AUGUST 2023

M.Sc. in Civil Engineering

OBADA RAKIA

REPUBLIC OF TÜRKİYE

GAZİANTEP UNIVERSITY

GRADUATE SCHOOL OF NATURAL & APPLIED SCIENCES

INVESTIGATING THE EFFECT OF SLOT ON SCOUR DEPTH REDUCTION AROUND BRIDGE PIERS

M.Sc. THESIS

IN

CIVIL ENGINEERING

BY

OBADA RAKIA

AUGUST 2023

INVESTIGATIONS THE EFFECT OF SLOT ON SCOUR DEPTH REDUCTIONS AROUND BRIDGE PIERS

M.Sc. Thesis

in

Civil Engineering

Gaziantep University

Supervisor

Prof. Dr. Mustafa GÜNAL

by

Obada RAKIA

AUGUST 2023

INVESTIGATING THE EFFECT OF SLOT ON SCOUR DEPTH REDUCTION AROUND BRIDGE PIERS

submitted by **Obada RAKIA** in partial fulfillment of the requirements for the degree of Master of Science in **Civil Engineering, Gaziantep University** is approved by,

Prof. Dr. Mehmet İshak YÜCE
Director of the Graduate School of Natural and Applied Sciences ………..............

Prof. Dr. Nildem TAYŞİ
Head of the Department of Civil Engineering ………..............

Prof. Dr. Mustafa GÜNAL
Supervisor, Civil Engineering, Gaziantep University ………..............

Graduation Date: 28 August 2023

Examining Committee Members:

Prof. Dr. Mustafa GÜNAL
Gaziantep University ………..............

Prof. Dr. Aytaç GÜVEN
Gaziantep University ………..............

Prof. Dr. Ali AYTEK
Gaziantep İslam Science and Technology University ………..............

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Obada RAKIA

ABSTRACT

INVESTIGATING THE EFFECT OF SLOT ON SCOUR DEPTH REDUCTION AROUND BRIDGE PIERS

RAKIA, Obada
M.Sc. in Civil Engineering
Supervisor: Prof. Dr. Mustafa GÜNAL
August 2023

64 pages

The scouring of sediments around bridge foundations leading to collapses remains a significant problem, causing both economic losses and risking human lives. The scouring of sediments around bridge foundations leading to collapses is the Morandi Bridge in Genoa, Italy. In August 2018, the bridge suffered a catastrophic failure due to severe scouring of its foundations caused by heavy rainfall. Researchers have been actively studying these phenomena and seeking effective measures to mitigate the impacts of scour around bridge elements. This study focuses on investigating the impact of incorporating slot through the bridge pier as a countermeasure to reduce scour depth using the Flow 3D software. Scour reduction solutions for bridge piers can be broadly categorized into flow-altering countermeasures and bed-armoring countermeasures. Flow-altering countermeasures aim to weaken the down-flow and horseshoe vortex, which are the main contributors to pier scour. This study specifically examines the effectiveness of different slot shapes introduced through the bridge pier as countermeasure methods. By employing various models and a reference model, the study evaluates the reduction in local scour depth achieved by the different slot configurations. The results obtained from comparing the various models will determine the optimal percentage of local scour reduction achievable using the proposed countermeasure methods.

Key Words: Bridge Pier, Scour, Flow 3D, horseshoe vortex, Slot

ÖZET

KÖPRÜ AYAKLARI ÇEVRESİNDEKİ OYULMA DERİNLİĞİNİN AZALTILMASINDA YARIK ETKİSİNİN İNCELENMESİ

RAKIA, Obada
Yüksek Lisans Tezi, İnşaat Mühendisliği
Danışman: Prof. Dr. Mustafa GÜNAL
Ağustos 2023
64 sayfa

Köprü ayağı temelleri etrafındaki malzemenin aşınarak köprünün çökmesine yol açması, hem ekonomik kayıplara neden olan hem de insan yaşamını tehlikeye atan önemli bir sorun olmaya devam etmektedir. Araştırmacılar aktif olarak bu olayları incelemekte ve köprü ayaklarının etrafındaki oyulmanın etkilerini azaltmak için etkili önlemler aramaktadır. Bu çalışma, Flow 3D yazılımını kullanarak oyulma derinliğini azaltmak için bir karşı önlem olarak köprü ayağına yarık eklemenin etkisini araştırmaya odaklanmaktadır. Köprü ayaklarına yönelik oyulma azaltma çözümleri genel olarak akışı değiştiren karşı önlemler ve yatak zırhlama karşı önlemleri olarak kategorize edilebilir. Akışı değiştiren karşı önlemler, at nalı girdap oyulmasına ana katkıda bulunan aşağı akışı ve at nalı girdabını zayıflatmayı amaçlamaktadır. Bu çalışma, özellikle köprü ayağı boyunca uygulanan farklı yarık şekillerinin karşı önlem yöntemleri olarak etkinliğini incelemektedir. Bu çalışma, farklı yarık konfigürasyonları ile yerel oyulma derinliğinde elde edilen azalmayı değerlendirmektedir. Çeşitli yarık modellerinin karşılaştırılmasından elde edilen sonuçlar, referans modele kıyasla oluşan yerel oyulmadaki azalma yüzdesini belirlemiştir.

Anahtar Kelimeler: Köprü ayağı, Oyulma, Flow 3D, At nalı girdabı, Yarık

Dedicated to my beloved family and dear siblings,

With deep love and gratitude, I dedicate this Master's thesis to you all. Your unwavering support and encouragement have been my foundation, and your presence in my academic journey is cherished. You inspire me to continue growing, and I hope this achievement fills you with pride.

With boundless love and gratitude,

ACKNOWLEDGEMENTS

I would like to thank my supervisor, Prof. Dr. Mustafa GÜNAL for his guidance and support throughout the study. I am thankful for his encouragement and motivation.

I am filled with immense appreciation and affection towards my family, particularly my mother, Mrs. Samira, and my father, Mr. Khaled Kamel. I also want to extend my gratitude to my sisters, Dr. Mavada and Dr. Bayan, as well as my dear younger siblings, Ola and Bushra. Their unwavering support has been a significant source of strength throughout my entire life.

I extend my heartfelt gratitude to all my friends in Turkey who have stood by me and provided unwavering support in achieving this task. Each one of them has made a significant and positive contribution to my journey.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Page

LIST OF SYMBOLS

h	Depth of water flow (m)
Q	Discharge (m^3/s)
Dp	Pier diameter
L	Ratio of the pier length to the pier width
ds	Local scour depth (cm)
U	Velocity of water flow (m/s)
Uc	Critical velocity (m^2/s)
d50	Median particle Size diameter of the sediments (mm)
a	Size of the sediment (mm)
Fr	Froude number
Re	Reynolds number
GS	Specific Gravity of sand
UC*	Critical Shear velocity (m/s)
σg	Standard deviation of the sand size
GS	Gravity of the sediment particle (m/s^2)
***ρ*s**	Density of sediment and correspondingly (kg/m^3)
ρ	Water density (kg/m^3)

LIST OFABBREVIATIONS

CFD	Computational Fluid Dynamic
FAVOM	Fractional Area Volume of Method
VOF	Volume-Of-Fluid
RNG	Renormalized group
FAVOR	Fractional Area Volume Method
FHWA	Federal Highways Administration

CHAPTER 1
INTRODUCTION

1.1 General Background

Local scour around bridge piers is a phenomenon that occurs in rivers and streams where the flow of water erodes and removes sediment from the riverbed in the vicinity of bridge piers. It poses a significant challenge to the stability and integrity of bridge infrastructure, making it a crucial aspect of hydraulic engineering and bridge design. The process of local scour begins with the flow of water approaching the pier. As the water flows around the pier, it undergoes a change in velocity and direction, resulting in the formation of vortices and turbulence. These flow patterns create localized areas of higher velocities and shear stresses, leading to the erosion and removal of bed sediment particles from the riverbed, which caused serious harm to crucial infrastructure of the bridge pier and cost the public and government's money. The scour depth, or the extent to which the riverbed is eroded around the pier, depends on various factors. Flow characteristics like velocity, turbulence intensity, and water depth play a significant role in determining the erosive forces acting on the sediment. Sediment properties, including grain size and cohesion, influence its susceptibility to erosion.(Melville & Coleman, 2000).

However, naturally, when the flowing water impinges an obstruction in an open channel-like stream or rivers it causes erosion in sediment at the bed river, transports and deposits river sediments, the lead to changing the height of the riverbed and adjusting its boundaries. Bridges are a vital element of the infrastructure of a country, it is important to protection of bridges from problems. As many scholars defined the scour as one of the major problems against the bridge's foundations. Bridges have been built for a thousand years to provide vital connections over various obstructions, such as rivers and railways, enabling transit to take the quickest route. However, there have been cases of bridges falling because to erosion, which has caused serious harm to crucial infrastructure and cost the public and governments money.

Scour is defined as a natural phenomenon that occurs in rivers because of the water flow, The erosion resulted from water in motion leads to scouring in which the bed's and sides' materials of the stream or near of the bridge piers and abatements are bulled/withdrawn. (Breusers et al., 1977)

Many researches indicate the Phenomena of sediment motion due to water effect as scour like (Lagasse & Richardson, 2001), defined the scour as lowering in the bed river level as result of erosion due to the water force and that lead to remove of sediment cover of the foundation of the bridge, also transport the bed material from the river sediment bank around the piers and abutments of the bridge. (Richardson (Lagasse & Richardson, 2001). Also, (Dey, 1999) indicate that scour is the changing in the river bed elevation, which happening around the bridge pier. Rivers and coastlines are fundamentally shaped by the natural processes of sediment erosion and deposition. However, these processes can become more complex and result in strong local scour when human actions like constructing bridges, placing pipelines, and carrying out offshore developments are involved, which brought up an intense local scour.

A local scour is an erosion that results from the flow influence of an obstruction and results in a decrease in bed elevation close to the obstruction. The presence of human interventions, such as the construction of bridges, installation of pipelines, and various offshore developments, adds complexity to the natural processes. These interventions have the potential to cause intensive local scour, as noted by (Graf & Altinakar, 2017). In their research. According to (Chiew & Melville, 1987), scour is the process of erosion in which bed material is eroded by the force of water. Scour occurs when the forces exerted by the flowing water on sediment particles exceed the stabilizing forces, leading to the removal of sediment or materials from the bed or banks of a watercourse. As explained by (Kirby, 2015) Scour is a naturally occurring process where flowing streams erode alluvial beds. It is a common phenomenon that can lead to the failure of bridges, particularly at their foundations comprising abutments and piers. According to a study conducted by the US Federal Highway Administration in 1973, out of 383 bridge failures analyzed, 25% were attributed to pier damage and 72% to abutment damage.(Lagasse et al., 2001).

Bridge scour is the erosion of the channel bed or banks that occurs in the vicinity of bridge foundations (i.e., bridge piers or abutments) because of water flowing across the bridge site. Bridge scour poses a significant risk to bridge integrity as it exposes the foundation and can result in insufficient support for the superstructures. In extreme cases, this can lead to the complete collapse of the bridge. Bridge scour has been recognized as a major factor contributing to bridge failures for a considerable period of time.

Scouring and other hydraulic-related factors are thought to be responsible for around 60% of all bridge collapses (Landers, 1992), Local scour around bridge foundations like piers and abutments is a typical cause of bridge failures. Local scour weakens the lateral strength of the foundations by eroding the soil around the piers (Rambabu et al., 2003)

Local scour is initiated by the formation of the horseshoe vortex regime at the base of piers. The piers create a pressure field that is sufficiently strong to generate the horseshoe vortex system. It is important to note that the horseshoe vortex is an outcome of scour, not the primary cause of it, as it pushes the down-flow towards the pier, leading to scour-hole formation. Additionally, the separation of the flow at the sides of the pier contributes to the creation of wake vortices. These vortices are unstable and alternate shedding from each side of the pier. Similar to small tornadoes, they lift sediment from the bed and contribute to the development of a scour hole downstream of the pier.

The reduction in sediment level around bridge piers or any hydraulic structures called scour depth. Several studies carried out to identify the scour depth using various ways. In this study, the scour depth in around of circular pier will be countermeasure methods. Scour can be classified into two main categories based on flow conditions: clear-water scour and live-bed scour. Clear-water scour occurs when there is fluid-structure interaction and the stream velocity (u) of the bed material is below the critical velocity (ucr). In this case, sediment particles do not move with the flowing fluid, and the scour is commonly known as clear-water scour. On the other hand, live-bed scour refers to the situation where the stream velocity (u) exceeds the critical velocity (ucr), causing sediment particles to be suspended in the flow. Scour can also be further categorized into three types: local scour, constriction scour, and general scour.

Statistics on bridges damages due to Scour failure. Based on statistics reports, scour is the most common reason of bridges failure in North America where the scour accounted for 80% of reasons of bridges failures, as shown in Figure1.1.

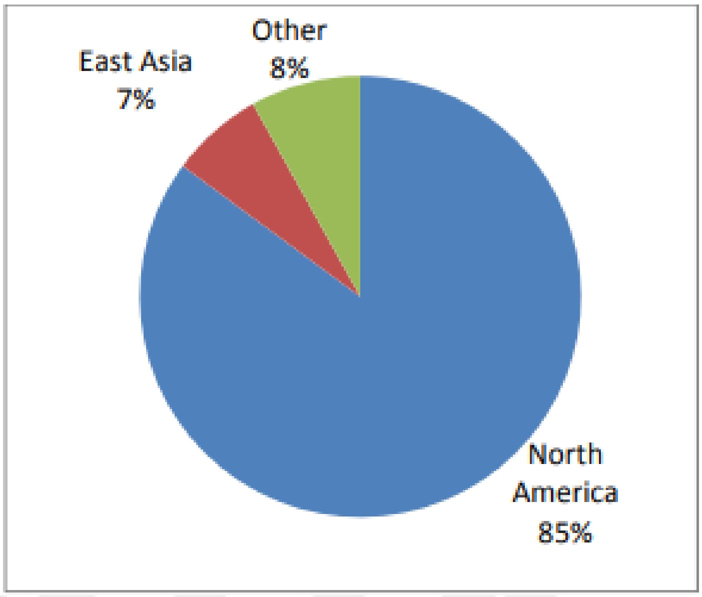


Figure 1.1 Distribution of Failed Bridge by Continents (Lee et al., 2013)

Every country's transportation system suffers significantly when a bridge fails as results of many reasons like foundation around scouring or bridges submerged by flood, as shown in Figure 1.2.

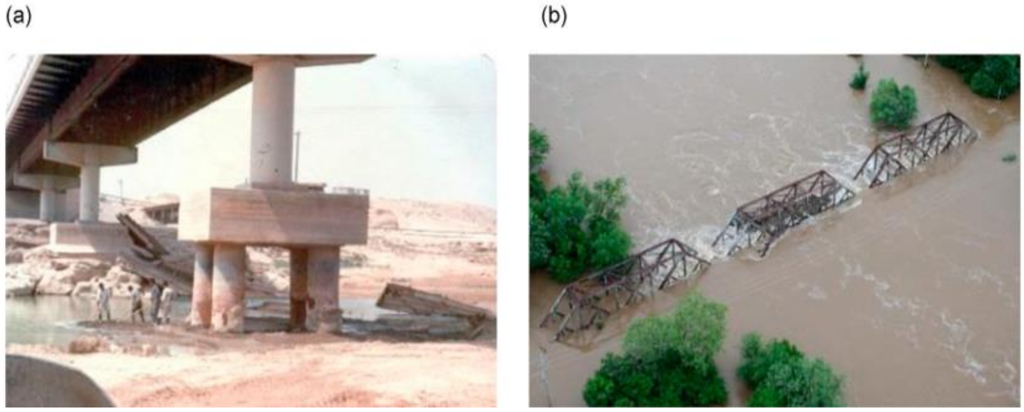


Figure 1.2 Bridge failures due to hydraulic. (a) Foundation scouring. (b) Bridges submerged by flood (Zhang et al., 2022)

In addition to causing injuries and fatalities, the interruption of services due to bridge failures has a significant negative impact on economic growth. Several studies such as (Zhang et al., 2022) have highlighted the economic consequences of such failures. For example, the collapse of the Quebec Bridge in 1907 resulted in 75 fatalities during construction (Pearson & Delatte, 2006), while the Silver Bridge collapse in 1967 led to 46 fatalities during service (Lichtenstein, 1993). The collapse of the Tuojiang Bridge during construction in 2007 caused 64 fatalities, 22 injuries, and a direct economic loss of approximately 39.747 million yuan (Peng, 2019). Similarly, the collapse of the Polcevera Viaduct in 2018, constructed by the Italian firm Morandi, resulted in 43 fatalities, 9 injuries, and a direct economic loss of about 100 million Euro (Morgese et al., 2020); (Nuti et al., 2020). Furthermore, between 1980 and 2012, there were 1062 reported bridge failures in the US, leading to significant financial costs for the nation (Lee et al., 2013)

1.2 Thesis Objective

The aim of this study is to evaluate the effectiveness of using slot countermeasure on a circular pier with various slot shapes to reduce scour depth around the pier, this investigation will utilize the models in same condition data of Ismael, A. et al. (2015) experimental model at Gaziantep University as a referenced study, then creating a scenarios of full depth water slot cases, by using four different slot shapes applied on circular pier which are rectangular slot, T-shape slot, Y-shape slot and sigma slot using CFD software for detailed analysis and simulation, in order to compare the findings of different slot shapes with those obtained from an experimental model using Computational Fluid Dynamics (CFD) software, this comparison will help to assess the impact of slot configurations on reducing scour depth around the bridge pier and identify the most effective slot shape that achieves the highest percentage of scour reduction.

