pier Scour depth

Equation 2.5 below was developed to predict the maximum scour depth around a bridge pier (Administration 1993). It can be used for both cases of scour either live bed or clear bed scour conditions. This was calculated to predict the theoretical scour depth.

$$\frac{y_s}{y_1} = 2.0\ k_1 k_2 k_3 \left[\frac{a}{y_1}\right]^{0.65} {Fr_1}^{0.43} \qquad \text{Eq. (2.4)}$$

Where,
L = Pier Length (m)
a = Pier width (m)
$Fr_1$ = Froude Number directly upstream of the pier
$V_1$ = Mean velocity of flow upstream of the pier
g = Acceleration of gravity
$k_1$= Correction for pier nose shape
$k_2$=Correction for the angle of attacked of flow
$k_3$=Correction factor for bed condition
$y_1$ = Depth upstream
$y_s$ = Depth of Scour

$$Where, k_1 = 1\ k_2 = 1\ k_3 = 1.1$$

$$y_s = \left(2.0 \times\ 1 \times 1 \times 1.1 \left[\frac{0.068}{0.070}\right]^{0.65} 0.113^{0.43}\right) \times 0.070$$

$$y_s = 0.059m$$

The Table below shows the theoretical scour depth for each critical velocity at the various water depths.

**Table 16 Jacob's Well – Theoretical Depth**

| **Critical Mean Velocity** | $Fr_1$ | **Y Depth** | **Q(m3/s)** | **Litres minute** | **YS (maximum depth of Scour theoretical** | **YS** |
|---|---|---|---|---|---|---|
| **Vc (m/s)** | | (m) | (m3/s) | L/min | (m) | (mm) |
| **0.1187** | 0.064 | 0.03 | 0.00219 | 131.41 | 0.034 | 34 |
| **0.1367** | 0.113 | 0.07 | 0.00589 | 353.12 | 0.059 | 59 |
| **0.1426** | 0.134 | 0.09 | 0.00789 | 473.43 | 0.070 | 70 |

## 4.6 FARO Laser scanner Focus 3D

This laser scanner was used to assist in calculating the scour depth around each tested pier. It ensured a greater degree of accuracy as it delivers very detailed 3D images when determining the scour depth and volume. This device allowed the analysis of the scour depth when compared to the theoretical calculation for the maximum scour depth forming a good starting point to compare efficiencies of the countermeasures (Eq 2.5). The laser is high speed with a 2mm tolerance level of accuracy (FARO 2015).

The scanner was placed in two positions one upstream and one downstream and diagonally opposite to allow analysis of the scour effects at the face and directly behind the pier. Scans were taken once the model was in place and prior to commencement of water flow. After completing the testing further scans were taken to allow comparison. The scans were processed into a software program called 'Scene' and then the data was further refined in I-Site. Vulcan, another surveying software program, then displayed the difference of scour in each scenario.

A FARO Scanner recognises spheres as datum points. Four spheres were strategically placed to allow the software to identify these spheres. This was completed as two scans were necessary each time to capture information from both ends of the pier. The software then detected these spheres as datum points merging the images into one.

### 4.6.1 FARO Scene Software

'Scene' was used to show 3D modelling of the scour holes. This program was used to transfer the images from the SD card into the computer to allow for further modelling.

### 4.6.2 Maptek - I-Site 3D laser Scanning Software

I-site was used to refine the image detail previously obtained by the FARO Scene software. The FARO scan captured a larger area of data than required so processing in I-Site was used to reduce the image to the area of interest.

### 4.6.3 Maptek - Vulcan

From I-Site the information was transferred to Vulcan, a mining software program. This software calculated the volume of scour. This program also allowed the images, before any water flow and after testing, to overlap showing the amount of scour occurring and the position of scour in relation to the bridge pier.

## 4.7 Positioning of model pier and countermeasures

The pier was positioned in the centre of the flume in the initial test 2.2m downstream from the inlet. A weight was placed on top of the pier to ensure no movement during testing.  Results around depth of water and movement of sediment were tested to provide a standard with which to compare.

The double submerged vanes were positioned upstream of the pier at a distance of 100mm from the face of the pier. The submerged vanes were set at 45º to the perpendicular to try and achieve a reduction in scour depth. This test placed the end of the vane closest to the pier directing the flow inwards towards the pier face (figure 4.23). The second configuration placed the end of the vane to the outside of the pier directing the flow away from the pier (figure 4.22).

The third countermeasure tested was the combined collars. This pier was once again positioned at the centre of the flume. These collars were rectangular in shape and the first collar was situated below bed level at a distance of D/6 beneath the surface with the second being at the surface of the bedding material and last being D/6 above the surface of the bedding material.

## 4.8 Testing method

Preliminary tests were completed to gauge the correct depth and velocity of water due to the limiting capacity for storage of water within the flume. The control pier was then tested under the same experimental conditions. The combined countermeasures, chosen from the process of elimination in the design tables, were also tested to allow for comparison of scour depth.

After positioning the control model in the centre of the sand and leveling this between both false floors a smooth surface was achieved for testing. The wall of the weir was raised to full height to retain the maximum depth of water prior to increasing the discharge from the inlet. The next step involved taking the initial FARO scans from each side of the model. The spheres were placed at four points around the flume and positioned so that both scanning placements captured the spheres as datum points. These scans were taken to show the bedding surface prior to water flow.

After these scans were completed water was introduced by slowly releasing the control valve until a rate of 20litre/min was achieved to ensure minimal disruption (e.g surge waves) to the bedding material. This rate was maintained until water started trickling over the weir which took approximately 4.30mins. The height of water retained by the weir was 0.030m. To achieve a higher depth in the flume for testing due to the restriction of the weir wall height the discharge was increased. The discharge was increased in increments of 50litres/min every 30seconds until required discharge of 500litres/min was achieved. The depth of water in the flume was maintained at 0.070m.

The next step in testing was observation and monitoring of all the variable conditions during testing. Photos of the models were taken every thirty minutes to illustrate if any changes in scour occurred. After testing for two hours the flume pump was turned off and the flume was drained of water. The bedding material was left to dry as the laser scanner could only identify changes in the bedding surface once devoid of water. Once the surface was dry enough scans were completed from each separate end of the flume to provide information on the changes. This process was repeated for each countermeasure for two hours at a time.

The main results were obtained by setting up the FARO scanner to capture the scour depth and volume around the pier. This allowed for comparison of the different countermeasures being tested. Once the results from the FARO scan were obtained they were then processed through three different software packages to show the differences in volume of scour. This allowed for the efficiency of the countermeasures to be interpreted.

## 4.9 Variables

The following variables could affect results and it was important to be aware when conducting analysis.