1.3 Thesis Structure

This thesis includes mainly of five chapters can be clarified as follows:

Chapter 1: Contains general background, description and identification of the problem aimed at by this research and the research objectives.

Chapter 2: Presents the literature review of the problem of local scour around cylindrical bridge pier, uses one type of countermeasures to reduce local scour and previous studies.

Chapter 3: Discusses the research methodology where, build the 3D numerical model.

Chapter 4: Shows the model scenarios with discussion of the result analysis

Chapter 5: Conclusions and suggestions.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

The construction of a bridge pier in a water flow introduces a disturbance to the natural flow of water. The distribution mentioned occurs during the separation of the three-dimensional boundary layer at the pier. This separation leads to the erosion of bed material due to the presence of turbulent flow structures and vortices, as described by (Chiew, 1992). Numerous researchers, including (Chiew & Melville, 1987), have defined local scour as the process of bed material being eroded by the forceful action of water. It involves a decrease in the elevation of the bed in the vicinity of an obstruction due to the flow interaction with the obstruction. Moreover, (Raleigh, 2015) noted that the development of both horseshoe and wake vortices around bridge piers as a result of this water's displacement from the surrounding soil is what causes scour around bridge piers, and these vortices cause scour hole around pier. A scour hole refers to a depressed area that forms in the riverbed near a structure when sediment is eroded and washed away, which is the major key cause of bridge pier failures. (Chiew, 1984).

Hence, in situations where the water flow undergoes a sudden and unforeseen alteration or encounters an obstruction that hinders its movement, various intricate vortices form around the pier, both in front, behind, and alongside it. The vortices mentioned above play a significant role in the erosion of sediment from the streambed. They are responsible for the removal of material in the vicinity of various structures such as piers, abutments, spurs, and embankments. This erosive action of flowing water has the tendency to exposes the bridge foundation, excavating and carrying away material and threating structural stability of the bridge pier as shown in Figure 2.1, leads to be undermined resulting and making the bridge prone to failure with unwanted economic and lives lost. (Khademi and Wahab 2005).

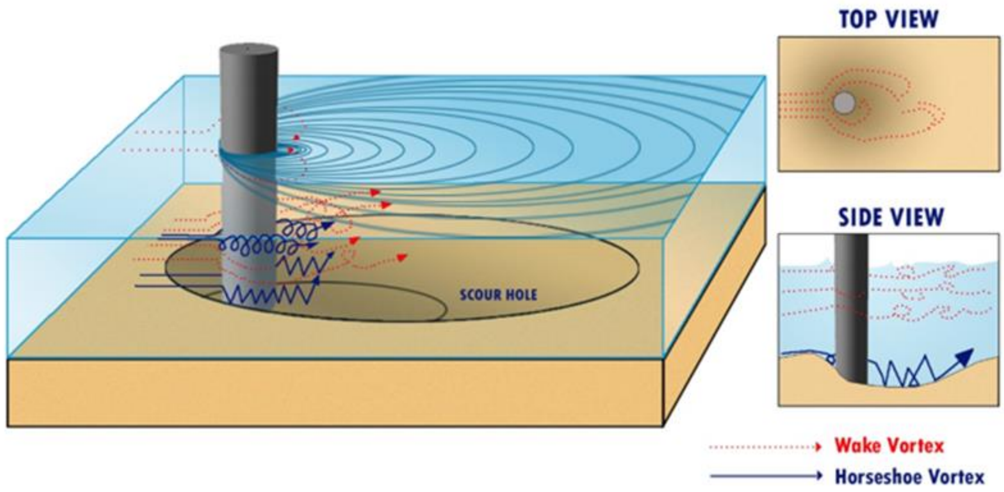


Figure 2.1 Horseshoe and wake vortices around a cylindrical pier (Guardian Retention Systems LLC 2017)

2.2 Types of scours

The formation of scour holes resulting from the water flow around bridge piers represents a significant factor in the failure of bridge pier foundations. At bridge sites, various distinct processes can contribute to alterations in the elevation of the riverbed. Many researchers as (Chiew, 1984) and (Raleigh, 2015), (Melville & Coleman, 2000) divided and explained the types of total scour as there are three main types of it (General scour, Localized scour, Local scour).

2.2.1 General scour

This type of scour happens as an aggradation or degradation of the bed level (increasing or decreasing the streambed) due to changes occurring upstream or downstream of the bridge, this type of scour occurs independently of the presence of the bridge, (Chiew, 1984). The broader definition of scour encompasses the adjustment of the bed elevation across a significant area, resulting from variations in hydrology, hydraulics, or sediment transport. Furthermore, scour can be classified into two categories based on the time scale: short-term scour and long-term scour.

2.2.1.1 Long-term

General scour can be caused by natural changes in the catchment or by the activities of human beings (Melville & Coleman, 2000), Long-term general scour typically takes place over extended stretches of time, spanning several years. As a result, the causes behind this phenomenon are often multifaceted and intricate. This type of scour is particularly evident in river sections where artificial structures like dams, weirs, or groundsills are present. It also occurs in watersheds where the lowering of the riverbed's base level has been caused by landslides or fault ruptures triggered by earthquakes.

2.2.1.2 Short-term

General scour refers to the alteration of a riverbed resulting from the occurrence of one or multiple closely spaced floods. Typically, this process is reversible, meaning that the disparity in riverbed elevations before and after the flood event is negligible. Consequently, general scour is not extensively considered in design estimations, and it may not reach an equilibrium state.(Lu et al., 2012)

2.2.2 Localized scour

This phenomenon is also referred to as constriction scour. When piers and abutments are present, the cross-sectional area of water flow decreases, resulting in an increase in flow velocity. The heightened velocity enhances the erosive force of the flow, leading to a decrease in the bed elevation in the region affected by the constriction. (Chiew, 1984) , the acceleration of water flow resulting from a bridge contraction can cause scouring throughout the entire contracted channel in the bridge opening. This reduction in channel width is typically associated with the presence of bridge abutments and/or large piers that encroach on the channel, especially when the size of these structures is significant compared to the cross-section of the channel.

2.2.3 Local scour

It is a term of localized scour; this phenomenon occurs directly due to the obstruction created by a pier or abutment, which disrupts the natural flow of water around and past the structure. (Chiew, 1984). When there is an obstruction like bridge pier/abutment in the cross-section of the stream, it creates changes in flow patterns regime due to decreasing the channel cross-section, naturally because of the high acceleration and vortices bed-stream starts to erode and create scour hole ambient around the pier or abutment that why it’s called local scour. In general, local scour can be divided into two categories according to amount of sediments being transported in and out of the scour hole. According to (Chiew, 1984), local scour can be categorized based on the sediment movement occurring within the scour hole.

Where: qs= qs2-qs1 (2.1)

qs: The rate of local scouring by the volume of sediment per unit of time

qs1: The rate of sediment transport into the scour hole in volume per unit of time

qs2: The rate of sediment transports out the scour hole in volume per unit of time

This leads to a definition of two types of local scour:

a) Clear-water scour: (qs1=0)

In situations where sediment is continuously removed from the scour hole without being replenished. it means the bed material upstream of the scour hole is not in motion or being supplied by the approaching flow, thus all materials that is transported from the contracted section is sediment being scoured (Richardson & Davis, 1995).

In such a scenario, the bed shear stresses outside the scour hole will either be equal to or lower than the critical shear stress of the bed particles. The critical shear stress refers to the shear stress level at which the flow initiates the movement of bed particles.

b) live-bed scour: (qs1, qs2 >0)

This phenomenon is commonly referred to as sediment transport-induced local scour, which involves the overall movement of sediment both upstream and downstream of the scour hole. In this case, the bed shear stress surpasses the critical shear stress of the bed, as stated by (Chiew, 1984). Live-bed scour takes place when sediment is continuously supplied to and removed from the scour hole, commonly observed in the main channel of a waterway during high-flow situations. The presence of sediment in the fluid induces shearing effects on the current bedding layer, contributing to this type of scour. As the flood intensity diminishes, the velocity decreases, allowing the sediment to refill the scour hole (Richardson & Davis, 1995).

2.3 Scour parameters

Local scour around bridge piers and abutments continues to be a significant factor in bridge failures resulting from hydraulic deficiencies. The interplay of turbulent boundary layer, time-varying flow patterns, and sediment transport mechanisms within and near the scour hole renders the phenomenon highly intricate. To better comprehend the factors influencing local scour at piers, it is essential to investigate the scour parameters and their implications.

In academic literature, a commonly employed classification system is utilized to categorize specific flow processes and their direct impact on the development of scour. This classification can be further subdivided based on structural type, typical diameter, and the nature of the load.

In addition to the characteristics of the bed material and the dimensions of the structure, the factors that primarily affect the load components are:

2.3.1 Flow velocity

The velocity of the undisturbed approach flow is directly related to the depth of the local scour hole. According to many researchers, including (Chiew & Melville, 1987), Under clear water conditions, the increase in local scour depth shows an approximate linear relationship with the ratio of shear velocity to critical shear velocity of around 0.5 ($u^*/uc^* = 0.5$) to that of unity, reaching a maximum at the critical velocity.

On other hand under live-bed condition most early researchers came to the conclusion that, for a given flow depth, the scour depth increases continuously with increasing velocities, either at an increasing or a decreasing rate.

However, subsequent studies by (Chabert & Engeldinger, 1956)), (Laursen, 1958), (Laursen, 1962) indicated that once the approach velocity (U) surpasses the critical velocity (U^*c) for sediment entrainment, further increase in flow velocity does not affect the scour hole. (Breusers et al., 1977) further stated that the flow velocity has no effect on the scour hole unless it reaches the critical velocity ($U=U^*c$).

2.3.2 Flow depth

Many researchers as (Chiew, 1984), (Ettema, 1980), and (Neill, 1973) said the flow depth is a factor effect on scour hole depth in both clear-water and live-bed conditions under certain value, where the shear velocity ratio (U^*/Uc) must kept constant.

The pier's placement in the channel creates a horseshoe vortex at the pier's base and a surface roller around the pier, and by the formation of surface roller at the leading edge of the pier, it effects the horseshoe vortex leading that for flow depth to affect the scour-hole depth, as shown in Figure 2.2.

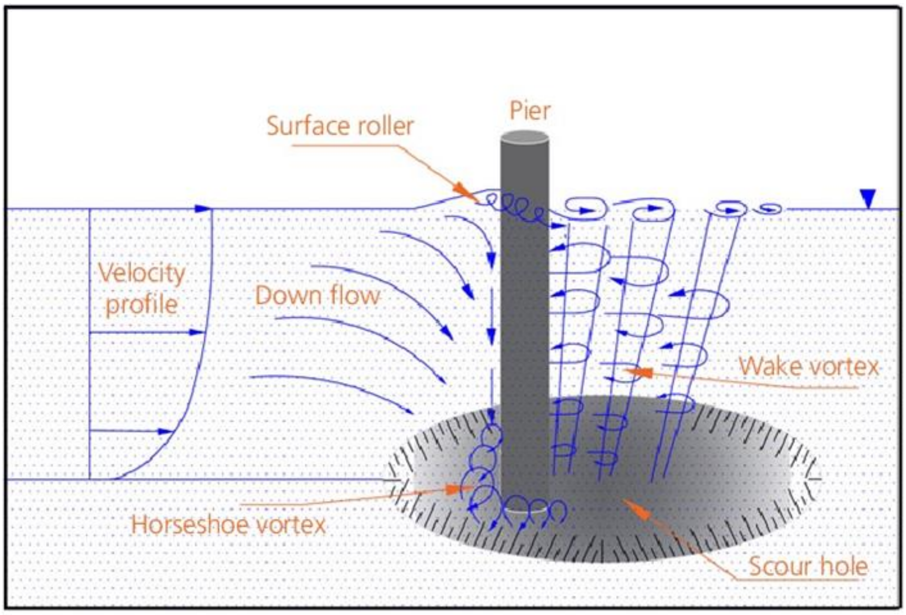


Figure 2.2 Flow field around bridge piers (Keshavarzi et al., 2018)

In other understanding, there is a relationship between flow depth affect and pier diameter and the two roller mechanisms, as (Ettema, 1980) indicates that the influence of flow depth is affected by the relative size of the pier and sediment. To understand that; in deep flow or narrow pier cases, there is no interference between horseshoe vortex and surface roller (which called two rollers), consequently, the local scour depth depends only on the pier diameter and not the flow depth. On other way, in shallow flow or wide pier cases there is interference between the two rollers that rotates in opposite direction, which surface roller becomes relatively more dominant and causes the horseshoe vortex to be less capable of entraining sediment, therefore the local scour depth is decreased with a decrease in the flow. While in intermediate pier width cases, the scour depth depends on both parameters flow depth and pier width.

2.3.3 Sediment Coarseness

According to (Melville & Coleman, 2000), the sediment coarseness is defined by dividing the pier diameter (Dp) by the sediment's mean particle size (d50) (i.e. D/d50). Many researchers as (Chiew, 1984), (Dey et al., 1995) and (Molinas, 2004) that investigated the effect of sediment grain size of local scour depth improvement, they said that both the scour rate and the scour depth decrease as the geometric standard deviation increases, The standard deviation of the particle size distribution can be used to determine how uniform it is, and its gradations (σg) (Chiew, 1984). (Ettema, 1980) has found in his experiments that since the sediment coarseness ration (D/d50) < 50 the local scour is effected by the sediment coarseness, for (D/d50) > 50 the sediment coarseness does not affect the local scour as it is independent of it. In addition, (Shen et al., 1966) stated that for fine materials (d5O < 0.50 mm), scour depths are independent of sediment size. In a comprehensive investigation conducted by (Ettema, 1976), the influence of sediment gradation on clear-water scour depths was thoroughly examined.

The study revealed that both the rate of scour and the eventual equilibrium scour depth decrease with an increase in the standard deviation of the particle size distribution. The following Table 2.1 presents the classification of the sediment particles.

Table 2.1 Classification of the sediment particles

Name of The Particle	Size Range	Loose Sediment	Consolidated Rock
Boulder	>256 mm	Gravel	Conglomerate or Breccia (depends on rounding)
Cobble	64 – 256 mm	Gravel	
Pebble	2 – 64 mm	Gravel	
Sand	1/16 – 2 mm	Sand	Sandstone
Slit	1/256 – 1/16 mm	Silt	Siltstone
Clay	<1/256 mm	Clay	Claystone, Mudstone, and Shale

2.3.4 Time variation

Local scour on bridge pier development is influenced by time and scour conditions, (Chabert & Engeldinger, 1956) proposed the assumption that equilibrium is reached when the scour depth remains relatively stable over time without significant changes. or as it increases by no more than 5% D in 24 hours (Mia & Nago, 2003). As Figure 2.3 shows the difference in evolution of scour reaching its equilibrium state depending on time in both live-bed and clear-water conditions.

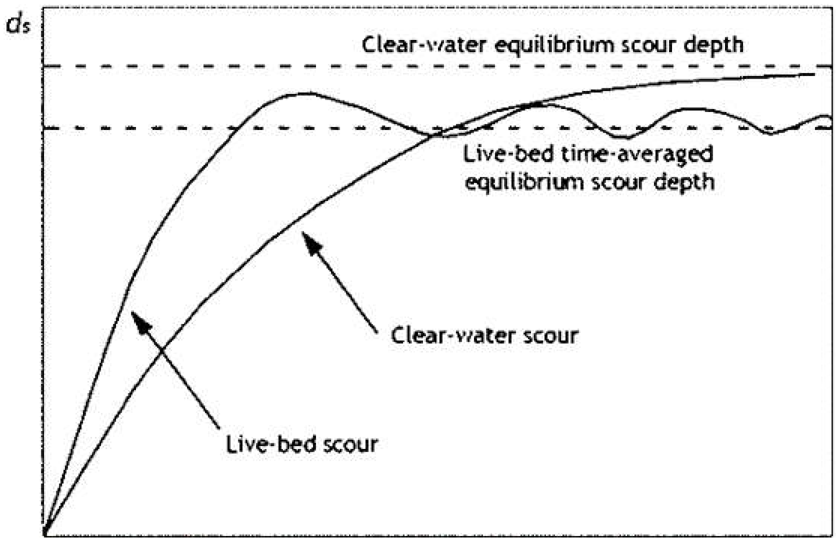


Figure 2.3 Time development of Clear-water and live-bed scour (Chabert & Engeldinger, 1956)

Under clear-water conditions, the scour depth slowly increases and approaches a stable state known as the equilibrium clear-water scour depth, this occurs when the flow is no longer capable of removing particles from the scour hole. Conversely, in live-bed conditions, the scour depth experiences rapid increases. This is due to the dynamic interplay between erosion and deposition, resulting in fluctuation around an equilibrium value known as the equilibrium live-bed scour depth. This equilibrium state is achieved when the average amount of sediment leaving the scour hole equals the average amount entering it, as highlighted by studies conducted by (Toth et al., 2000)) (Richardson & Davis, 1995). In comparison to clear-water flow circumstances, live-bed equilibrium is attained much faster. It varies around an average value that reflects the passage of bed forms.

Many researchers have studied the time required to obtain the scale of these experiments affects the equilibrium under long-time period due to the possibility that the outcomes of a short run period will produce scour depths that are lower than the equilibrium scour depth. (Kumar et al., 1999) concluded their experiment after 3 hours, as the depth of scouring had reached a value below 1 mm. They considered this to be the equilibrium state of scouring.

However, (Aksoy et al., 2017) found that collecting data for a shorter duration, such as 10 hours, could lead to an underestimation of scour depth by up to 50% compared to the equilibrium scour depth. Therefore, it is essential for scour equilibrium experiments to know where should it stop, (Melville & Chiew, 1999) have answered the question by using this formula:

$$\frac{d(dse)}{dt} \leq \frac{0.05D}{24\ hr} \tag{2.2}$$

Based on this equation, if the variation in the scour hole is below 5% of the pier diameter within a 24-hour period, it is considered that the experimental test has reached equilibrium scour depth.

2.3.5 Bridge Pier and Attack Flow Angle

(Tison, 1961) conducted an extensive study that suggested that the scour around bridge piers may be affected by the curvature of the streamlines. According to (Shen et al., 1969), the shapes of piers can be classified into two categories:

a) The Blunt-nose pier, characterized by a prominent horseshoe vortex system, exhibits the maximum scour depth near the upstream surface of the pier. This is determined by the powerful flow patterns generated by the pier's shape. The shape and geometry of the piers, particularly at the upstream surface, play a significant role in determining the depth of scouring. The specific shape of the pier downstream, as well as the length of the pier, have a lesser impact on the scour depth when considering the use of a blunt-nosed pier oriented in the direction of the flow.

b) The sharp-nosed pier exhibits a weaker system of horseshoe vortex, resulting in the maximum depth of scour being located near the downstream face of the pier. According to the observations of (Laursen & Toch, 1956) , in the case of long piers exposed to a strong attack angle, the position of the maximum scour depths shifts towards the downstream and settles near the edge of the pier. (Chabert & Engeldinger) conducted a previous study in 1956, examining the scour around six different shapes of piers (depicted in Figure 2.4 and Figure 2.5). The study findings revealed the following:

(i) Piers belonging to Group 1, specifically pier forms numbered as 1, 2, 4, and 6 in Figure 2.4, exhibited nearly identical maximum scour depths under similar flow conditions.

(ii) For pier form 3, the maximum scour depths ranged from 33% to 86% compared to the corresponding equivalent flow velocities from Group 1. This indicates that higher flow velocities resulted in larger scour depth rates.

(iii) Regarding pier shape 5, the differences in maximum scour depths varied from 50% to 100% compared to Group 1 for the same equivalent flow velocities. Notably, higher flow velocities led to larger rates of scour depths. Figure 2.6 illustrates the forms of the piers and the impact of the attack angle.

The Figure 2.5 clearly indicates that the scour depths can be reduced by streamlining the pier with a zero-attack angle. However, this advantage diminishes when the attack angle exceeds 10°. An exception to this trend is observed in the case of two cylindrical piers arranged at a distance of three pier diameters, where the angle of attack has only a negligible impact on scouring.

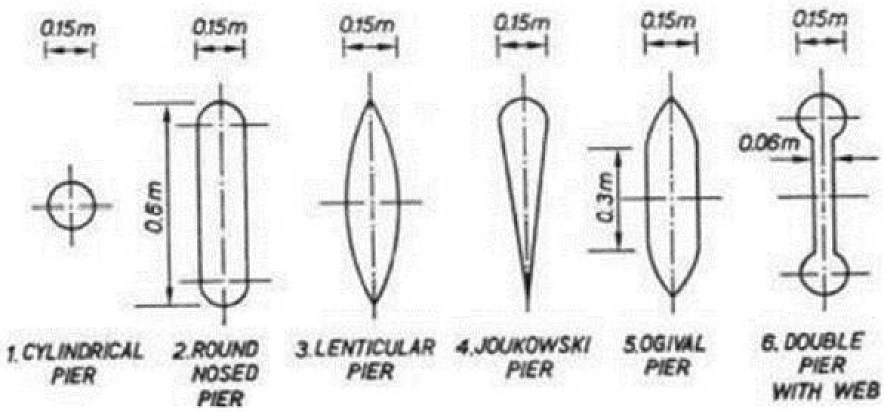


Figure 2.4 Several piers' shapes were examined for scour reduction by (Chabert & Engeldinger, 1956)

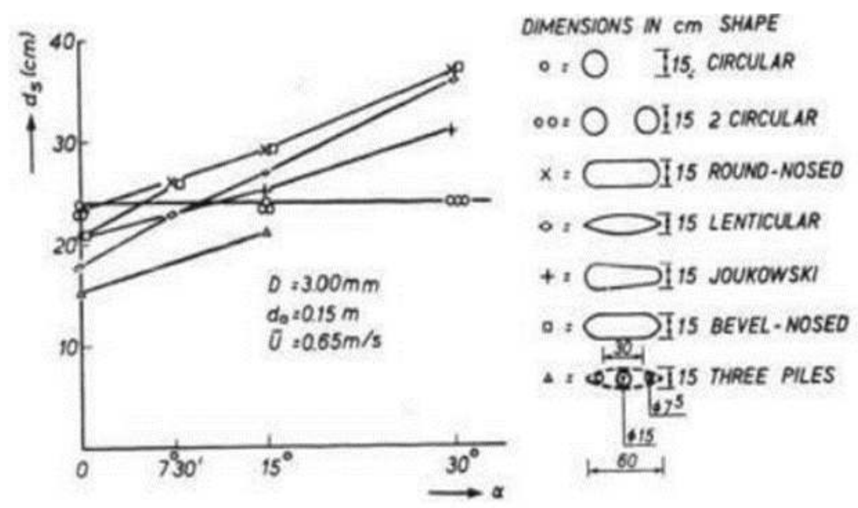


Figure 2.5 Effect of the angle of attack with the depth of scouring for different pier shapes (Chabert & Engeldinger, 1956)

In a previous study conducted by Paintal and Gard in 1956, it was found that the rear side of the pier had no significant effect on scouring, while the upstream nose of the pier had a significant influence. They conducted experiments on piers with upstream triangular faces, varying the apex angles between 15° and 180°. Their findings revealed that as the apex angles increased, the maximum scour depth also increased. Interestingly, they observed that the length of the pier had no influence on the rate of maximum scour depths for the tested pier shapes, considering a sediment particle size of 2.5 mm in diameter.

2.4 Mechanism of local scour

Local scour, also known as soil erosion caused by flowing water around an obstruction, is a complex phenomenon in engineering. The scour mechanism primarily involves the development of vortices due to pressure differences when the water velocity profile encounters the obstruction. Researchers, such as (Chabert & Engeldinger, 1956), (Melville, 1975), (Dargahi, 1990), have highlighted the intricate flow patterns and scour mechanisms around bridge piers. When the approaching flow encounters the structure, its velocity decreases to zero at the face of the structure, resulting in increased pressure. The maximum pressure occurs near the surface, where the flow decelerates the most, and decreases downward. As the flow velocity decreases from the surface to the bed, the pressure gradient decreases as well. This pressure gradient induces a downward flow resembling a vertical jet vortex along the pier (Melville & Coleman, 2000). As shown in Figure 2.6.

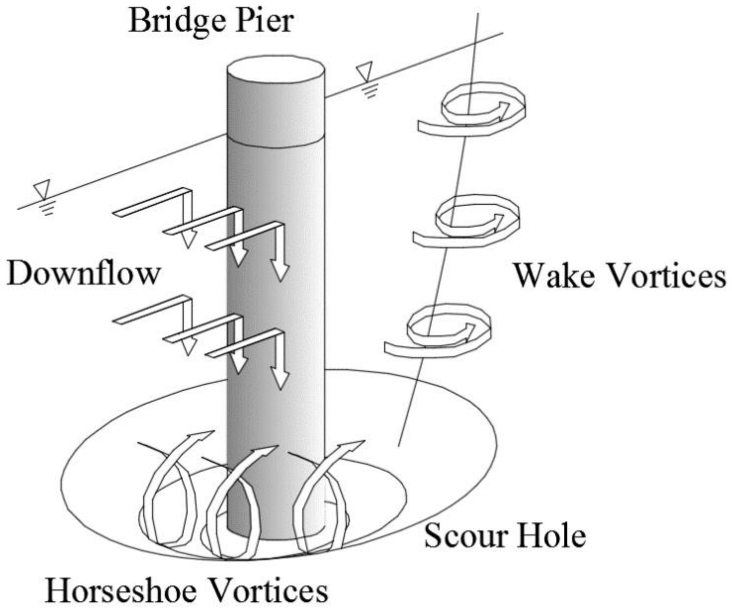


Figure 2.6 Schematic of local scour-modified from (Anzlin et al., 2018)

As this downward flow impinges on the streambed, it excavates a hole in front of the pier, continuously rolling up and forming a complex vortex system through interaction with the incoming flow. This strong vortex motion, known as the horseshoe vortex, entrains bed sediments near the pier base and extends downstream, passing along the sides of the pier. The dislodged particles are rapidly carried away by the horseshoe vortex, resulting in scouring (Melville & Coleman, 2000).

Moreover, the flow acceleration along the sides of the pier leads to the formation of openings in the riverbed, facilitating the transportation of eroded sediment from the scour hole located at the upstream edge of the pier. Flow separation on the sides generates unstable wake vortices that shed intermittently. These wake vortices act like small tornadoes, lifting sediment from the bed and creating their own scour hole. The scour mechanism under waves is based on the sweeping motion of shed vortices, which transport sediment particles (Melville & Coleman, 2000).

Various factors influence the extent and severity of local scour, including flow velocity, flow depth, sediment characteristics, and geometry of the structure. The scour depth can be affected by parameters such as the Froude number, Reynolds number, sediment size, and bed roughness.

Several studies have investigated the mechanism of local scour and its mitigation measures. For example, the work of (Melville & Coleman, 2000) explored the scour process around bridge piers and proposed guidelines for bridge design to mitigate scour. Another study by (Chiew & Melville, 1987) focused on the prediction of scour depth and developed empirical equations based on laboratory experiments.

Overall, understanding the mechanism of local scour is crucial for designing and implementing effective countermeasures to protect structures from scour-related failures. Researchers continue to investigate this phenomenon to improve our knowledge and develop reliable methods for scour prediction and mitigation.

2.4.1 Horseshoe vortex

When a solid object interrupts the flow of water, it creates a phenomenon called vortex shedding downstream. This object alters the water's velocity and pressure in its vicinity as well as in the downstream region (Palau-Salvador et al., 2010). As the water encounters the obstruction, it separates and generates an unsteady flow downstream. This flow separation at the upstream edge of the scour hole leads to the formation of a horseshoe vortex characterized by intense turbulence and vortices. The horseshoe vortex extends downstream, encompassing the sides of the pier and merging with the general flow turbulence. The presence of this vortex system exerts high shear stresses on the bed material beneath it, effectively transporting dislodged sediment particles away from the pier (Breusers & Raudkivi, 1991).

Studies have shown that the configuration and dimensions of the bridge pier have a notable impact on the distribution of bed friction velocity induced by the horseshoe vortex system (Esmaeili et al., 2013). The horseshoe vortex is generated when the flow separates at the upstream surface of the pier, resulting in the formation of the initial scour hole. As the flow approaches the pier, it decelerates, interacts with the upstream surface, and descends vertically along the pier towards the bed layer and pier foundation. As in Figure 2.7.

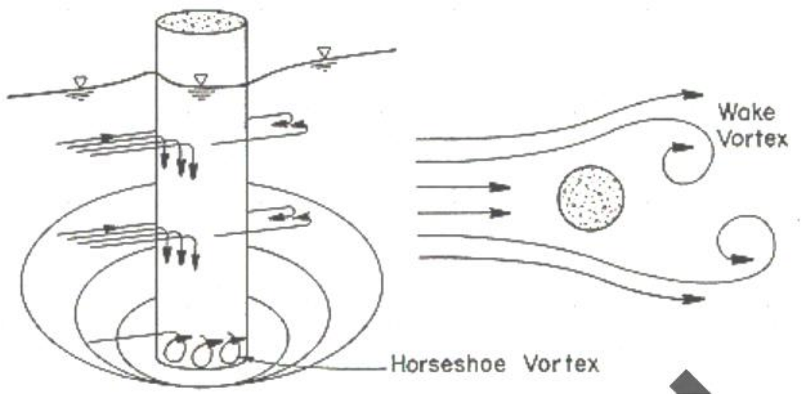


Figure 2.7 Schematic Representation of Scour at a Cylindrical Pier (Lagasse et al., 2001)

2.4.2 Wake vortex

In addition to the horseshoe vortex located near the base of the pier, there are also wake vortices that form vertically downstream of the pier. These wake vortices are generated when the flow separates along the edges of the pier. They exhibit an alternating shedding pattern from one side of the pier to the other and lack stability (Dargahi, 1990). This phenomenon is a result of the flow separation around the bridge pier, influencing the flow pattern downstream (Younis & Zhou, 2006). Each of these concentrated vortices acts as a "vacuum cleaner" due to its low-pressure center (Melville, 1975). The presence of rip-rap or other countermeasures upstream of the bridge pier can lead to scouring issues caused by wake vortices (Stevens et al., 1991). Although the impact of horseshoe vortices on large-diameter bridge piers is minimal, wake vortices continue to contribute to scouring downstream (Stevens et al., 1991). As shown in Figure 2.8 the combination of horseshoe and wake vortices significantly influences the scouring process around bridge piers.

2.5 Scour Prediction Governing Equations

Several empirical equations have been developed to estimate the local scour depth around bridge piers, as outlined by (McIntosh, 1989). These equations are categorized based on the type of local scour, whether it is clear water scour or live-bed scour. Various methods, such as curve fitting and regression analysis, have been employed to derive these equations and compute the maximum scour depths. Table 2.2 provides a summary of some equations commonly used for estimating scour depth.

Table 2.2. Summary of predicted equilibrium scour depth equations

Researcher	Equations	Description
Breusers (1965)	ds = 1.4b	ds are maximum scour depth b is pier diameter
Laursen and Toch (1956)	$dsp = 1.5\ bp\ 0.7Y0.3$	d sp is the pier scour depth (m), bp is width of the pier (m), Y is the depth of approach flow, for live bed scour
Laursen and Toch (1956)	$dsp = 1.35\ bp\ 0.7Y0.3$	For clear-water scour
Shen II	$dsp = 3.4\ bp\ 0.67\ F0.67\ Y0.33$	F is the Froude number of the approach flow
Larras (1963)	$ys = 1.42\ KS2b0.75$	KS2 is a coefficient based on the shape of the pier nose.
HEC-18 equation	ys / y0 = 2 $K1\ K2\ K$ $\left(\frac{b}{y_0}\right)^{0.65}$ $F0^{0.43}$	F is a Froude number K1 K2 K3 is coefficient
Raudkivi and Ettema(1983)	y = 2.3bKσ	where K = f(σg) = 1 for uniform sediment, σg= geometric standard deviation of the grain size distribution
Shen et al.(1969)	yse = 0.000223Rb0.619	where Rb = pier Reynolds number

2.6 Local scour countermeasures

The erosion occurring around a solid pier is caused by the downward flow on its upstream face and the horseshoe-shaped vortex formed at its base. Consequently, an effective approach to mitigate this scour is to diminish or even inhibit the development of both the downward flow and the horseshoe vortex (Kumar et al., 1999). Scour mitigation measures for bridge piers can be classified into two primary categories: flow-altering countermeasures and bed-armoring countermeasures. Flow-altering countermeasures are designed to diminish the strength of the down-flow and the horseshoe vortex, which are the key factors contributing to pier scour, as explained by (Parker et al., 1998) and (Chiew & Lim, 2003). The objective of these countermeasures is to reduce the intensity of the down-flow and horseshoe vortex, which are the primary mechanisms responsible for pier scour.

On the other hand, bed-armoring countermeasures involve the use of physical barriers to protect the pier from scour. These barriers, such as riprap stones, Reno mattresses, cabled-tied blocks, or gabions, act as shields that resist erosion and prevent sediment transport around the pier. They are typically large and heavy, making them difficult for the flow to displace.

Flow-altering countermeasures have been further investigated and classified into three categories based on their shape and performance: pier attachments (Threading, Collars and horizontal plates), bed attachments (Sleeve and collared sleeve), and openings through piers (Pier group, Pier Slot).

Each category offers different methods to modify the flow characteristics and reduce the scour potential around the piers, this study aims to use pier slot as a countermeasure.

2.6.1 Pier attachments

In the flow-altering countermeasures category, there is a method to mitigate the strength of the down-flow and horseshoe vortex by installing specific devices on the piers. These devices include threading, collars, and horizontal plates.

a) Threading

Threading, proposed by (Dey et al., 2006), It is a cost-effective and straightforward method of countermeasure installation. It involves wrapping cables spirally around the pier, creating threads. These threads effectively weaken the down-flow and horseshoe vortex. The effectiveness of threading in reducing scour depth is influenced by factors such as cable diameter, number of threads, and threading angle. As the cable diameter increases and more threads are used while reducing the threading angle, the scour reduction becomes more significant. Acoustic Doppler velocimeter measurements conducted in the field have provided evidence that the cables not only diminish the intensity of the down-flow but also divert the horseshoe vortex away from the pier. This redirection of the vortex leads to a more significant reduction in the depth of scour.

b) Collars and horizontal plates

Collars, which are thin horizontal plates, are installed around bridge piers to provide a flow-altering countermeasure. These collars are typically circular disks that are attached to the pier perimeter, The purpose of the collars is to delay the scour process and slow down the development of the scour hole at the pier.