- The water could be released too quickly causing a surge downstream;
- The flow may vary in intensity and velocity for each individual experiment so it was important to complete readings at consistent intervals to ensure the same flow;
- The time may run for a minute more or less on one experiment which may affect the outcome;
- Positioning of the countermeasures and or pier

## 4.10 Conclusion Methodology

Combinations generally tested more efficiently than countermeasure techniques working independently. The most effective combinations appeared to cover the weakness of the other. It would be rational to study the strengths and weakness of all existing countermeasure methods working independently so that strengths could be matched with weakness. Due to time and construction constraints this was not possible. Using the literature review on the studies of individual countermeasures the combinations were formed. The aim of this research was to nullify the weakness of independent countermeasures by introducing another.

The performance of these countermeasures was measured by:

- The FARO scanner was used to find the maximum depth of scour. The depth of scour from each test was compared with the control model. The scour reduction volume efficiency was compared to assess performance of the combined countermeasures.

Once testing was completed the information collected above allowed for comparison of the three different combinations of countermeasures. Ranking by measurement of the scour reduction determined the success of this experiment. The design with the least amount of erosion will be recommended for use.

# 5.0 Results & Analysis

## 5.1 Introduction

This section explains the results obtained during testing in the large and small flume at USQ Toowoomba. The results compared the scour reduction volume efficiency immediately around a control pier and piers using combined countermeasures. Three different combined countermeasures were tested to determine their efficiency.

## 5.2 Initial results from the large flume

Figures 5.1, 5.2 and 5.3 show the only results obtained from the large flume. Figure 5.1 shows the flume in operation. Figures 5.2 and 5.3 below show the deformation of sand immediately around the pier. It is clear from the image that a deviation of the sand had started to occur behind the pier and this was due to the wake vortices. These figures, 5.2 and 5.3, also clearly identify the initial signs of erosion around the base of the pier. After only 30 minutes of testing the pump failed and was unable to be fixed after many repeated attempts. As this was no longer viable as a test measure new models were made to enable results to be obtained using the small flume.

**Figure 5.1 Large flume showing water flowing in the initial trial**

Arrow indicates water flow

**Figure 5.2 Downstream view of erosion after initial testing of 30mins.**

**Figure 5.3 Upstream view of erosion after initial testing of 30 mins.**

## 5.3 Initial Results from the small flume

The small flume involved testing the control pier at different depths of flow and velocities to establish the correct parameters to use for testing. Experiments were conducted where critical mean velocity was achieved for the various depths to ensure sedimentation flow. Initial testing at 600L/min occurred, in turn creating a higher depth of flow, equaling 90mm. Deformation was extreme with the sand particles totally pushed downstream exposing a large portion of the bottom testing platform within an hour of testing. Testing was then undertaken at the minimum point of critical velocity 360L/min where sediment transportation in theory should occur. After 2 hours only minimal disruption to the surface had occurred determining that this test parameter was too low. It was seen that the horseshoe shape of erosion was occurring but after 2 hours of testing the deformation was only half way around the pier. Testing was then commenced at 500L/min as this produced sufficient depth within the flume for a turbulent flow allowing realistic results to be obtained during a flood event. These were the parameters adopted.

The velocities tested above were determined by using Table 16, Critical Mean Velocities. A restriction due to the retention capacity of the weir meant depths at varying velocities did not correlate directly to the theoretical critical velocities as stated in the table. Theoretically these figures were the minimum and were surpassed in velocity. This meant that the lower depths were tested with higher velocities to permit sediment transportation to occur.

## 5.4 Theoretical calculation of scour depth

The theoretical calculation was completed in Table 16 above to show the expected depth of erosion. Testing at these velocities proved to be on the cusp of minimal sediment transportation occurring, so velocity was increased until the sediment transportation rate was seen to occur more frequently. To increase the rate of erosion the discharge was increased to 500L/min. The calculation below shows the expected depth of scour at this discharge.

$$\frac{y_s}{y_1} = 2.0\ k_1 k_2 k_3 \left[\frac{a}{y_1}\right]^{0.65} {Fr_1}^{0.43} \qquad \text{Eq. (2.4)}$$

Where,
L = Pier Length (m)
a = Pier width (m)
$Fr_1$ = Froude Number directly upstream of the pier
$V_1$ = Mean velocity of flow upstream of the pier
g = Acceleration of gravity
$k_1$= Correction for pier nose shape
$k_2$=Correction for the angle of attacked of flow
$k_3$=Correction factor for bed condition
$y_1$ = Depth upstream
$y_s$ = Depth of Scour

$$Where, k_1 = 1\ k_2 = 1\ k_3 = 1.1$$

$$Fr = 0.234 \quad \therefore Subcritical\ Flow$$

$$y_s = \left(2.0 \times \ 1 \times 1 \times 1.1 \left[\frac{0.068}{0.070}\right]^{0.65} 0.234^{0.43}\right) \times 0.070$$

$$y_s = 0.081m$$

From this equation the expected theoretical depth was 81mm.

The table below shows the theoretical critical mean velocity for sediment transportation to commence.

**Table 17 Theoretical calculation of scour for test depth and flow rate**

| Critical Mean Velocity | $Fr_1$ | Y Depth | Q(m3/s) | Litres minute | YS (maximum depth of Scour theoretical | YS |
|---|---|---|---|---|---|---|
| **Vc (m/s)** | | (m) | (m3/s) | L/min | (m) | (mm) |
| 0.1935 | 0.234 | 0.07 | 0.00833 | 500 | 0.081 | 81 |

## 5.5 Control Pier

The first test involved the cylindrical pier to provide a control against which the efficiency of the combined countermeasures could be quantified. The following parameters were adopted for all tests: - average mean velocity of 0.194m/s and depth of 70mm. After reaching the required velocity and water depth, initial observations showed the commencement of scour at the face of the pier. The scour formed in a shape similar to that of a horseshoe and continued to wrap around the face of the pier gradually encompassing the whole pier. Scour occurred within the first 30 minutes and was well defined after the first hour (figures 5.4 & 5.5). Sand particles formed a rolling movement as they were uplifted by the force of the flow. Wake vortices occurred behind the pier and there was also a deposition of sand creating a crater effect at the base of, and in the wake of the pier.

**Figure 5.4 Erosion around control pier after 2hrs of testing**

**Figure 5.5 Erosion behind control pier after 2hrs of testing**

Below in figure 5.6 the FARO scan image provides an overview of the deposition in the area. Table 18 shows the depth of erosion and movement of sediment.