Studies by (Mashair et al., 2004) and (Alabi, 2006) have shown that the presence of collars significantly reduces the rate of scouring. By obstructing the flow around the pier perimeter, the collars create a barrier that hinders the erosion process. This delay in scour development provides valuable time for additional protective measures to be implemented and minimizes the potential risks associated with excessive scour.

Additionally, horizontal plates can be attached to the upstream face of the pier, serving as another flow-altering countermeasure. These plates further modify the flow patterns and contribute to the reduction of scour depth. (Kim et al., 2005) and (Parker et al., 1998) have investigated the effectiveness of such horizontal plates in mitigating pier scour.

Various shapes and configurations of plates, also known as vanes, have been tested as countermeasures for bridge piers. When a vane is attached to a pier, it serves to divert the flow away from the pier, thereby reducing the strength of the horseshoe vortex that forms around it (Ghorbani & Kells, 2008). The design and placement of the vanes play a crucial role in their effectiveness. By strategically positioning the vanes, the flow patterns and dynamics can be altered to minimize the impact on the pier and reduce the scouring potential.

The shape and configuration of the vanes can be optimized to achieve the desired flow diversion and vortex reduction.

Studies conducted by (Ghorbani & Kells, 2008) have investigated the performance of different vane designs in mitigating pier scour. The results have demonstrated the potential of vanes in reducing the strength of the horseshoe vortex and subsequently minimizing the scour depth around bridge piers.

2.6.2 Bed attachment

Bed-attachments are implemented to redirect or diminish the incoming flow and alter the characteristics of the boundary layer. Consequently, the strength of the down-flow and the horseshoe vortex is diminished. Multiple approaches have been proposed to achieve this, such as the utilization of sacrificial piles, vanes and sills, surface guide panels, as well as sleeve and collared sleeve techniques. These approaches aim to disrupt the flow patterns and modify the flow dynamics near the bed surface to mitigate the scouring effects. By diverting or weakening the flow and influencing the boundary layer behavior, bed-attachments play a crucial role in reducing the scour potential around bridge piers. These countermeasures provide additional protection by altering the flow characteristics and decreasing the forces that contribute to scour formation.

a) Sleeve and collared sleeve

The sleeve and collared sleeve countermeasures are used to minimize scour around bridge piers. These methods involve installing protective sleeves or collars around the piers to mitigate the erosive effects of the flowing water. The sleeve technique utilizes a sleeve as a physical barrier, shielding the pier from direct flow impact and reducing scour depth. On the other hand, the collared sleeve technique adds a collar at the upstream end of the sleeve, diverting the flow away from the pier and further reducing scour potential. (Singh et al., 2001) investigated the effectiveness of collared sleeve countermeasures through physical model experiments and observed significant reductions in scour depth compared to unprotected piers. Both the sleeve and collared sleeve techniques are effective in mitigating scour as they create a barrier that shields the pier from erosive forces and redirect the flow away from the pier, thereby minimizing scour potential.

2.6.3 Openings through piers

By allowing a fraction of the incoming flow to pass through openings inside or between piers, the strength of the down-flow and the horseshoe vortex can be reduced.

Three primary configurations have been suggested for this approach: internal connecting tubes, pier groups, and slots. Internal tubes involve the use of interconnected tubes positioned within a pier, with a specified width (b). This countermeasure allows for the diversion of flow through the tubes, altering the flow patterns and reducing the strength of the down-flow and horseshoe and wake vortices. This configuration effectively modifies the hydraulic conditions around the pier and mitigates the scour potential.

a) Pier group

Pier groups involve the use of smaller piers, each with a diameter (b), replacing a single solid pier. (Vittal et al., 1994) introduced two configurations for pier groups: partial and full pier groups. In the partial pier group configuration, three smaller piers are used, with one portion of the pier group extending to a certain depth within the flow, while the remaining portion of the pier remains solid up to the bridge deck. This arrangement replaces the use of solid piers and allows for the modification of flow patterns and reduction of scour potential in the affected area.

b) Pier Slot

The pier slot countermeasure is an effective technique used to reduce the scour depth around bridge piers. It involves the creation of openings or slots within or near the piers, which helps divert the down-flow and weaken the horseshoe vortex, thereby minimizing the scouring effect, as the major principle of slot countermeasures mechanism.

The slot countermeasure has been extensively studied and researched by various scholars in the field, in a series of experiments conducted by (Chiew, 1992), it was observed that a slot positioned closer to the bed level demonstrated higher effectiveness in terms of providing protection compared to a slot positioned near the water surface. Figure 2.8 shows the various types of pier slots which have been used by several investigators.

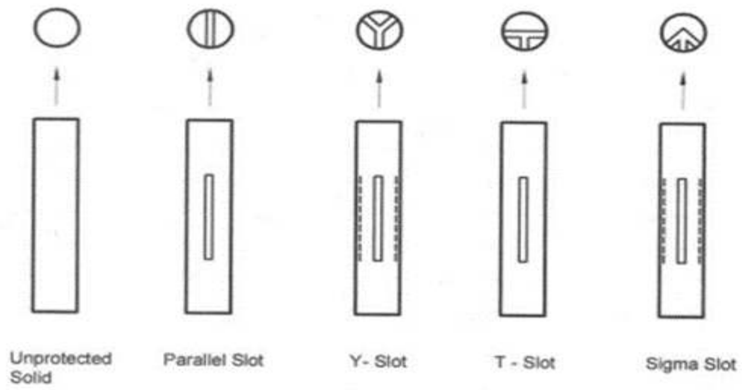


Figure 2.8 Various Types of Slots (Akhlaghi et al., 2020)

While (Kumar et al., 1999) conducted experiments to investigate the effectiveness of pier slots. They found that extending the length of the slot below the bed surface led to a significant reduction in scour depth. This indicates that deeper slots are more effective in mitigating scour, as it shows in Figure 2.9.

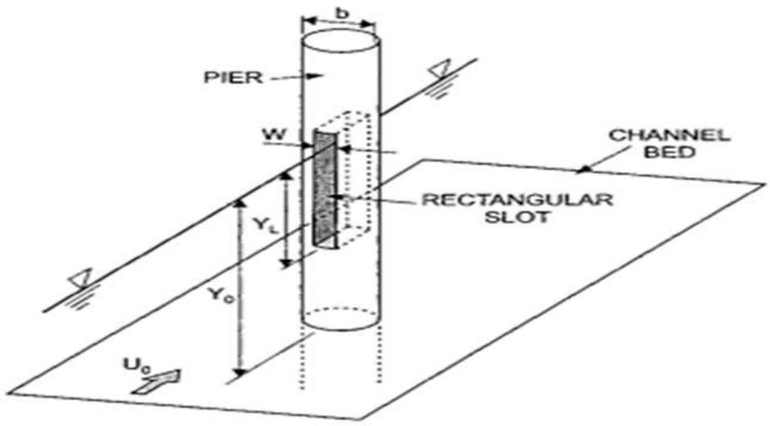


Figure 2.9 slot in bridge pier (Kumar et al., 1999)

(Grimaldi et al., 2009) studied the performance of slots with different embedded depths. Their research showed that increasing the embedded depth of the slots resulted in improved protection efficiency. They reported an average protection efficiency of 30% for the tested configurations. (Melville & Coleman, 2000) examined the limitations of the slot countermeasure. They highlighted that the effectiveness of slots can be influenced by factors such as flow direction, alignment, and potential blockage due to debris. These factors may reduce the overall protection efficiency.

While (Tafarojnoruz et al., 2010) further emphasized the limitations of slot countermeasures, particularly in terms of debris blockage. Their study highlighted that the presence of debris can significantly impact the performance of slots and reduce their effectiveness in mitigating scour.

Pier slot countermeasures provide a valuable approach to reducing scour depth around bridge piers. They have been proven effective in various studies, with the length and depth of the slots playing a crucial role. However, the presence of debris and other flow-related factors can affect their overall efficiency. It is important to consider these factors when designing and implementing pier slot countermeasures for effective scour mitigation, as the following chapters it can be seen the methodology in the present study uses pier slot countermeasure and observing the efficiency of the tested models.

CHAPTER 3
METHOLODGY

3.1 Introduction

This research project focused on investigating sediment scouring around a bridge pier using a three-dimensional numerical model. The study was conducted at Gaziantep University's laboratory within the civil engineering department, as previously carried out by Ismael, A. et al. 2015. Drawing upon the findings of the experimental study, the FLOW-3D software was employed to construct a comprehensive three-dimensional numerical model of sediment scouring. The subsequent section presents a detailed summary of the accomplished research endeavor.

3.2 Physical Composition and Experimental Procedures

The experiment was carried out in a rectangular flume, the characteristics of which are shown in Figure 3.1. The sides of the flume were made of smooth glass. The sediment section component reaches 3 m in length and 0.8 m in width, with a soil depth of 0.2 m.

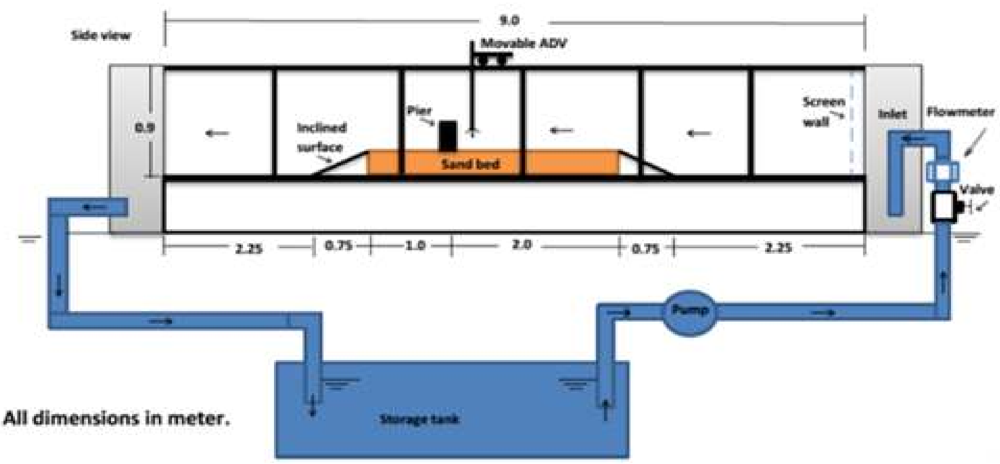


Figure 3.1 The flume layout (Ismael, A. et al. 2015).

3.3 Tested Pier Shapes and grain size based on the experimental data

(Ismael, A. et al. 2015) used four different pier shapes in their experimental, which are described below:

(1) Round nosed pier (10-10) cm

(2) Upstream-facing round nosed pier with three different diameters ((10-8), (10-6) and (10-4) cm)

(3) Upstream-facing shaped pier

(4) Circular pier (10) cm

Piers were made of thermo-stone and painted to reduce the surface roughness of the piers; Figure 3.2 depicts images and dimensions of bridge piers that have been tested in the experimental.

Figure 3.2 dimensions of tested bridge piers (Ismael, A. et al. 2015).

After considering the suggestions of various researchers, the decision was made to select a circular pier with a diameter of 10 cm as the reference model. This model will serve as a basis for comparing the results obtained after implementing a slot countermeasure technique, specifically the use of a slot to redirect the downward flow and minimize the impact on the bed. The upcoming section will provide further details on this approach. The selection of flow conditions, pier diameter, and sand size was influenced by the experimental study conducted by (Ismael, A. et al. 2015).

3.4 Data preparation

To calibrate the numerical model, a single cylinder pier was selected as the reference pier. The numerical simulation was conducted under conditions and properties similar to those of a laboratory investigation conducted by (Ismael, A. et al. 2015). The model incorporated data regarding flow conditions, geometry, and sediment properties, applying the mechanical sieve analysis and a specific gravity test on the study to classify the soil material is used. The test conditions are given below:

Flow Conditions:

- Discharge: 0.058 m^3/s
- Water Depth: 0.125 m
- Velocity: 0.58 m/s

Geometry:

- Pier Diameter: 0.1 m
- Pier Length: 0.45 m
- Flume Length: 3 m
- Flume Width: 0.2 m

Sediment Properties:

- Type of Sediment: Sand
- Sediment Size: 1.45 mm
- Specific Gravity: 2.65 g/cm^3
- Sediment Layer: 0.20 m

3.5 Numerical Model Procedure

The research Numerical methodology involved the following steps:

1. Experimental Setup: The experimental data from Ismael, A. et al. 2015, served as the baseline for the study, providing the reference for scour characteristics.
2. Model Setup: The scour model was developed, considering the relevant boundary conditions and parameters identified in the experimental setup. Manual calibration was employed to adjust the model parameters to replicate the scour around the pier accurately.

3. Scenario Analysis: Once the model calibration was completed, it was used to simulate and analyze the scour characteristics for different slot shapes (T-shape, Y-shape, rectangular shape, and sigma shape).
4. Result Comparison: The results from different scenarios were compared against the reference model to assess the significance and impact of the different slot shapes on scour depth and scour profile. The significance of examining different slot shapes on scour depth and scour profile lies in its potential to contribute to the reduction of sediment transport and local scour around piers. By evaluating the various slot shapes, the study aims to provide findings that can have implications for the design and engineering of structures, such as bridges and piers, to mitigate potential scour-related risks. The study intends to determine the optimal percentage of scour reduction achievable by comparing different slot results with a reference model. The purpose of this study is to calculate the efficiency of various slot shapes created through a bridge pier as scour depth reduction countermeasures by using FLOW 3D software for the analysis.

3.6 Local Scour Using FLOW-3D.

In this study, the numerical modeling was conducted using Flow-3D software, a powerful computational fluid dynamics (CFD) tool developed by Flow Science Incorporation. Flow-3D is widely used in various industries such as aerospace, automotive, and marine engineering, as well as in academia and research, for simulating fluid flow, heat transfer, and related phenomena. The software implements a structured perpendicular grid using the fractional area volume (FAVOR) method, which enables the simulation of complex geometries. To model free surface flow, the Volume-Of-Fluid (VOF) method is employed, allowing for accurate tracing of air, fluid, or fluid adjacent to fluid boundaries. This approach records the volume of fluid in each individual cell while disregarding the surrounding air, resulting in sharp edges between flowing fluid and air without the need for fine meshes. Flow-3D has proven effective in modeling local scour, as described by (Brethour, 2001), by considering the geometry of obstacles in the fluid domain through fractional face area and volume calculations.

3.7 FLOW-3D Model Set-Up and Calibration

In present study, the targeted countermeasure is opening through pier as slot countermeasure method for reducing local scour around circular bridge piers, and the tested slots that mentioned in section 1.2 was simulated using Flow 3D software. The software setup and configuration process involve the many steps. Flow-3D offers various physical options to users, such as sediment and scour, which require consideration of specific parameters. Among the critical parameters are sediment scour, gravity and non-inertial reference frames, viscosity, and turbulence. Each of these physics options also includes other distinct choices that users can make when setting up simulations in the software. Gravity and Non-Inertial Reference Frame has been enabled and must be set to a value of -9.81 m/s^2.

This model for sediment scouring makes assumptions about sediment that is non-cohesive and uses predictions of erosion, advection, and deposition to estimate how the sediment will move. The sediment scours model assumes different properties, as shown in Table 3.2

Table 3.2 Mechanical properties of the Sediment scour

Parameters	**Value**
Grain size	0.00145(m)
Mass density	2650(kg/cm^3)
The critical packing fraction	0.64
Critical Shields parameter	0.05
Bed roughness/d50 ratio	1
Entrainment coefficient	0.018
Bed- load coefficient	8
Angle of repose	32

3.8 Scale Effect

Introducing slots through a pier in a numerical model for minimizing local scour can exhibit a scale effect when compared to real-world scenarios. Numerical simulations, while highly useful, inherently entail discretization and simplification of physical processes. This discretization can lead to variations in the representation of parameters like slot dimensions and sediment characteristics. Consequently, small-scale details, such as the size and placement of slots, might be either exaggerated or downplayed in the model. Moreover, the complex interplay of forces, sediment transport, and fluid dynamics can be influenced by non-dimensional factors like Reynolds and Froude numbers, which may behave differently at different scales. These nuances can contribute to deviations between model predictions and actual field conditions. Therefore, while numerical models serve as invaluable tools for preliminary assessments, it is vital to validate their results through physical experiments or in-situ observations to ensure accurate representation of local scour mitigation strategies. This iterative validation process is influential in developing reliable and effective scour countermeasures in real-world applications.

To a better understand the scale effect concept, it's important to note that the impact of the ratio between scour depth and pier diameter in numerical simulations corresponds directly to a similar change observed in real-world scenarios. This correlation is illustrated in Results and Discussion chapter, which shows the ultimate outcome of scour development for all various CFD slot models, where the standard for scour depth (represented by the non-dimensional factor ds/Dp, with ds representing scour depth in cm and Dp representing the diameter of the circular pier in cm) is applied. (See Figure 4.15).

3.9 Viscosity and Turbulence

In the context of predicting and simulating turbulence, there are two commonly used equations: the $K - \varepsilon$ model and the Re-Normalization Group model (RNG), along with the big eddy simulation model. Several studies, including those by (Dailey et al., 2003), have shown that the RNG model provides greater accuracy in predicting turbulence flow characteristics compared to the $K - \varepsilon$ standard model. Additionally, the RNG model has been found to closely align with laboratory results.

Since the two model equations have the same formula, the following points show the enhancements which RNG has:

1- The RNG (Re-Normalization Group) model is an enhanced version of the standard k-epsilon model, a popular turbulence model used in simulations. It incorporates a correction factor to account for the dissipation of energy by small-scale turbulence, which differs from the prediction of the standard model. The correction factor is determined through statistical analysis of the turbulent flow and aims to enhance the model's accuracy across a broader range of flow conditions.

2- The RNG k-epsilon model has been shown to be more accurate than the standard k-epsilon model for a wide range of turbulent flows, including boundary layers, separated flows, quickly strained flows and swirling flows, like big eddy simulation model. The model is widely used in industry for engineering applications such as aircraft design, combustion modeling, and environmental flow analysis.

3- The RNG k-epsilon model solves for two variables, k and epsilon, which represent the turbulent kinetic energy and the rate of dissipation of turbulent kinetic energy, respectively, while the standard k- ε model practices defined by the user as constant values.

4- The standard k-epsilon model is designed for large Reynolds numbers, while the RNG model uses an analytically derived differential method for dynamic viscosity to account for low Reynolds number effects.

The previous characteristics make the RNG k-epsilon model more accurate and reliable for a broader range of flows compared to the standard k-epsilon model, the standard k-epsilon model includes an additional transport equation for the turbulent dissipation, ε_T, and it is expressed in a typical form:

$$\frac{\partial \varepsilon_T}{\partial_T} + \frac{1}{V_F}\left\{\left(v_\varepsilon\, A_x\, \frac{\partial \varepsilon_T}{\partial_x}\right) + \left(v\, A_y\, R\, \frac{\partial \varepsilon_T}{\partial_y}\right) + \frac{\partial}{\partial_z}\left(w\, A_z\, \frac{\partial \varepsilon_T}{\partial_z}\right)\right\} = \frac{CDIs1.\varepsilon_T}{K_T}\,(PT + CDIS3.G_T) + Diff_\varepsilon - CDIS2\,\frac{\varepsilon^2 T}{K_T} \quad (3.1)$$

All CDIS1, CDIS2, and CDIS3 are dimensionless user-changeable parameters and have defaults of (1.44, 1.92, and 0.2) for the model. The1diffusion of dissipation, $Diff\varepsilon$,1is:

$$Diff_\varepsilon = \frac{1}{V_F}\left\{\frac{\partial}{\partial_x}\left(v_\varepsilon\, A_x\, \frac{\partial \varepsilon_T}{\partial_x}\right) R\,\frac{\partial}{\partial_y}\left(v_\varepsilon\, A_y\, R\, \frac{\partial \varepsilon_T}{\partial_y}\right) + \frac{\partial}{\partial_z}\left(w_\varepsilon\, A_z\, \frac{\partial \varepsilon_T}{\partial_z}\right) + \frac{v_\varepsilon A_x\, \varepsilon_T}{x}\right\} \quad (3.2)$$

The RNG theory employs equations that are related to the equations used in the k-epsilon model. Additionally, the empirical equation constants used in the standard k-epsilon model are explicitly derived in the RNG theory. In general, the RNG theory is fully applicable to the standard $k - \varepsilon$ model. Specifically, the RNG model is known to provide more accurate and specific representation of both low-intensity turbulence flows and flows with high shear regions. In addition, the default values of CDIS1 and CNU in the RNG model are not the same as those used in the standard $k - \varepsilon$ model. The values in the RNG model are 1.42 and 0.085, respectively.

CDIS2 is measured from the turbulent kinetic energy (kT) also as the turbulent assembly of (PT) terms. In wholly turbulence transportation theories, the turbulent kinematic viscosity is calculated as:

$$\varepsilon_{T,min} = CNU\sqrt{\frac{3}{2}\frac{k_T{}^{3/2}}{\text{TLEN}}} \tag{3.3}$$

Where εT is the turbulent kinematic viscosity.

3.10 Geometry Set-Up

Flow-3D software provides various forms to create components, but for complex structures, software such as Auto-Cad or SOLID WORKS that can draw using STL extensions must be used. For each model, the geometry of individual piers was designed in SOLID WORKS and saved as an STL file for importing into Flow-3D. To enhance modeling efficiency, the X, Y, Z coordinates must be specified in SOLID WORKS to ensure proper positioning in Flow-3D. The geometry of the canal and sand layer can be defined within Flow-3D and is depicted in Figure 3.3.

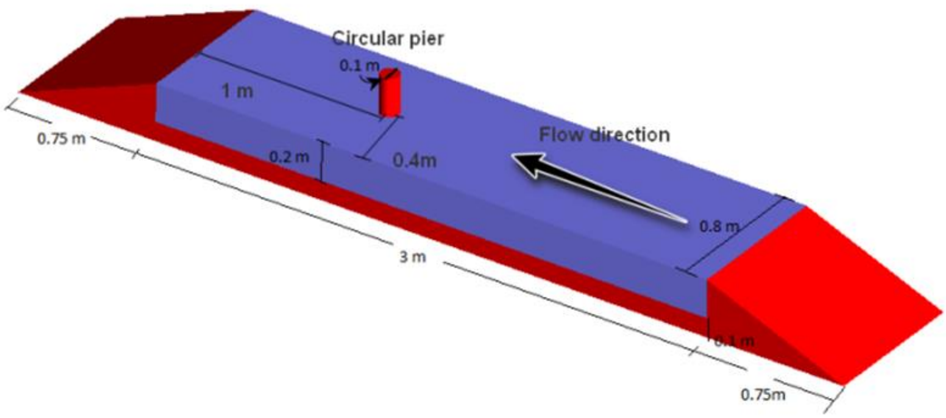


Figure 3.3 Dimensions of the channel

3.11 Meshing Set-Up and Specifying Boundary and Initial Conditions

FLOW-3D is a software tool that uses orthogonal grids in both Cartesian and cylindrical coordinate systems for modeling purposes. Choosing between these network types affects the geometry definitions within the program. FLOW-3D uses the FAVOR method, which constrains cell volumes and outer regions in the orthogonal grid, allowing complex geometries to be created. This approach enables independent classifications of the network and the geometry, making it possible to modify the geometry without redefining the entire network. Compared with the frame-equipped coordinates, this method simplifies the network generation process. Moreover, FLOW-3D supports multi-block lattice, enabling the definition of multiple lattice blocks and facilitating modeling of compound flow domains. Additional mesh blocks can be nested within other blocks at borders, forming linked blocks and enhancing the versatility of meshing in Flow 3D (Flow Science, 2008).

The size of the mesh block is a crucial factor that affects both the accuracy of the results and the running time of the simulation. In this study, the computational domain was distributed the mesh sizes in X, Y, and Z directions which are 0.025 m for section work of the entire canal with width 0.8 m, length 2 m, and sediment layer 0.2 m, which were conducted on a three-dimensional mesh block with ٦٩,678 uniform cells

The simulated models in this study are characterized by a single capital letter symbol, denoting the boundary condition. The boundary conditions have two distinct borders, either minimum or maximum, and each of these borders plays a crucial role in influencing the simulation outcomes significantly.

To input a specific flow rate into the Flow-3D software, three methods can be employed: Volume Flow Rate, Specified Velocity, and Specified Pressure. These methods are applicable to the inlet discharge system. In this case, the inlet discharge was set to 0.058 m3/s, with a velocity of 0.58 m/s and a fluid elevation of 0.425 m above Z = 0. Referring to Figure 3.4, the inlet boundary condition for the lower boundary in the Y direction (Y min) was specified as Velocity, while the outlet boundary at the upper boundary (Y max), representing the end of the flume, was set as Outflow. At the lower boundary in the Z direction (Z min), the bottom of the flume was designated as a wall boundary condition. Conversely, at the upper boundary in the

Z direction (Z max), the Pressure boundary condition was chosen to represent a free surface. For both X-direction boundaries (X min and X max), wall boundary conditions were selected to represent the sides of the channel, as depicted in Figure 3.5.

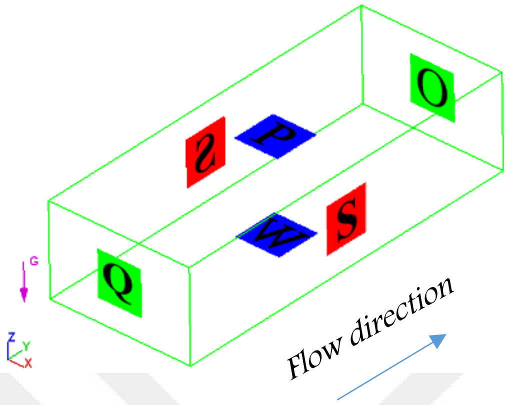


Figure 3.4 Boundary conditions for the model.

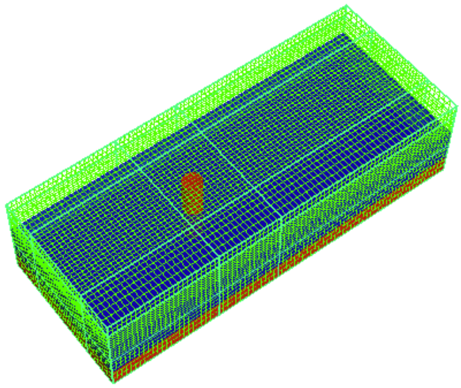


Figure 3.5 Computational mesh around pier model

3.12 Model calibration

Calibration is a process used to assess the reliability of a model by adjusting independent variables such as parameters and fluxes until the results fall within reasonable ranges that accurately represent the real-world situation. In this case, by using Flow-3D simulation program, the scour model was calibrated using experimental data from Ismael, A. et al. 2015, under steady-state conditions. Manual calibration was employed to simulate the scour around the pier to ensure the reference model reliability before running the model for different scenarios as shown in Figure 3.6. Which is satisfied, it is essential to calibrate the model in a similar manner as the experimental model.

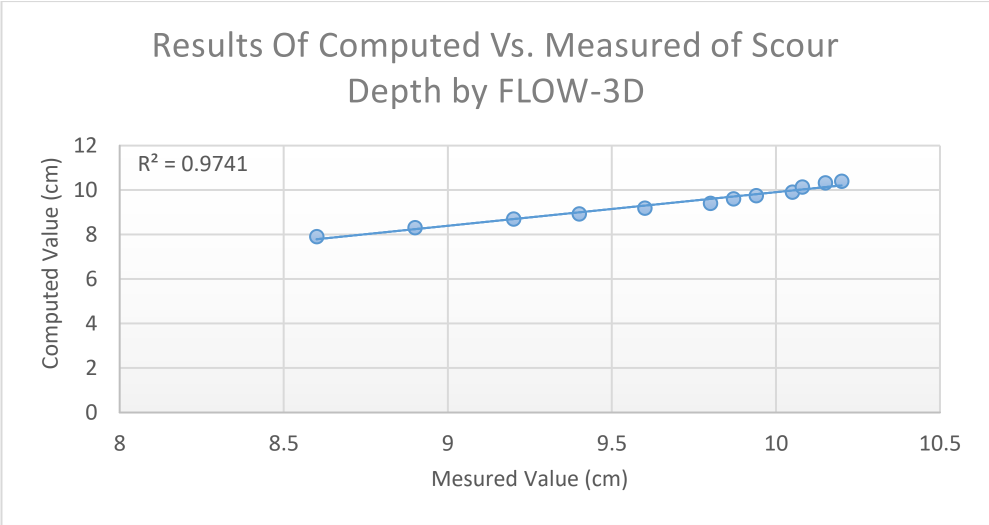


Figure 3.6 Scheme of computed and measured scour depth.

3.13 Slots Definitions and Dimensions

A slot positioned close to the bed redirects the downward flow through its aperture, leading to a decrease in erosive impact. This redirection causes the approach flow in the lower boundary layer to accelerate, acting like a horizontal jet. As the downward flow at the pier is perpendicular to this jet, it can be deflected away from the bed, resulting in reduced scour. On the other hand, a slot placed near the free surface allows the upper portion of the flow to pass through it without redirection as (Chiew, 1992) conclude, this sections contains the scenarios of different pier slot shapes with their dimensions as full water depth elevation are all applied on bridge pier of 10 cm diameter:

1- The **reference model** (R-m) (10 cm)

2- A slot with a **sigma shape** through the pier (σ-s) (0.25) cm

3- A slot with a **Y-shape** through the pier (У-s) (0.25) cm

4- A slot with a **T- shape** through the pier (T-s) (0.25) cm

5- A slot with a **Rectangular-shape slot** through the pier (R- s) (0.25) cm

3.14 Model cases with slot countermeasure

A slot countermeasure involves creating slots or openings in the structure, usually at strategic locations, to alter the flow patterns and reduce the intensity of the scouring process. These slots can modify the hydraulic conditions, redirect the flow, or dissipate the energy of the water, thereby minimizing the erosion and scouring around the structure, it will be considered four different model scenarios to analyze the extent to which the implementation of slots in the circular pier reduces the depth of local scouring, In this study, four different cases were examined, each utilizing a rectangular slot design. Three of these cases involved full water depth slot elevations. T-slot for a circular pier, and Y-slot for circular pier, and sigma-slot for a circular pier, and a rectangular slot in a circular pier. In all slot cases, the width of the slots was consistent and equal to 0.25 times the diameter of the circular pier (Dp), which amounted to 2.5 cm, all the cases and their shapes and dimensions are clarified in Figure 3.7 which shows 3D-Point of View of slots shapes and Figures (3.8, 3.9, 3.10 and 3.11) show 3D-Point of View of slots shapes in another angle.

Circular pier with T-slot (0.25) cm open width	**Circular pier with Y-slot (0.25) cm open width**	**Circular pier with rectangular slot (0.25) cm open width**	**Circular pier with sigma slot (0.25) cm open width**

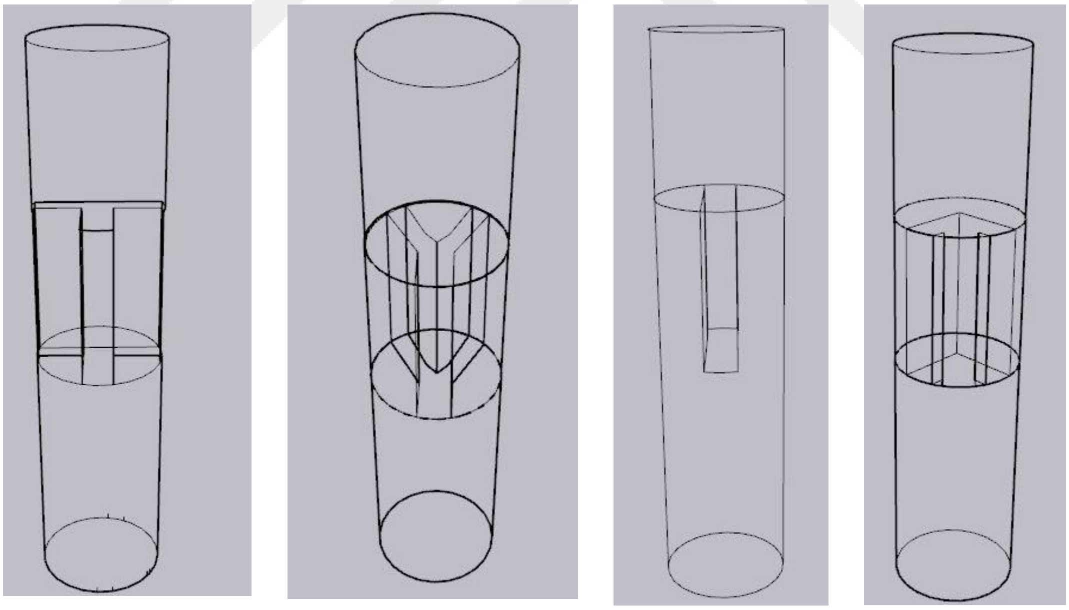
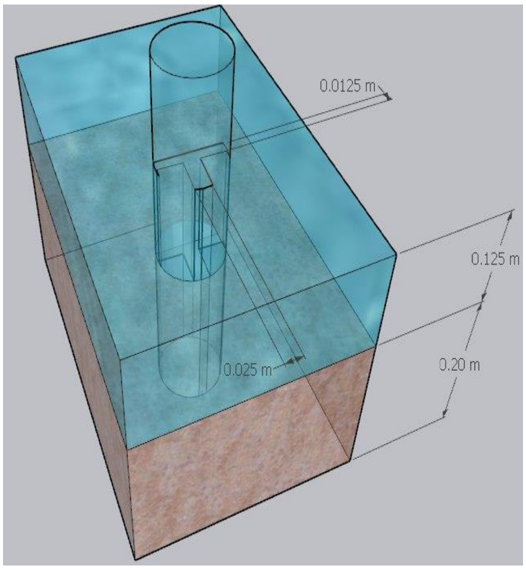


Figure 3.7 Sketch of shape and location of Slot through the piers 3D- Point of View