**Table 18 Depth Colour Chart Control Pier**

| | |
|---|---|
| -30mm to -20mm | 20mm to 30mm |
| -20mm to -10mm | 30mm to 40mm |
| -10mm to 0 | 40mm to 50mm |
| 0 to 10mm | 50mm to 60mm |
| 10mm to 20mm | 60mm to 67.61mm |

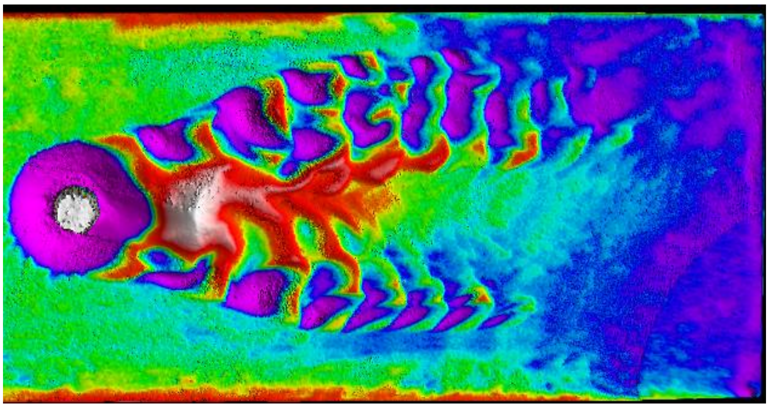


**Figure 5.6 Top View of Control Pier - Vulcan Software Depth Profile**

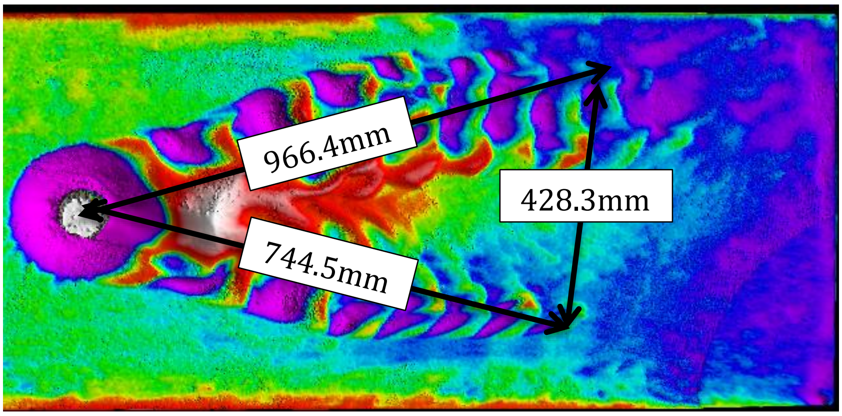



**Figure 5.7 The distance of deposition of sand from the control pier after testing for 2 hours at 500L/min**

Figure 5.8 shows the erosion in purple around the control pier. This is quite a significant bowl shape with a definite deposit of sand after the wake in white.

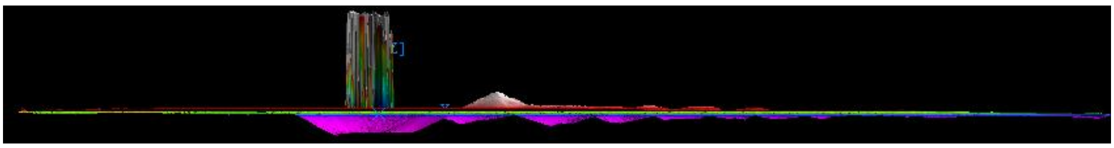


**Figure 5.8 Side View of Control Pier – Vulcan Software showing the depth of erosion**

## 5.6 Countermeasure 1 -Inward facing vanes with plate attached to pier

The next test involved a pier with a plate attached level with the bedding surface and inward facing vanes. As initially assumed there was a large amount of erosion occurring at the vanes with reduced scour depth at the face of the pier (figure 5.10). There was a buildup of sand in front of the diameter of the plate but erosion still occurred at the sides of the pier continuing in the horseshoe shape however this was certainly reduced in comparison to the control pier results. A noticeable change was at the wake of the pier where there was a visible buildup of sand. The rear left side showed more turbulent deposition of sand and this could have been produced by flow alignment at the face of the pier causing an increase in erosion (figure 5.9).

**Figure 5.9 Inward vanes & attached plate upstream photo after 2hr testing**

**Figure 5.10 Inward vanes & attached plate side view photo after 2hr testing**

Figure 5.11 is a topographical view of the scour deformation over the bedding surface. Table 19 to the right indicates the depth profile.

**Table 19 Depth Colour Chart Inward vanes & attached plate**

| | |
|---|---|
| -30mm to -20mm | 20mm to 30mm |
| -20mm to -10mm | 30mm to 40mm |
| -10mm to 0 | 40mm to 50mm |
| 0 to 10mm | 50mm to 60mm |
| 10mm to 20mm | 60mm to 67.61mm |

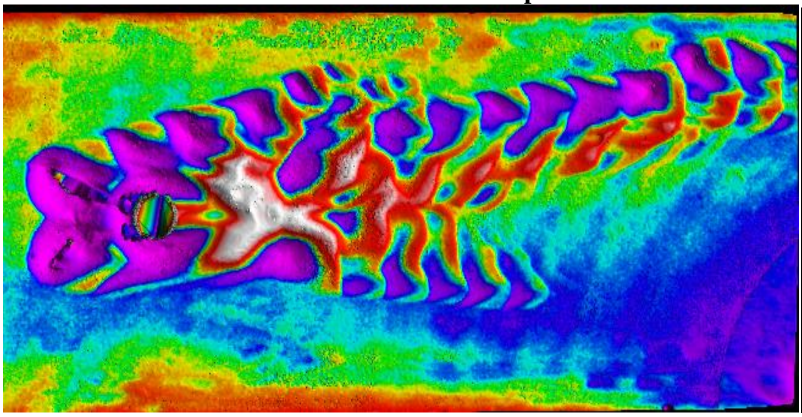


**Figure 5.11 Inward facing vanes and plate attached to pier - Vulcan Software Depth Profile**

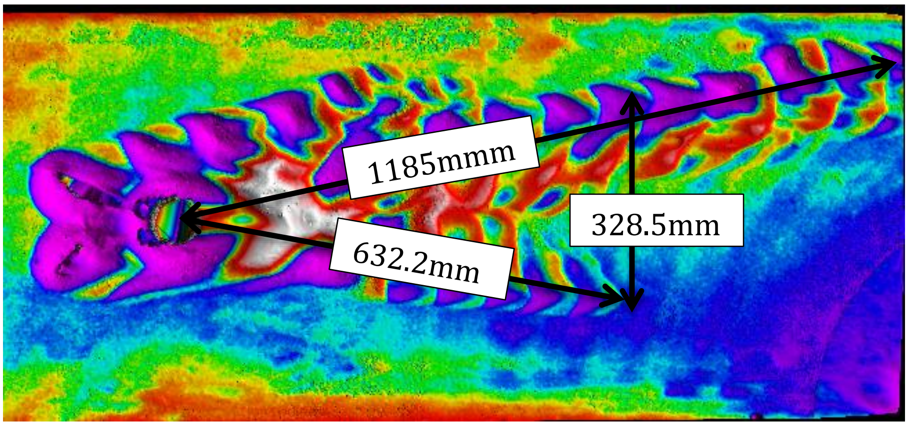



**Figure 5.12 The distance of deposition of sand from the pier with plate attached after testing for 2 hours at 500L/min,**

Figure 5.13 shows the erosion in purple around the vanes at the front of the pier. Scour is also obvious around the pier and there is as deposit of sand after the pier which shows as white. Some erosion has occurred to the both sides of the rear of the pier as a buildup of sediment.