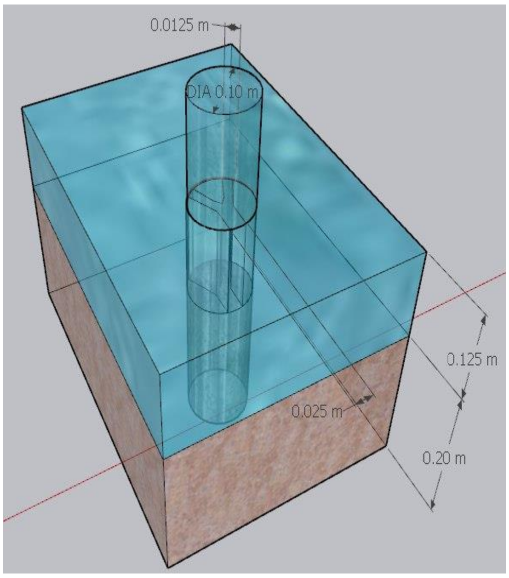
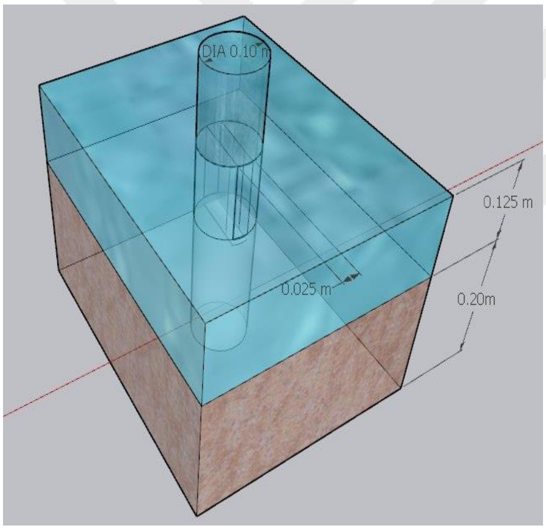


Figure 3.8 Circular pier with T-slot (0.25) cm open width

Figure 3.9 Circular pier with Y-slot (0.25) cm open width



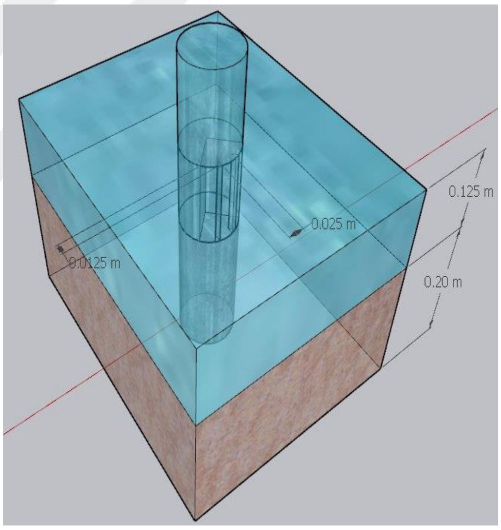


Figure 3.10 Circular pier with Rectangular-slot (0.25) cm open width

Figure 3.11 Circular pier with Sigma-slot (0.25) cm open width

CHAPTER 4
Results and Discussions

4.1 Introduction

The results chapter aims to present and analyze the findings of the study that examines the impact of different slot shapes on scour depth and scour profile. The research objectives are to assess the significance of the slot shapes on the scour characteristics and to test specific hypotheses related to scour depth and scour profile. The methodology employed in this study involved calibrating the scour model using experimental data from Ismael, A. et al. 2015, under steady-state conditions. The calibration process ensured that the model accurately represents the real-world situation by comparing the model results to the experimental data. The calibration reached a satisfactory level, with a match of approximately 94%, as in Figure 4.1. This section contains a discussion of the results obtained from the models that were examined and their comparison with the reference model.

The colored bar names as packed sediment elevation net change represents the local scour depth around bridge pier in all cases, while the colored bar names as y-velocity represents the average flow velocity around bridge pier in all cases.

4.2 The outcomes and the discussion of models

4.2.1 CFD reference model (R-m) compared to the experimental model (Circular pier experimental model from Ismael, A. et al. 2015)

In this section, the first step will compare the CFD reference model with the experimental model of a circular pier conducted by Ismael, A. et al. 2015. The calibration process yielded suitable results, with an approximate 97% match, as demonstrated in the accompanying Figures 3.16. Moreover, the Figure 4.1 illustrate the similarity in the development of scour over time between the CFD reference model and the experimental model when compared the scour depth results in both experimental and computational models for the cylindrical pier without slot the maximum scour depth reach about 10.2 cm in the experimental and 10.4 cm CFD reference model, while Figure 4.2 shows local scour and flow velocity profiles findings highlight the capability of the computed referenced model in reducing scour depth around the circular pier.

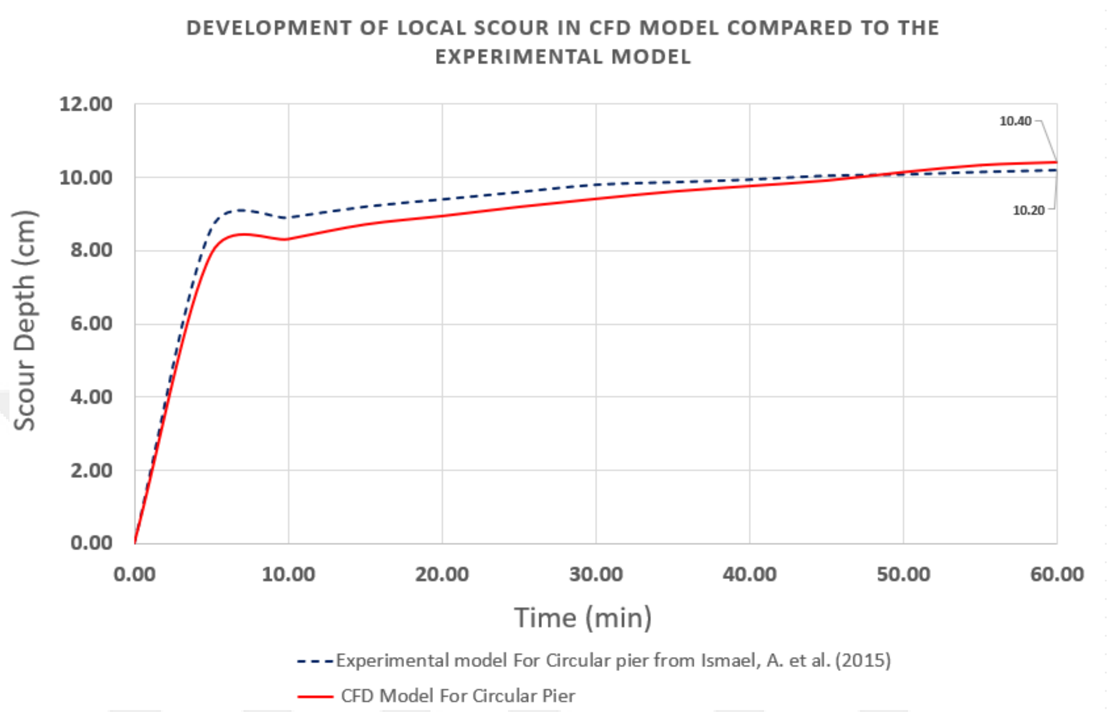


Figure 4.1 Compared of scours development findings for both experimental and computational models for the circular pier without slot.

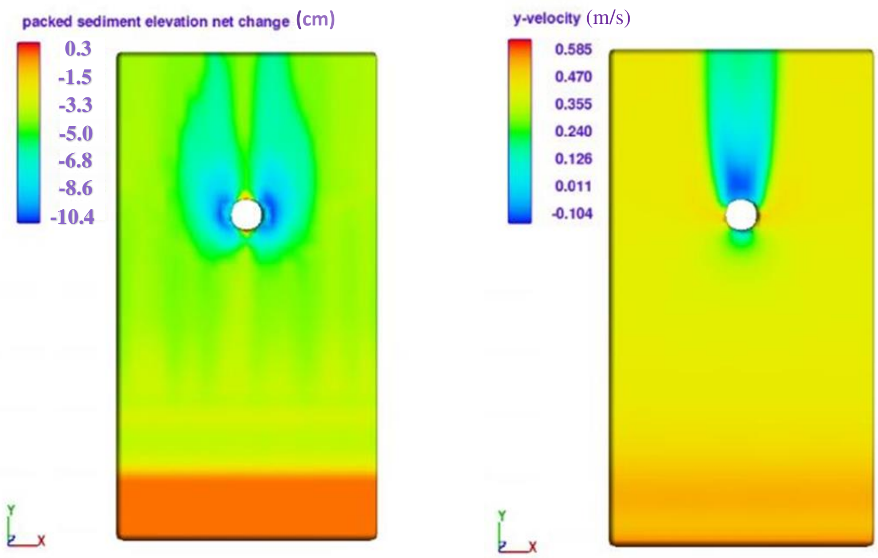


Figure 4.2 Flow velocity field profile and local scour profile for CFD model pier.

4.2.2 Effects of slot on scour reduction

The impact of adding different slot shapes on the reduction of local scour depth around a circular pier. Local scour occurs when the flow is enforced against the upstream surface of the pier, resulting in the formation of a forceful vortex due to the collision of the flowing water with the pier. This vortex, in turn, causes sediment removal around the base of the pier, potentially affecting its foundations. To mitigate the formation of scour holes, two approaches can be considered. The first involves reducing the downward flow directed towards the sediment bed surface, while the second focuses on diverting the downward flow away from the sediment bed surrounding the pier. The presence of a slot in the pier serves as a conduit for water, functioning like a jet that helps minimize the creation of conflicting pressure gradients and reduces the intensity of the horseshoe vortex. To achieve the research objective, various the slot shape was examined to analyze their effectiveness in reducing scour around bridge piers. By investigating the effect of different slot configurations, this study aims to contribute to the understanding of how to mitigate scour depth and protect the stability of circular piers.

4.2.3 CFD reference model compared A slot with a Sigma shape (ơ-s) through the pier model.

When comparing a CFD reference model of a circular pier with a sigma-shaped slot, the presence of the sigma-shaped slot throughout the circular pier is represented in Figure 4.3, Development of local scour experimental model CFD reference pier with CFD Sigma Slot." In this case, the highest scour depth was 7.14 cm. However, the existence of the sigma-shaped slot resulted in a considerable reduction in maximum scour depth. When compared to the circular pier without a slot, the reduction percentage was approximately 31.34%, as illustrated in Figures 4.4 and 4.5 these findings highlight the capability of the sigma-shaped slot in reducing scour depth around the circular pier. The presence of the sigma-shaped slot influenced the flow dynamics, leading to a redistribution of flow and a result reduction in erosive forces near the pier.

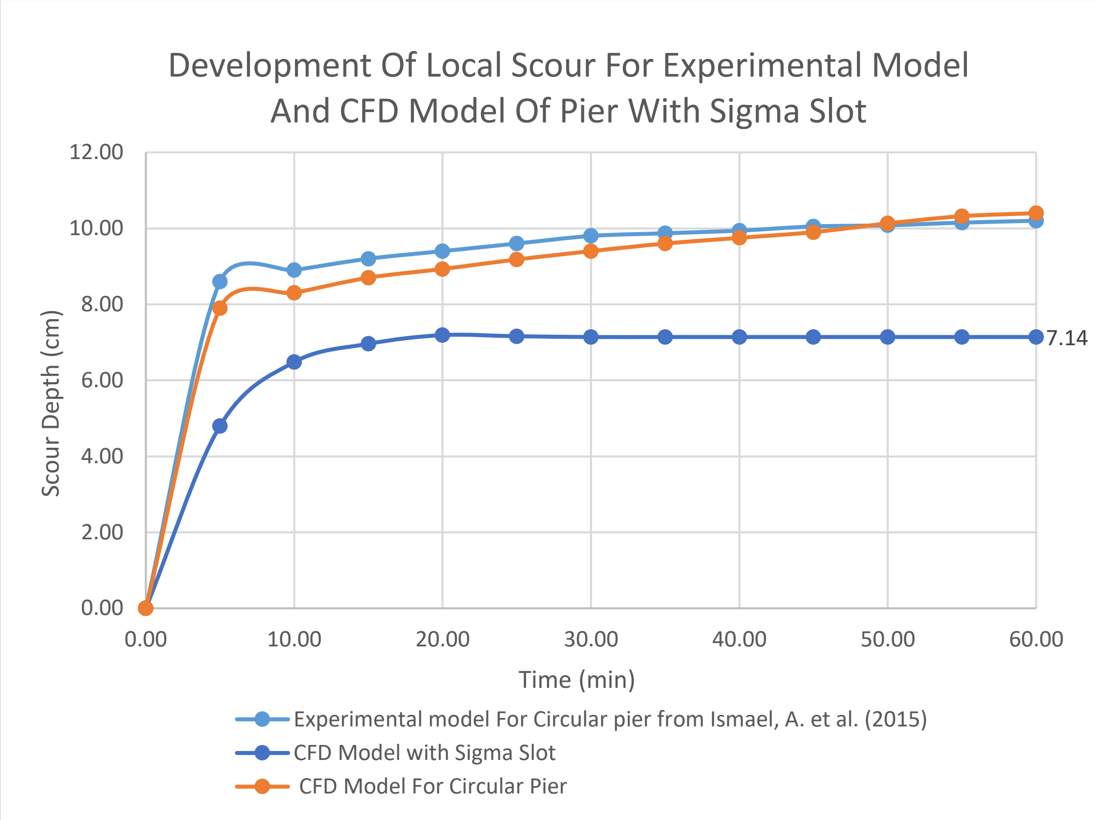


Figure 4.3 Development of local scour for experimental model amd CFD model of pier with sigma slot

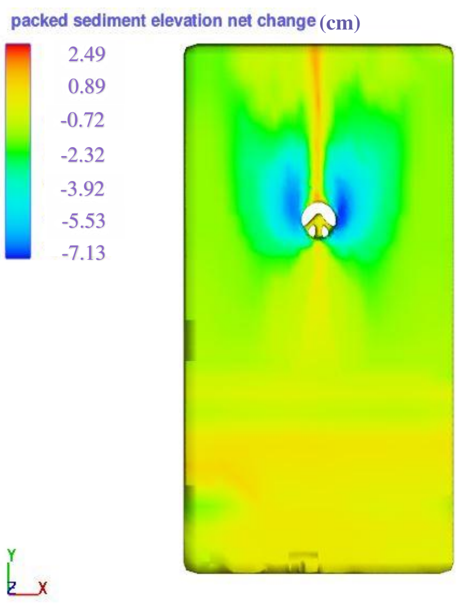


Figure 4.4 Local scour profile for CFD model pier with sigma slot.

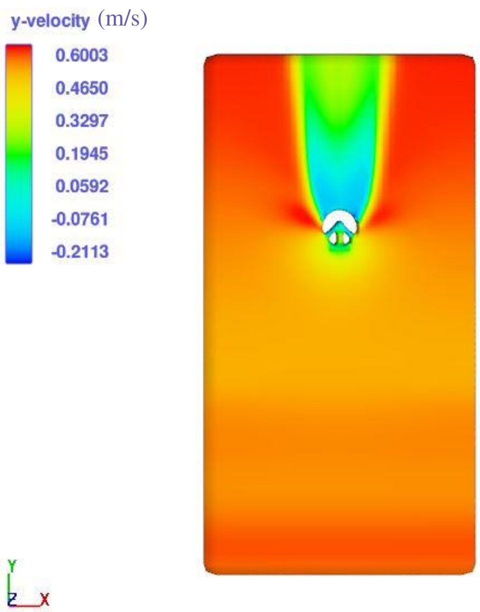


Figure 4.5 Flow velocity field profile for CFD model pier with sigma slot.

The mechanism behind the scour reduction achieved by the sigma-shaped slot involves several factors. By introducing the sigma-shaped slot, the flow is divided into multiple paths, allowing for better distribution of the flow field. This flow division helps in reducing the intensity of vortices and turbulence near the pier, thereby mitigating the scouring effects and resulting in a decrease in scour depth. Figure 4.5 represents the flow velocity field profile for the CFD model pier with the sigma-shaped slot, further illustrating the altered flow patterns and reduced velocities near the pier. This modification in the flow dynamics contributes to the reduction in scour depth observed.

4.2.4 CFD reference model compared A slot with a Y shape (У-s) through the pier model.

When comparing a CFD reference model of a circular pier with a Y-shaped slot, the inclusion of the Y-shaped slot throughout the circular pier can be observed (as shown in Figure 4.6). In a surprising manner, this modification resulted in a significant decrease in the maximum scour depth. The measured maximum scour depth in this case was 3.69 cm. Comparing this to the circular pier without a slot, the reduction percentage was approximately 64.52%, as depicted in Figure 4.7 and Figure 4.8. These findings highlight the remarkable effectiveness of the Y-shaped slot in reducing scour depth around the circular pier. The presence of the Y-shaped slot altered the flow patterns by providing additional flow paths and redistributing the flow energy. This diversion and dispersion of the flow helped to mitigate the concentration of erosive forces near the pier, resulting in a significant reduction in the maximum scour depth observed.

The Y-shaped slot configuration played a crucial role in modifying the flow dynamics by allowing the flow to follow multiple paths, it effectively distributed the flow energy, thereby reducing the intensity of vortices and turbulence responsible for scour development. This improved flow distribution helped mitigate the erosive effects near the pier and contributed to the reduction in scour depth as shown in Figure 4.7.