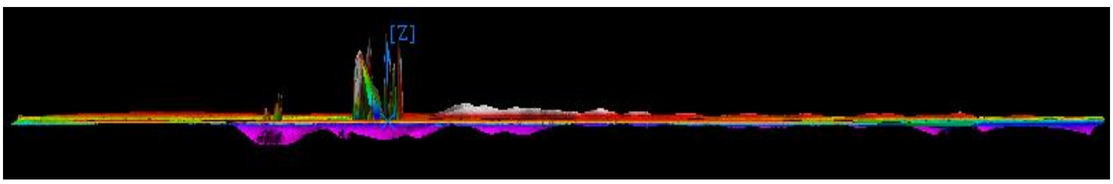



**Figure 5.13 Sectional view of inward facing vanes and plate attached to pier, Vulcan Software**

## 5.7 Countermeasure 2 -Outward Facing Vanes with plate attached to pier

The outward facing vanes were tested next and scour occurred at the face similar to the control pier but not to the same extent width wise (figure 5.14). There was an obvious deposit of sand directly behind the pier mounding higher than the original level of sand prior to testing (figure 5.15).

**Figure 5.14 Outward vanes & attached plate upstream photos after 2hr testing**

**Figure 5.15 Outward vanes & attached plate side view photo after 2hr testing**

Figure 5.16 is a topographical view of the scour deformation over the bedding surface. Table 20 to the right indicates the depth profile.

**Table 20 Depth Colour Chart outward vanes & attached plate**

| | | | |
|---|---|---|---|
| | -30mm to -20mm | | 20mm to 30mm |
| | -20mm to -10mm | | 30mm to 40mm |
| | -10mm to 0 | | 40mm to 50mm |
| | 0 to 10mm | | 50mm to 60mm |
| | 10mm to 20mm | | 60mm to 67.61mm |

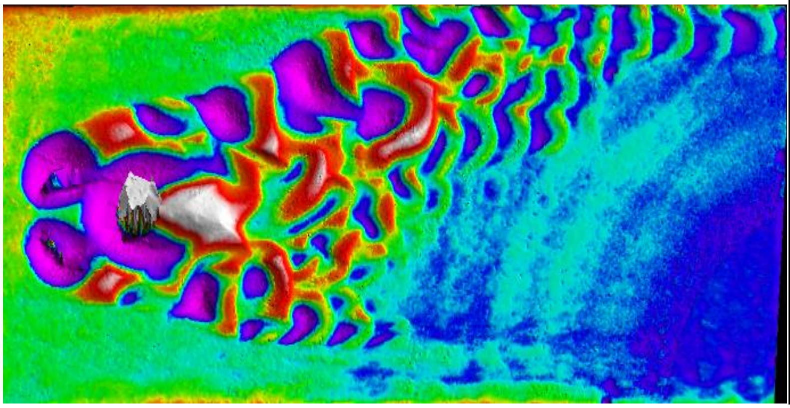


**Figure 5.16 Outward facing vanes and plate attached to pier - Vulcan Software Depth Profile**

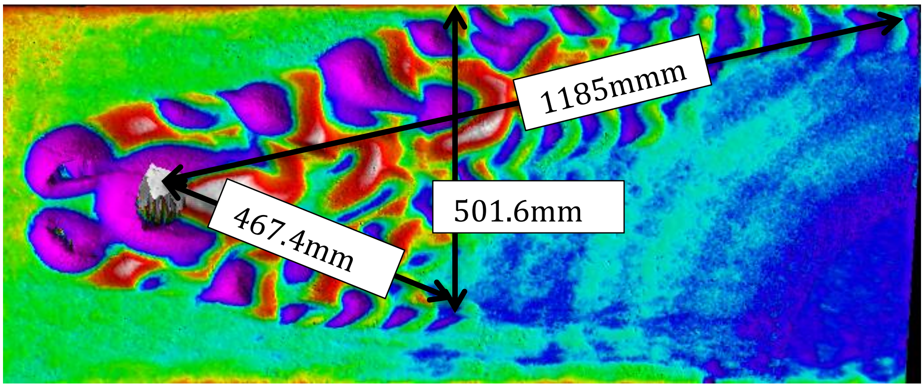



**Figure 5.17 The distance of deposition of sand from the pier with plate attached after testing for 2 hours at 500L/min,**

Figure 5.18 shows the erosion in purple around the vanes at the front of the pier. Scour around the pier is also obvious. There is as deposit of sand after the pier which shows as white with some erosion also occurring to the sides of the buildup of sediment immediately behind the pier. The erosion depth looks to be more even from this sectional view.

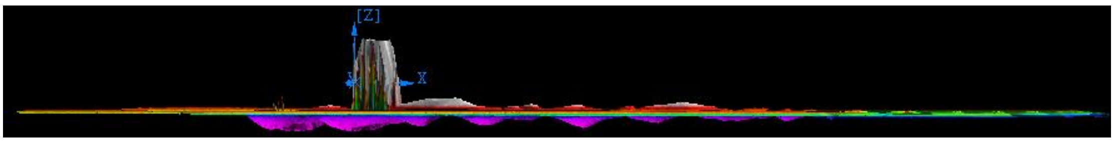



**Figure 5.18 Sectional view of Outward facing vanes and plate attached to pier**

## 5.8 Countermeasure 3 –Three Collars

The three collars was the final test undertaken. This model exhibited the greatest reduction in scour immediately around the pier with a similar buildup of sand immediately behind as the outward facing vanes had shown (figures 5.19 & 5.20)

**Figure 5.19 Three collars upstream after 2hr testing**

**Figure 5.20 Three Collars side view photo after 2hr testing**

Figure 5.21 is a topographical view of the scour deformation over the bedding surface. Table 21 to the right indicates the depth profile.

**Table 21 Depth Colour Chart three collars**

| | |
|---|---|
| -30mm to -20mm | 20mm to 30mm |
| -20mm to -10mm | 30mm to 40mm |
| -10mm to 0 | 40mm to 50mm |
| 0 to 10mm | 50mm to 60mm |
| 10mm to 20mm | 60mm to 67.61mm |

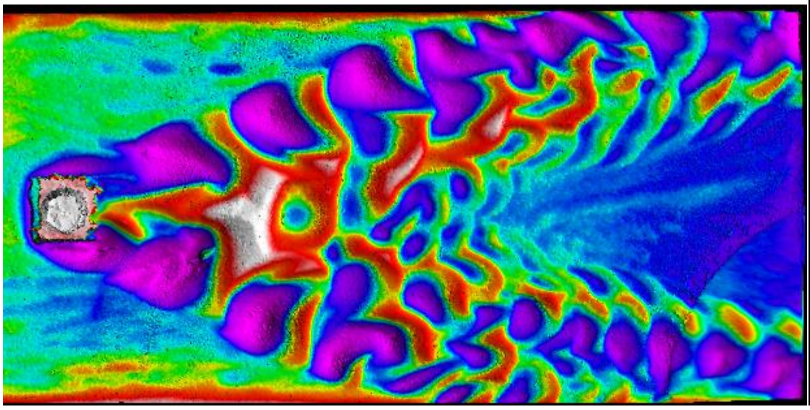


**Figure 5.21 Three Collars - Vulcan Software Depth Profile**

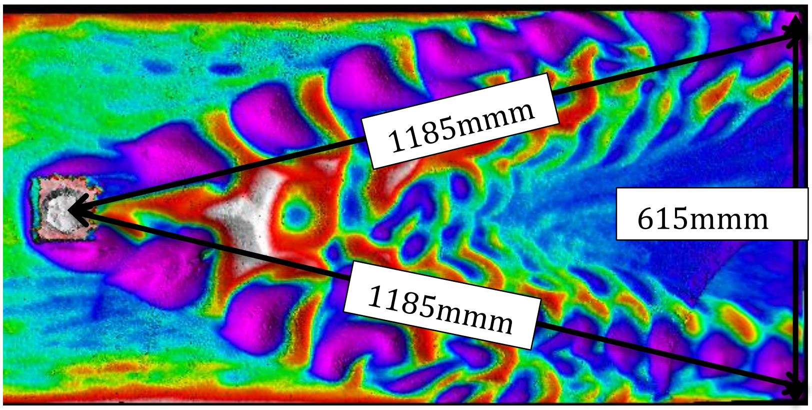



**Figure 5.22The distance of deposition of sand from the pier with three collars after testing for 2 hours at 500L/min,**

Figure 5.23 shows minimal scour around the front of the pier. Downstream of the pier there is as deposit of sand which shows as white with some consistent erosion showing either side at the rear of the pier. The erosion depth looks to be more even from this sectional view.

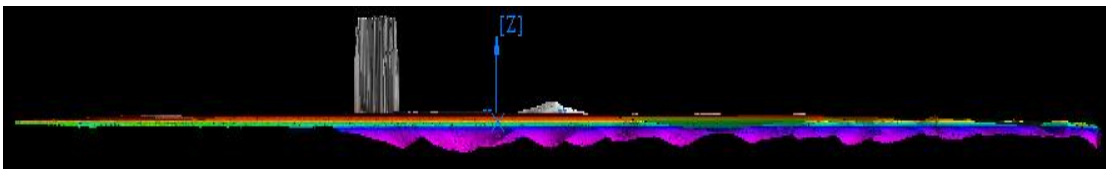


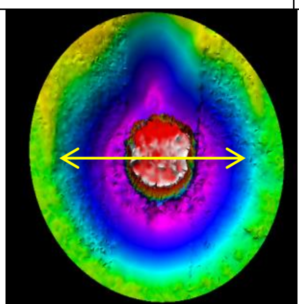
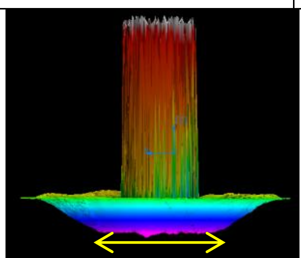

**Figure 5.23 Sectional view Three Collars**

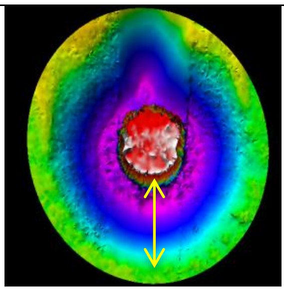
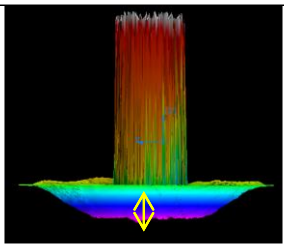
## 5.9 Volume of Erosion -Comparison of countermeasures with control pier

Commencing with a datum point on top of the pier and using the relimiting tool available on the Vulcan software program a circle with a diameter of 26.32cm was chosen as the area of interest. This area was chosen as it captured the full extent of local scour around the control pier as highlighted in Figure 5.25 below. This same area was then identified for each countermeasure allowing for comparison of erosion of the models tested.

## 5.10 Scour Hole Dimensions

**Table 22 Physical Modelling of scour holes**

| | Illustrations showing measured distances | Control Pier | Inward Facing Vanes with Plate attached to Pier | Outward Facing Vanes with Plate attached to Pier | Three Collars attached to Pier |
|---|---|---|---|---|---|
| Cross Sectional Width of Scour |  | 217. 2mm | 149.1mm | 147.7mm | 175.6mm |
| Bottom Scour Width |  | 106.3mm | 104.2mm | 89.3mm | 121.5mm |

| | | | | | |
|---|---|---|---|---|---|
| Distance of scour from upstream face of pier |  | 76.2mm | 37.6mm | 56.4mm | 27.8mm |
| Depth of scour hole at upstream face |  | 30 mm | 14.8mm | 19.8mm | 5.5mm |

## 5.11 Measurement of volume of local scour

Local scour around the pier was measured using Vulcan software from a datum point marked on all piers. Using images from this software a circle was extruded to include the greatest extent of scour seen around the control pier. Figure 5.24 below shows the extent of scour around the control pier. This is outlined in white.

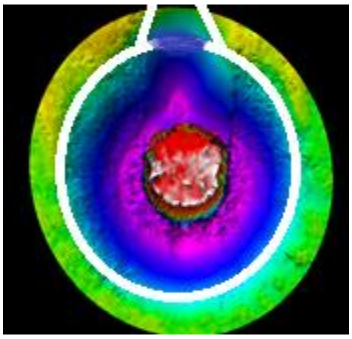


**Figure 5.24 Outline of extent of local scour for comparison**

From the datum point in the centre of the pier, a circle was drawn with a radius of 13.16cm to capture the majority of local scour. This allowed for the initial volume to be calculated using the depth of 3cm. The volume equals area multiplied by depth. Volumes from Vulcan software were calculated in $cm^3$