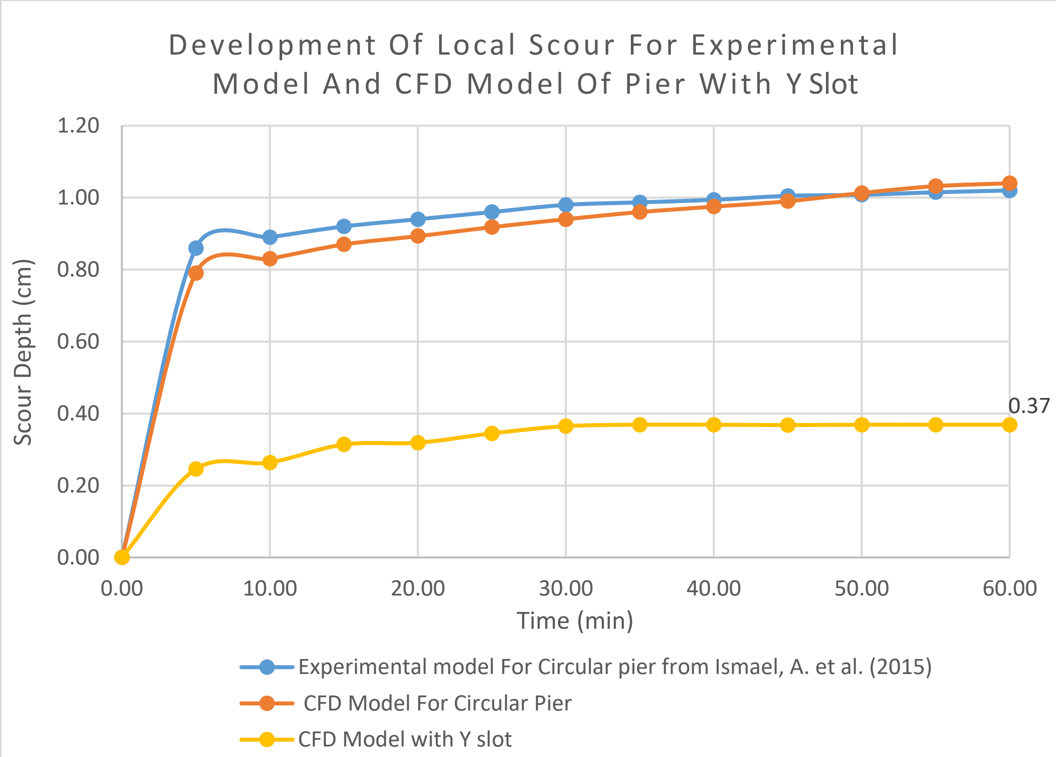
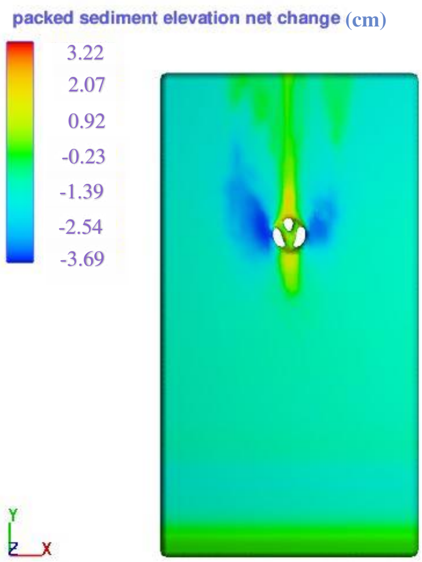


Figure 4.6 Compared of scour development findings for both experimental and computational models of circular pier with Y slot.



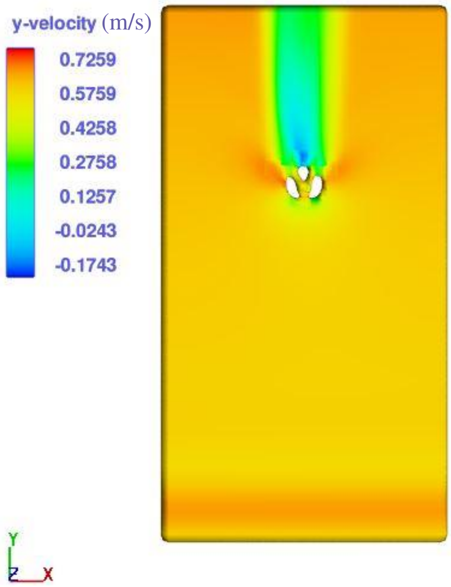


Figure 4.7 Local scour profile for CFD model pier with Y slot.

Figure 4.8 Flow velocity field profile for CFD model pier with Y slot.

4.2.5 CFD reference model compared A slot with a T shape (T-s) through the pier model.

When comparing a CFD reference model of a circular pier with a T-shaped slot, the addition of an upper half slot through the circular pier was observed (see Figure 4.9). Surprisingly, this modification resulted in a significant decrease in the maximum scour depth. The measured maximum scour depth in this case was about 4 cm. However, with the adding of the T-shaped slot, the reduction in maximum scour depth was approximately 61.54% when compared to the circular pier without a slot (CFD reference model) as illustrated in Figure 4.10 and Figure 4.11. These findings highlight the remarkable effectiveness of the T-shaped slot in reducing scour depth around the circular pier. The presence of the slot altered the flow forms, causing a redirection of water and a decrease in erosive forces near the pier, consequently, this led to a significant reduction in the maximum scour depth observed as illustrated in Figure 4.9.

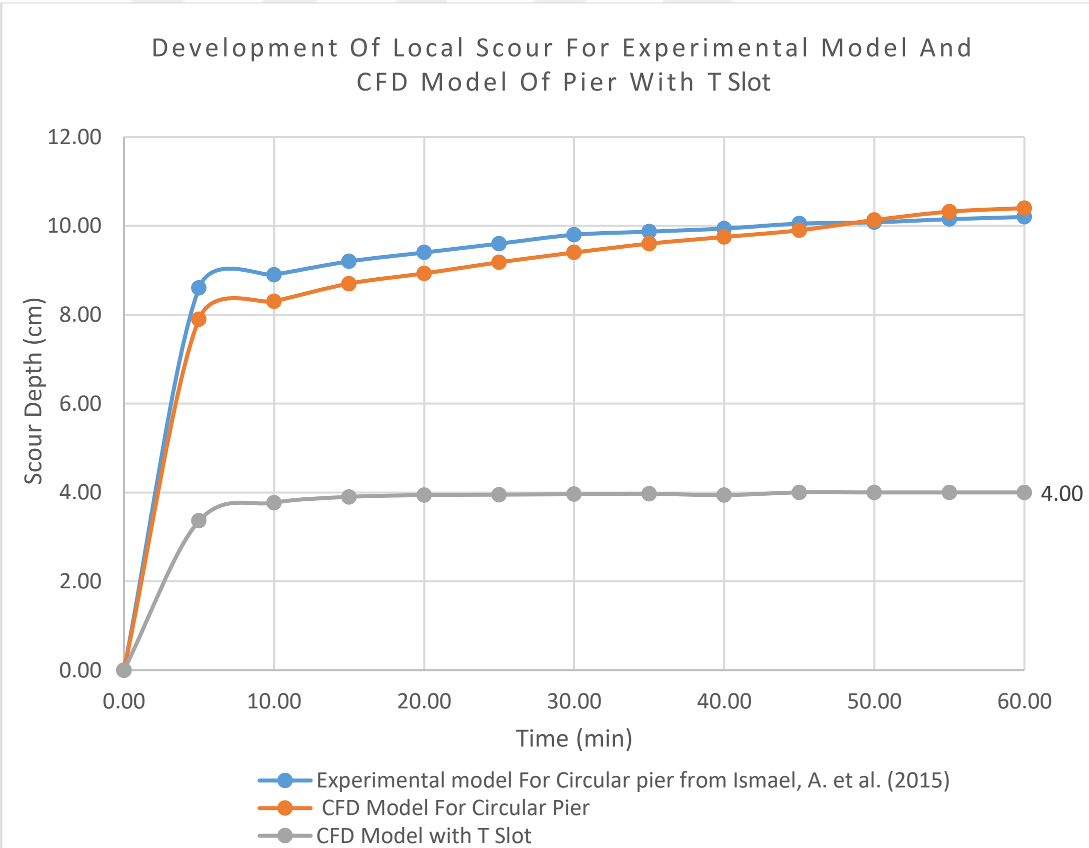


Figure 4.9 Development of local scour for experimental model and CFD model of pier with T slot

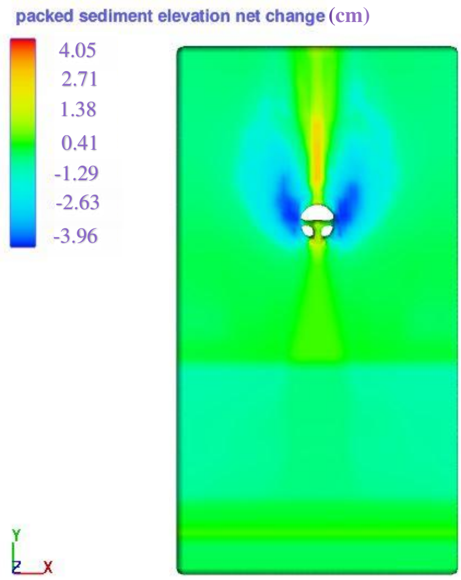


Figure 4.10 Local scour profile for CFD model pier with T slot.

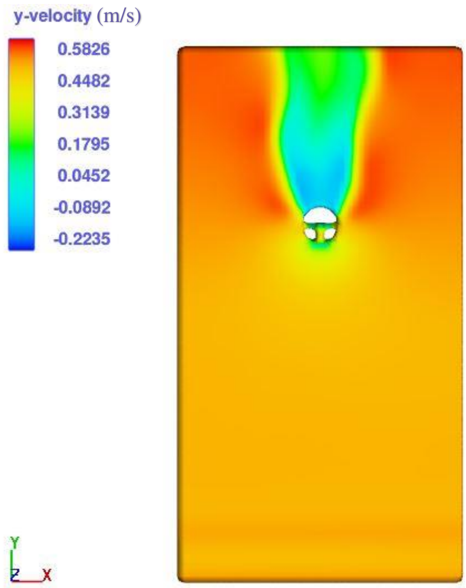


Figure 4.11 Flow velocity field profile for CFD model pier with T slot.

4.2.6 CFD reference model compared A slot with a Rectangular shape (R-s) through the pier model.

When comparing a CFD reference model of a circular pier with Rectangular slot, the mechanism behind the Rectangular slot's effectiveness in reducing scour depth around the circular pier is its flow diversion and dispersion properties. The slot set-up extends completely from the water's surface to the pier's bed level, providing an additional path for the flowing water. This flow diversion allows a portion of the water to pass through the pier's immediate vicinity. When the flow comes across the Rectangular slot, it modifies direction and disperses along the pier's sides.

This flow energy redistribution serves to reduce the concentration of erosive forces at the pier's lateral edge. As a result, scour development is decreased at the pier's front and back ends, resulting in the reported 100% scour reduction in these areas. However, The measured maximum scour depth in this case was 7.46 cm as shown in Figure 4.12. Comparing this to the circular pier without a slot, and the observed 28.27% reduction in scour depth at the lateral side of the pier as illustrated in Figure 4.13 and Figure 4.14, suggests that the Rectangular slot's performance may be influenced by flow conditions specific to this area. The presence of slots effects on lateral vortex also its ability to divert and disperse the flow completely. The Rectangular slot's mechanism of scour reduction revolves around its ability to divert and disperse the flow, thereby reducing erosive forces near the circular pier. Its effectiveness is evident in achieving 100% scour reduction at the front and rear portions of the pier. However, achieving higher scour reduction percentages at the lateral side of the pier requires a deeper understanding of flow dynamics specific to this region and may involve design modifications for optimal performance.

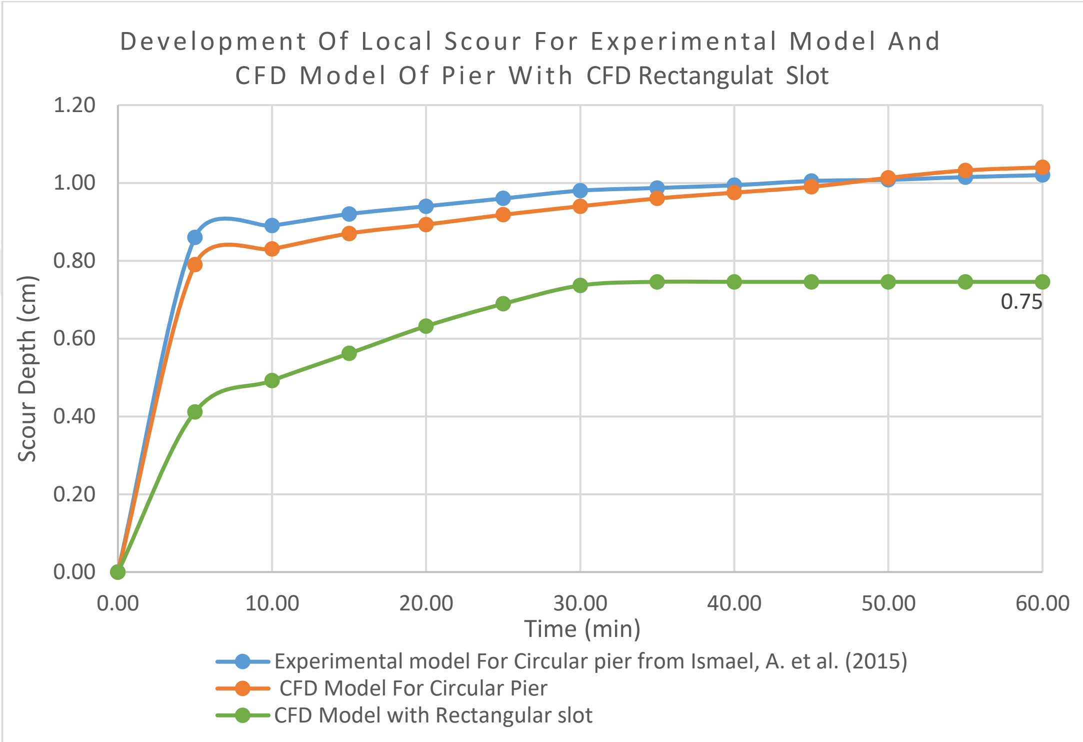
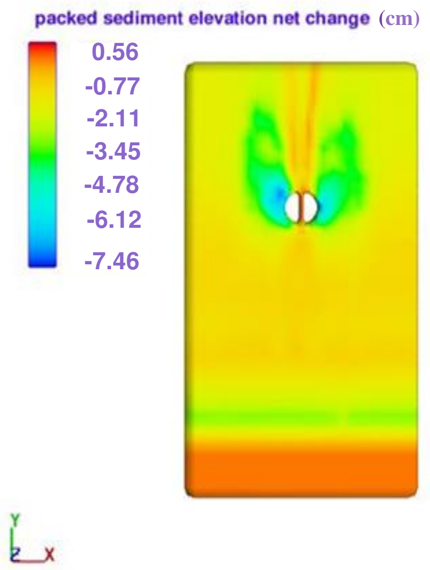


Figure 4.12 Development of local scour for experimental model and CFD model of pier with Rectangular-slot



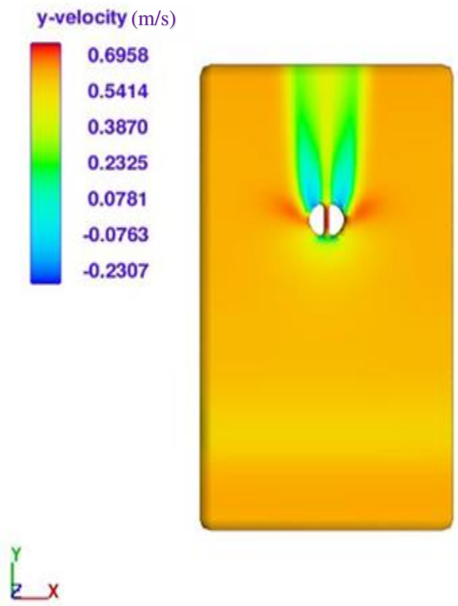


Figure 4.13 Local scour profile for CFD model pier with Rectangular-slot.

Figure 4.14 Flow velocity field profile for CFD model pier with Rectangular-slot.

4.3 Over all discussions

In this study, the findings from both experimental and computational models for all the investigated cases summarized in Figure 4.15 and Figure 4.16, which provides a comprehensive summary of. Figures 4.15 and 4.16 present a visual representation of the development and comparison of scour depths for different slot configurations around the circular pier. It allows for a clear understanding of the effectiveness of each slot configuration in reducing scour depth.