$$Base\ area = \pi \times 13.16cm^2 = 544cm^2$$

Depth = 3cm

$$Volume = 544cm^2 \times 3cm = 1632cm^3$$

Yellow arrow indicates radius of 13.16cm

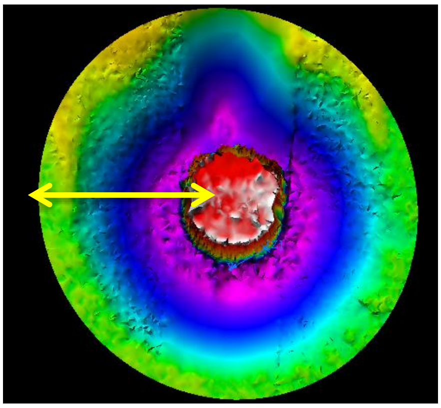
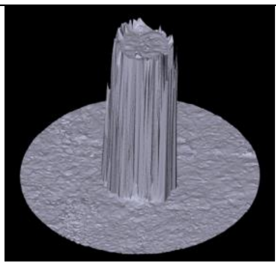
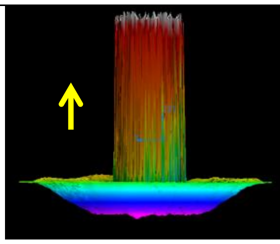
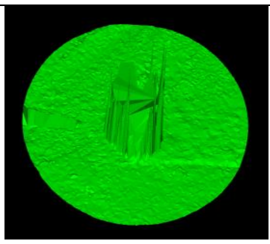
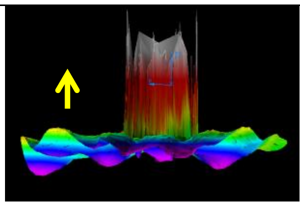
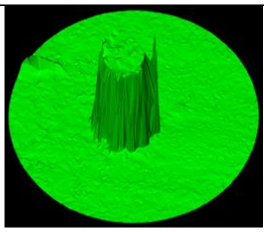
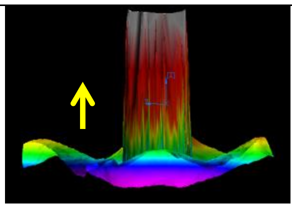
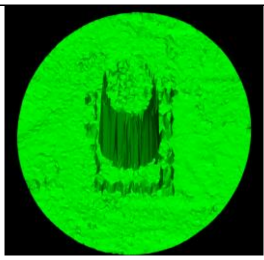
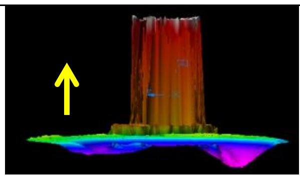


**Figure 5.25 shows the radius capturing the extent of local scour around bridge pier**

From Table 23 when comparing percentages back to the volume of erosion of the control pier both vane and plate countermeasures reduced scour volume by approximately half of that of the control pier. The combined countermeasure of three collars reduced this percentage again to approximately one quarter of the control pier in scour volume.

**Table 23 Percentage of scour over relimited area taken from Vulcan software**

| | Relimited Test volume prior to water flow= 1632 $cm^3$ | Scour Removed Image (Arrow indicates direction of flow) | Percentage of scour when compared to before test volume |
|---|---|---|---|
| Control Pier |  |  =642.743 $cm^3$ | $= \frac{642.743cm^3}{1632cm^3} \times 100$ $= 39.38\%$ |

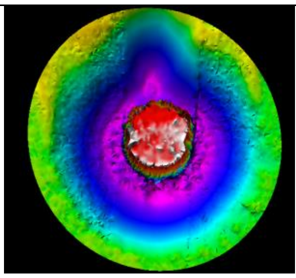
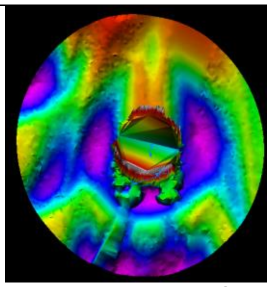
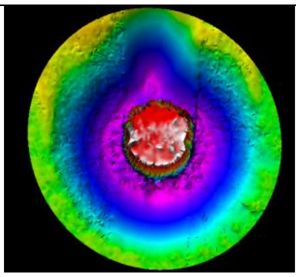
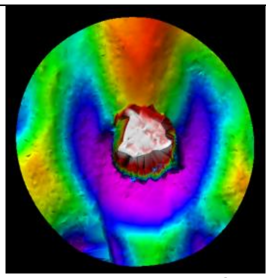
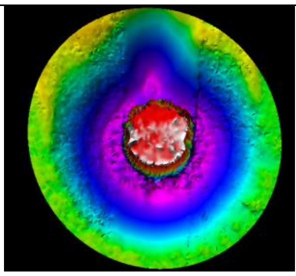
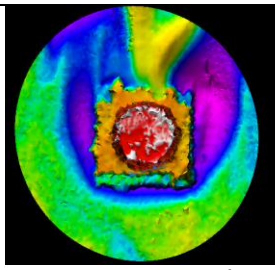
| | | | |
|---|---|---|---|
| Inward facing vanes with pier attached plate |  |  $= 391.916\ cm^3$ | $= \frac{391.916cm^3}{1632cm^3} \times 100$ $= 24.01\%$ |
| Outward facing vanes with pier attached plate |  |  $=358.133\ cm^3$ | $= \frac{358.133cm^3}{1632cm^3} \times 100$ $= 21.94\%$ |
| Three Collars |  |  $=137.437\ cm^3$ | $= \frac{137.457cm^3}{1632cm^3} \times 100$ $= 8.42\%$ |

Efficiencies below were tabulated against the control pier and based on erosion volume (Table 24). The formula below has been derived to allow for comparison of the various combined countermeasures against the control pier scour volume efficiency.

$$r_V = \frac{V_c - V_a}{V_c} \times 100 \qquad \text{Eq. (5.1)}$$

Where, $r_V = volume\ of\ scour\ percentage\ of\ reduction, V_c = Control\ pier\ volume\ of\ scour, V_a = Combined\ countermeasure\ volume\ of\ scour$

**Table 24 Reduction of scour volume against control pier**

| | Control Pier relimited section | Combined countermeasure relimited section | |
|---|---|---|---|
| Inward facing vanes with pier attached plate |  $= 642.743\ cm^3$ |  $= 391.916\ cm^3$ | $r_V = \frac{642.743\ cm^3 - 391.916}{642.743\ cm^3} \times 100$ =39% |
| Outward facing vanes with pier attached plate |  $= 642.743\ cm^3$ |  $= 358.133\ cm^3$ | $r_V = \frac{642.743\ cm^3 - 358.133}{642.743\ cm^3} \times 100$ =44% |
| Three Collars |  $= 642.743\ cm^3$ |  $= 137.457\ cm^3$ | $r_V = \frac{642.743\ cm^3 - 137.457}{642.743\ cm^3} \times 100$ =79% |

Using Vulcan software the whole bedding platform was scanned and the results over the entire volume of sand were tabulated. Table 25 below shows the amount of sand displaced eg volume of erosion removed.

As the control pier is equal to the inward facing entire amount of erosion over the test surface. There is more erosion downstream but our focus is around local scour which affects the structural stability of the pier whereas scour over a greater test platform is not relevant to this research. The figures below are all very similar because of the percentage of the total area they should not be taken into consideration. Even though these numbers are small over the entire field but local scour is the significant measure where and these figures do not show the difference.

**Table 25 Testing Platform – Entire Bedding surface**

| | Reduction of Scour |
|---|---|
| Control Pier | 3.8% |
| Inward Facing Vanes & Attached Plate | 3.8% |
| Outward Facing Vanes & Attached Plate | 5.6% |
| Three Collars | 4.4% |

## 5.5 Conclusion

From the results above all three combined countermeasures chosen through the design matrix in Chapter 3 could be implemented for use in existing structures. The location, size of channel and known velocity of flow would help determine the best combined countermeasure in each circumstance.

# 6.0 Discussion

## 6.1 Introduction

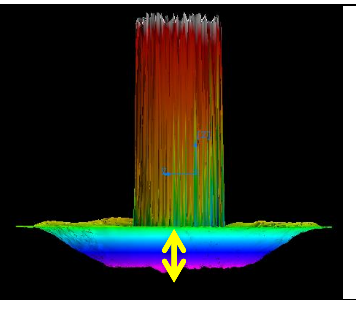
The results above are further discussed as well as exploring any contributing factors to possible errors. Discussion also enters into the opportunity of the implementation of one or more of the combined countermeasures into field practice.

All piers were tested at a depth of 70ml with an average velocity of 0.194m/s.

## 6.2 Scour Hole Depth

From the analysis of the models, through the Vulcan software program, the following measurements at the upstream face from the bedding surface to the bottom of the scour hole were measured. Table 26 shows a comparison of the depths between the control pier and the combined countermeasures.

**Table 26 - Upstream scour depth measurements**

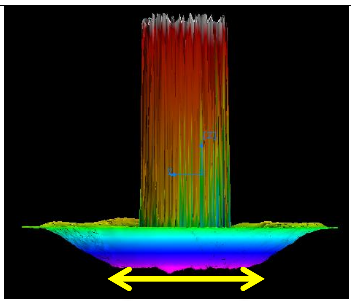
| | Illustrations showing measured distances | Control Pier | Inward Facing Vanes with Plate attached to Pier | Outward Facing Vanes with Plate attached to Pier | Three Collars attached to Pier |
|---|---|---|---|---|---|
| Depth of scour hole at upstream face |  | 30 mm | 14.8mm | 19.8mm | 5.5mm |

The control pier eroded to the bottom of the flume (30mm) whereas three collars (5.5mm) showed a significant reduction in the depth to which scour occurred. The vanes and attached plate in both configurations also showed a considerable reduction in the depth when compared to the control (Table 26).

Scour around the three collars was only 5.5mm. The first collar was placed at D/6 above the bedding surface, the second collar was placed at the bedding surface and the third one D/6 (11.33mm) below the bedding surface. As these numbers show scour only developed up to half way between the collar at the bedding surface and the collar below the bedding surface (5.5mm).

The plate attached to the pier in both configurations using vanes showed a reduction in the effect of the horseshoe vortices but scour still developed beneath the plate at 14.8 and 19.8mm. With this study it is unsure whether scour would have continued to develop to the same extent as the control pier if testing had continued. However it does still show a significant decrease in the time period and could prove a useful tool in the reduction of scour.

**Table 27 - Bottom scour width**

| | Illustrations showing measured distances | Control Pier | Inward Facing Vanes with Plate attached to Pier | Outward Facing Vanes with Plate attached to Pier | Three Collars attached to Pier |
|---|---|---|---|---|---|
| Bottom Scour Width |  | 106.3mm | 104.2mm | 89.3mm | 121.5mm |

The bottom scour width as Table 27 shows for the three collars at 121.5mm is actually greater than all the other pier combinations including the control. This is due to the fact that the collars themselves measured 102mm so even though scour occurred around the collar once again the total volume of erosion was less for the three collars.

**Table 28 - Cross sectional width of scour**

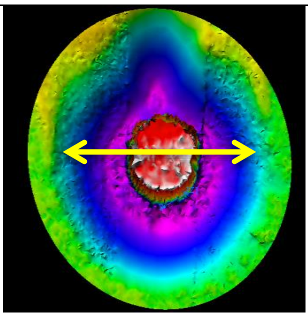
| | Illustrations showing measured distances | Control Pier | Inward Facing Vanes with Plate attached to Pier | Outward Facing Vanes with Plate attached to Pier | Three Collars attached to Pier |
|---|---|---|---|---|---|
| Cross Sectional Width of Scour |  | 217.2mm | 149.1mm | 147.7mm | 175.6mm |

Table 28 above measures the cross sectional width of scour at the bedding level for each diagram. The three collars shows a greater width of scour in comparison to the plate and vane combination but the overall total volume of erosion is still considerably less for the combination of three collars than either vane combination and all combinations show less erosion than the control pier.

**Table 29 - Distance of scour from upstream face of pier**

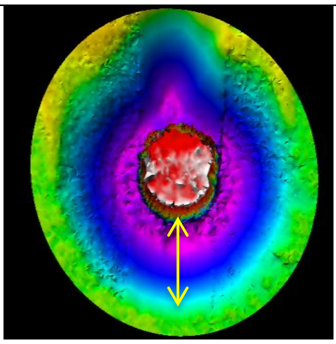
| | Illustrations showing measured distances | Control Pier | Inward Facing Vanes with Plate attached to Pier | Outward Facing Vanes with Plate attached to Pier | Three Collars attached to Pier |
|---|---|---|---|---|---|
| Distance of scour from upstream face of pier |  | 76.2mm | 37.6mm | 56.4mm | 27.8mm |

Table 29 shows the scour distance from the upstream face of the pier. The three collars showed the least amount of scour at only 27.8mm which was considerable lower than the control pier at 76.2mm. The inward vanes also showed a significant reduction when compared to control pier. The reduction in scour at the front of the pier by using the combined countermeasures is due to weakened horseshoe vortices.

The vanes have clearly shown a reduction in the width of scour around the pier by redirecting the flow path. The depth however remained considerable.

Using the theoretical calculation for scour the expected scour depth was 66.80mm.
Due to the testing platform only having a bedding thickness of 30mm no comparison could be made between the depth achieved and the theoretical depth. Because of the limitation of the flume height and for the purpose of this research testing was undertaken at higher flow depths. To compare to the theoretical calculation with the limitations of the flume height testing would have to have been conducted at a flow depth of 25mm or lower. Testing was conducted at 70mm.

## 6.3 Scour development and shape

Table 24 shows the development of the horseshoe shape for each pier with a combined countermeasure. The control pier initially formed the traditional horseshoe shape but at the end of testing the control pier erosion appeared to be in a bowl shape with a pointy nose at the rear. The rear nose shape could relate to wake vortices forming a wing like shape (figure 2.2), but because the test didn't run for a long enough period of time and the depth of the flume was too shallow the vortices didn't develop. Had testing continued for a longer period of time the usual winged formation at the back of the pier may have formed. Water as it hit the front of the pier was deviating around the sides of the pier and may have been crisscrossing at the back of the pier and so the true wake appearance had not yet developed.

The horseshoe development however can be seen in the combined countermeasures. The horseshoe effect is suppressed by the plate and or collars in the figures xxxx. This in turn reduced the effect and shape of development of scour.

There is a clear buildup of sand behind each pier where a countermeasure has been employed. This is due to the weakened wake vortices. The deposition of sediment immediately behind the pier is associated with the movement of the wake vortices. Both vane configurations redirected the flow of water causing a diminishing effect on the production of wake vortices.

The literature review also suggests that the formation of local scour around the pier forms in a horseshoe shape commencing at the upstream face of the pier then wraps around the base of the pier in the same direction of flow. This horseshoe is the most significant formation causing local scour. The control pier shows a horseshoe shape occurring but the combined countermeasures show a weakened development of the horseshoe formation.

In each of figures 5.7, 5.12, 5.17 and 5.22 above it is clear that disturbance of sediment occurs behind the pier for a maximum distance varying between models of 0.9m to 1.2m. The control pier and the three countermeasure designs all show a significantly greater amount of scour on the left side when looking downstream from the front of the pier. This could be due to alignment issues but the pier is cylindrical making this suggestion invalid so the only other thought is that the flume may not have been perfectly balanced.

## 6.4 Scour hole volume

The vanes in conjunction with the plate have reduced the extent of erosion around the pier. The inward facing vanes directed the water flow towards the face of the pier; however the resultant horseshoe formed in figure 5.11 shows a 39% reduction in erosion compared to the control. When this is compared with the outward facing vanes the comparison is less favourable (figure 5.16). The outward facing vanes provided a 44% reduction in erosion compared to the control pier. The most favourable result when compared to the control pier was the three collars. The scour hole was reduced by

79% establishing that when this option is available during construction it would be an optimum choice (figure 5.21).

## 6.5 Research Limitations

The results presented must be considered on the basis of the limitations of testing in a flume. These results are accurate for the same configurations with the same testing parameters. As the conditions in a flume will vary to real conditions in the field these limitations must be considered. It must be stated that most limitations were unexpected prior to undertaking this research and have been stated below.

The capacity of the small flume was the first limitation as constant filling and draining was required. When testing commenced with 20L/min through the system it was necessary to fill the tank level above the invert inlet with a hose to stop the pump sucking air, thus minimising any surges through the system. At the completion of each test to allow for scanning under dry conditions the tank had to be drained.

Another constraint encountered prior to testing was the depth of the flume. This limiting factor played a major role in defining the testing parameters and duration. Testing was cut off at two hours due to exposure of the flume floor. This meant that erosion ceased before reaching equilibrium where no more scour would occur.

At the inlet of the flume the baffles did not provide sufficient uniform distribution of the flow over the width. To improve this, fly screen mesh was introduced to the face of the baffle to provide a more uniform flow.

The Manuflow velocity meter attached to the small hydraulic flume showed fluctuations throughout testing of ± 4L/min meaning that the accuracy of discharge could not be maintained. This could have affected the comparison of erosion between models. It was noted that this irregularity caused small surges further affecting the accuracy of results.

Data collected provided an acceptable picture for the purpose of this research. Small improvements could be made in future research to improve upon the results presented in this dissertation.

## 6.6 Areas of Future Research

Through literature studied and this research paper the performance of collars as a combined countermeasure is shown to provide a significant improvement in the reduction of local scour. Cost will continue to be a limitation for bridge piers already constructed however the knowledge that these improvements could provide greater confidence in times of flood is worth a thought. Future research into a more in depth understanding as to how the collars and or vanes and plates reduce the effect of erosion on bridge piers is well worth considering.

Future works relating to scour mitigation

- Complete further testing using different shaped piers and countermeasures
- Use varied depths and velocities for comparison
- Complete testing in large agricultural flume and compare to lab results above
- Test efficiency of individual countermeasures against combined countermeasures

# 7.0 Conclusion

This project has produced some interesting results providing information for scour mitigating techniques around bridge piers.

The basis of this research aimed to reduce the effect of local scour around bridge piers through testing of combined countermeasures. Submerged vanes, bed sills, sacrificial piles, collars, threading and pier slots were evaluated with results concluding that single countermeasures did not always provide adequate protection to bridge piers. Previous results provided from other studies claimed to have good results but were shown to be unreliable due to inadequate design of testing (Tafarojnoruz 2012). In the reduction of local scour this research hopes to provide a safer bridge design and longer life expectancy of these structures thus minimising the cost associated with reconstruction or repairs.

Combined countermeasures have been noted to provide improved results and can be modified to remain economical. Combined countermeasures were chosen based on affordability, practicality and constructability. The efficiency of these combined countermeasures to reduce the scour depth would be the factor upon which recommendations would be made.

The three combined countermeasures could all be used in bridges in most circumstances. In small channels where there is a large volume of traffic beneath the bridge a vane and plate attached pier may prove to be a better countermeasure than collars which would extend further out around the pier. If the piers are then close together the extra diameter of collar could be close to the next pier and prohibit traffic flow below the bridge.

Where flood situations are not uncommon then the three collars would be an ideal combined countermeasure as when sediment transportation occurs during a flood event the collars would prevent any further erosion around the pier and make the pier safer than a pier without any countermeasure.

Future construction of bridge piers incorporating these combined countermeasures would be well advised by current engineers when designing new bridges.

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# Appendix A- Project Specification

University of Southern Queensland

FACULTY OF HEALTH, ENGINEERING AND SCIENCES

**ENG4111/4112 RESEARCH PROJECT**

**PROJECT SPECIFICATION**

**STUDENT: Andrew Raleigh**

**TOPIC:** How to Mitigate the Effects of Scour on Bridge Piers Through the Use of Combined Countermeasures

**SUPERVISOR: Dr Joseph Foley, Senior Research Fellow (Water Engineering and Irrigation)**

**PROJECT AIM:** The aim of this research is to examine mitigation techniques designed to reduce the effects of scour at bridge piers. Studies completed by others will be reviewed so that the strengths and weaknesses of existing scour mitigation methods can be recognised. By grouping and analysing the strengths and weaknesses of other designs, a new design could be developed. The new design will be tested in a large flume and its effectiveness recorded.

**PROGRAMME: (Issue B, 24th April 2015) as amended from time to time**

1) Review existing mitigation techniques designed to reduce scour around bridges piers by reading current literature and writing extensively on the subject
2) Report on these current techniques and evaluate strengths and weakness of bridge pier design via a matrix.
3) Design and build new physical models of bridge piers with mitigation techniques to be tested in the large ag-plot flume
4) Test for scour depths with each different model and evaluate
5) Conduct data analysis of models tested, to allow for comparison between a control and new designs
6) Recommend a combined countermeasure to mitigate scour around bridge piers based on test results.

If time permits:

7) Design new bridge piers from the results and recommendations of testing.

**AGREED**

A. Raleigh **(Student)** J.P. Foley **(Supervisor)**

28/10/ 2015 28/10/ 2015

**Examiner/Co-examiner** ______________________ ___/ ___/ 2015