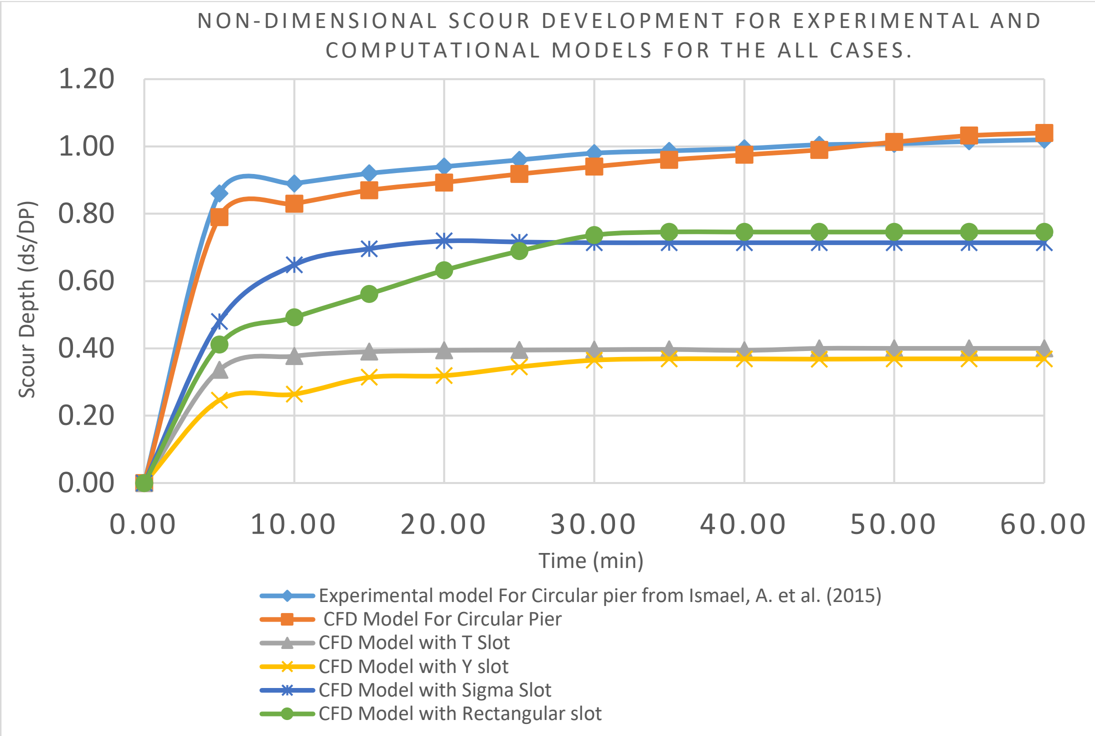


Figure 4.15 Scour development for experimental and computational models for all cases.

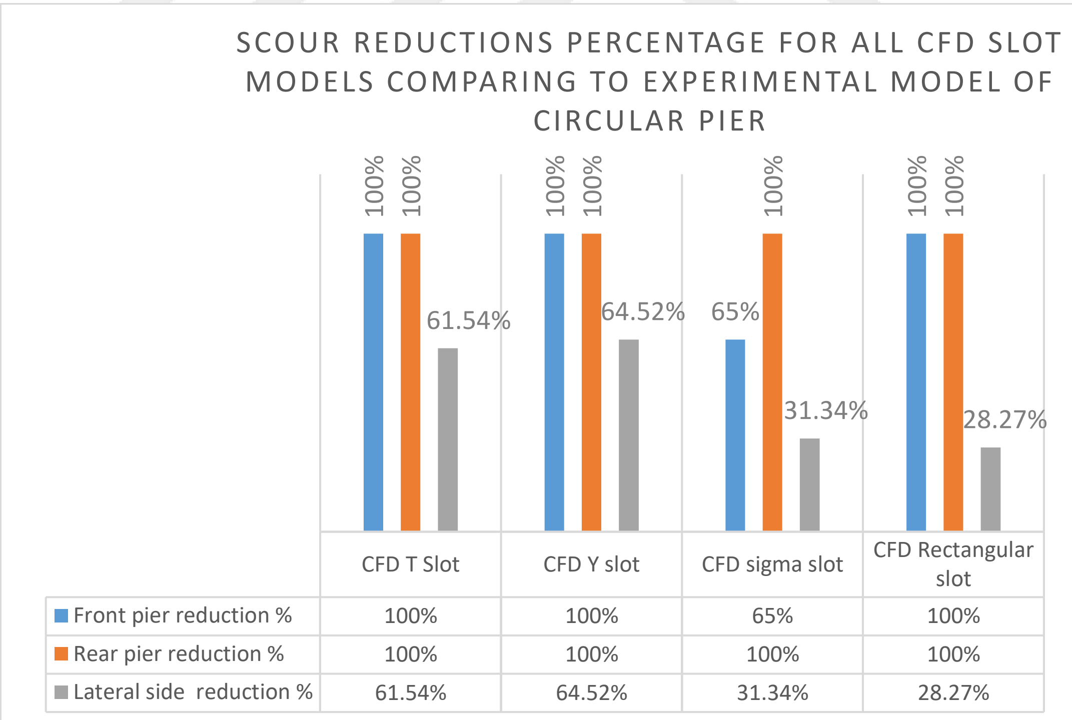


Figure 4.16 Scour reductions percentage for all CFD slot models comparing to experimental model of circular pier.

Based on the results obtained from comparing the CFD reference model of a circular pier with various slot configurations, including the T-shaped slot, Y-shaped slot, Rectangular-shaped slot and sigma-shaped slot, the following conclusions can be drawn:

The T-shaped slot proved to be effective in reducing scour depth around the circular pier. The lateral side of the pier experienced a maximum scour depth of approximately 4 cm, representing a reduction percentage of about 61.54%. The addition of the T-shaped slot altered flow patterns and reduced erosive forces near the pier, resulting in a substantial decrease in scour depth. Notably, the reduction percentage reached 100% in the front and rear portions of the pier as illustration in Figure 4.15, Figure 4.16.

Similarly, the Y-shaped slot demonstrated its effectiveness in reducing scour depth. The lateral side of the pier experienced a maximum scour depth of around 3.69 cm, indicating a reduction percentage of approximately 64.52% as illustration in Figure 4.15, Figure 4.16. The Y-shaped slot distributed the flow more evenly, diverting and dispersing it to mitigate the concentration of erosive forces near the pier. Remarkably, the reduction percentage reached 100% in both the front and rear portions of the pier.

Regarding the sigma-shaped slot, which extended throughout the entire water depth of the pier, it also exhibited effectiveness in reducing scour depth. The lateral side of the pier experienced a maximum scour depth of about 7.14 cm, resulting in a reduction percentage of approximately 31.35%. As illustration in Figure 4.15, Figure 4.16.

The installation of the Rectangular slot extends from the water's surface to the pier's bed level, creating an additional pathway for water flow. This diversion of flow along the pier's sides effectively reduces erosive forces near the circular pier, resulting in a complete 100% scour reduction at the pier's front and back ends. However, the measured maximum scour depth in this case was 7.46 cm, so achieving a 28.27% reduction in scour depth at the lateral side of the pier as illustration in Figure 4.15, Figure 4.16, which requires a more comprehensive understanding of the flow dynamics unique to that particular area. It is evident that the Rectangular slot's performance may be affected by the flow conditions specific to this region.

The sigma-shaped slot modified flow patterns, redistributing flow energy and reducing the intensity of vortices and turbulence near the pier. Although the reduction percentage was comparatively lower than the other slot configurations, it still led to a substantial decrease in scour depth. In the front portion of the pier, the reduction percentage reached 61.82%, while it reached 100% in the rear.

All of cases (the T-shaped, Y-shaped, Rectangular-shaped and sigma-shaped slots) proved effective in reducing scour depth around the circular pier. Each slot configuration altered flow patterns and mitigated erosive forces near the pier, resulting in significant reductions in scour depth. The specific reduction percentages varied, with the T-shaped slot achieving a reduction of approximately 61.54%, the Y-shaped slot achieving around 64.52%, and Rectangular-shaped achieving 28.27%, and the sigma-shaped slot achieving roughly 31.35%. These findings highlight the potential of different slot configurations in mitigating scour depth around circular piers, providing valuable insights for practical applications and engineering designs.

4.3.1 Flow field velocity around the models

A consistent average flow rate of approximately 0.058 m3/s was observed in all cases studied, resulting in an average velocity of approximately 0.58 m/s. The velocity of the flow rate upstream of the pier is shown in the Figures (4.17, 4.18, 4.19, 4.20 and 4.21) by a velocity-colored bar. However, when the flow comes across the pier, the flow behavior changes significantly when protective methods used, depending upon the type of slot implemented through the pier.

The velocity-colored bar in the Figures below represent the flow behavior before the pier in an obvious manner, showing the uniformity of the flow rate. However, when the flow patterns come across the pier with different slot types, they diverge, influencing the scour development around the circular pier. The differences in flow behavior shown in the Figures highlight the importance of slot design in modifying the flow behavior, which reducing erosive forces and vortices intensity around the bridge pier, and thus influencing the scour depth.

Typically, when a slot is present, it can influence the flow patterns and mitigate turbulence and vortex formation near the pier, consequently affecting the scouring process. The slot acts as a flow modifier, redirecting or spreading the water flow. This redirection or dispersion plays a crucial role in diminishing the strength of vortices and turbulence around the pier, thereby lowering the maximum scour depth. The T-shaped slot can create a barrier to the flow, causing the flow to be diverted away from the pier sides and reducing the scour depth in the lateral sides. On the other hand, The Y-shaped slot can provide additional pathways for the flow, distributing it more efficiently in the same direction of the main flow, that allows the outlet flow comes out faster which leads to break the vortices in the lateral sides and rear of the pier which resulting in reducing of erosive forces. The Rectangular-slot configuration stretches entirely from the water's surface to the pier's bed level, offering an extra pathway for the flowing water, like the Y-shaped slot but with a lesser impact on reducing scour depth. This is because the outflow from the Rectangular-slot is diverted in the same direction as the main flow, unlike the Y-shaped slot, which diverts the flow in two inclined paths close to the main flow direction. This flow diversion allows a portion of the water to pass through the immediate vicinity of the pier. The presence of the slot affects the weakening of the lateral vortex and its ability to fully divert and disperse the flow.

The sigma-shaped slot can affect the flow patterns around the pier in a manner similar to the T and Y-shaped slots but with less effects. By introducing additional flow paths and altering the flow dynamics by the outlet of the slot opposite to the flow direction of the flow, in this case, the sigma-shaped slot can help in reducing the intensity of vortices and turbulence around the pier, ultimately leading to a reduction in scour depth.

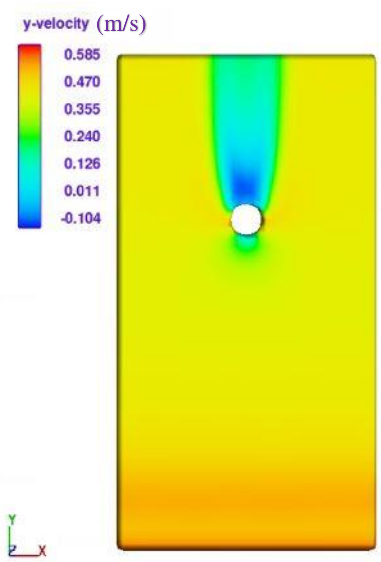


Figure 4.17 Flow velocity field for CFD reference model

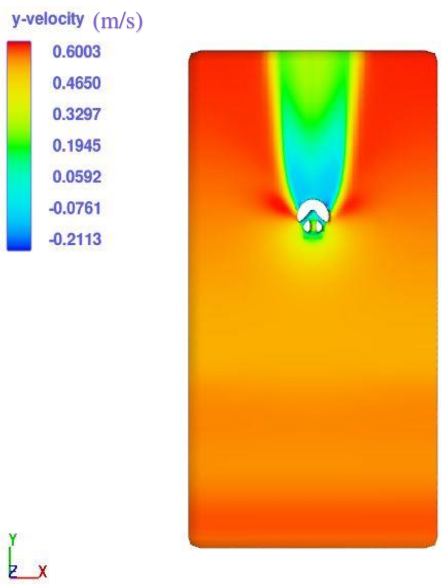


Figure 4.18 Flow velocity field for CFD model with sigma slot.

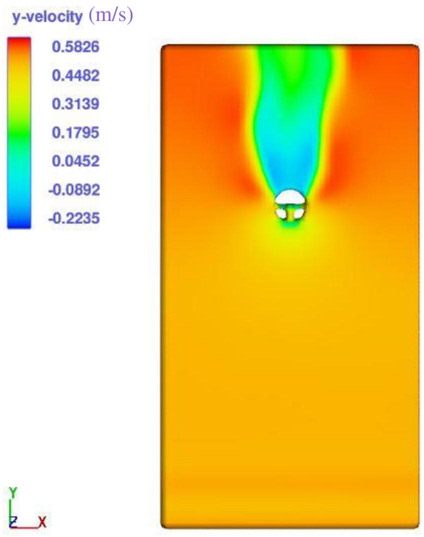


Figure 4.19 Flow velocity field for CFD model with T-shape slot.

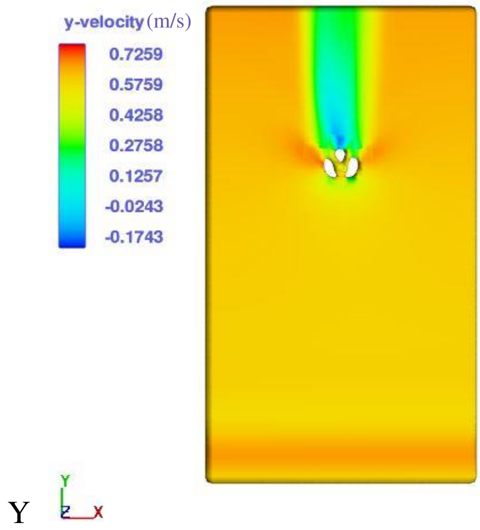


Figure 4.20 Flow velocity field for CFD model with Y-shape slot.

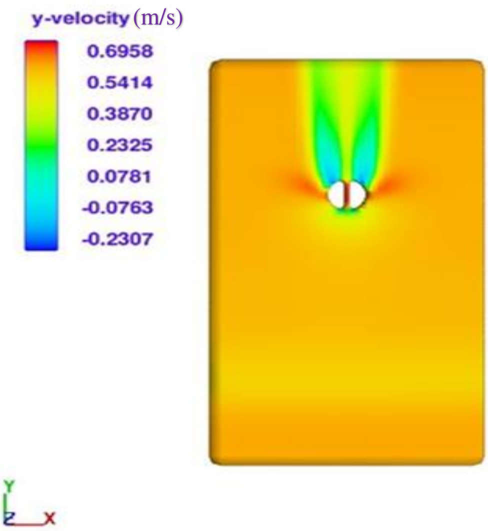


Figure 4.21 Flow velocity field for CFD model with Rectangular-shape slot

CHAPTER 5
CONCLUSION

5.1 Conclusion

Finally, a comparison of different slot layouts (T-shaped, Y-shaped, Rectangular-shaped, and Sigma-shaped) on minimizing scour depth around a circular pier produced considerable results. These slots have proven to be helpful in reducing scour depth, demonstrating their potential for practical applications in engineering designs.

- The T-shaped slot reduced the scour depth by approximately 61.54%. The T-shaped slot successfully minimized scour development by modifying flow patterns and minimizing erosive forces near the pier. Similarly, the Y-shaped slot reduced scour depth by about 64.52%, shifting flow and dispersing erosive forces. While the rectangular-shaped slot reduced scour depth by approximately 28.27%, the sigma-shaped slot lowered scour depth by roughly 31.35% while also changing flow patterns and reducing the strength of vortices and turbulence near the pier.
- The addition of a T-shaped slot resulted in a significant reduction in the maximum scour depth.
- The measured maximum scour depth was 4 cm, representing a reduction percentage of approximately 61.54% compared to the circular pier without a slot.
- The T-shaped slot altered the flow patterns and reduced erosive forces near the pier, leading to the observed reduction in scour depth and this finding highlights the effectiveness of the T-shaped slot in mitigating scour around circular piers.
- The inclusion of a Y-shaped slot led to a significant decrease in the maximum scour depth. The measured maximum scour depth was 3.69 cm, indicating a reduction percentage of approximately 64.52% compared to the circular pier without a slot.

- The Y-shaped slot modified flow patterns, improved flow distribution, and reduced erosive forces near the pier, resulting in the observed reduction in scour depth.
- These results emphasize the effectiveness of the Y-shaped slot in reducing scour depth around circular piers.
- The inclusion of a Rectangular-shaped slot along the circular pier resulted in a considerable reduction in the maximum scour depth. The measured maximum scour depth was 7.46 cm, signifying a decrease of approximately 28.27% when compared to the circular pier without a slot.
- The Rectangular-slot arrangement spans from the water's surface to the pier's bed level, creating an extra route for the flowing water. This flow diversion enables a portion of the water to pass through the immediate vicinity of the pier. As the flow encounters the Rectangular slot, it changes direction and disperses along the sides of the pier.
- The incorporation of a sigma-shaped slot throughout the circular pier led to a significant decrease in the maximum scour depth. The measured maximum scour depth was 7.14 cm, representing a reduction percentage of around 31.35% compared to the circular pier without a slot.
- The sigma-shaped slot influenced flow dynamics, redistributing flow energy, and mitigating erosive forces near the pier, resulting in the observed reduction in scour depth.
- The flow velocity field profile further demonstrated the altered flow patterns and reduced velocities near the pier due to the sigma-shaped slot. These findings indicate the effectiveness of the sigma-shaped slot in reducing scour depth around circular piers.

These findings highlight the significance of taking various slot configurations into account when designing structures to reduce scour around circular piers. Choosing the most appropriate slot configuration should be based on the specific conditions of the site and the desired level of scour reduction. To gain a more comprehensive understanding of the flow mechanisms and to enhance the design of slot configurations, additional research and analysis, including numerical simulations and experimental studies, would be beneficial.

By applying on an effective scour countermeasures, such as suitable slot configurations, offers substantial risk reduction to structures. This has important practical implications for the safety and durability of infrastructure in diverse water environments, including rivers, bridges, and offshore installations. In conclusion, the study demonstrates the effectiveness of T-shaped, Y-shaped, Rectangular-shaped, and sigma-shaped slots in reducing scour depth around circular piers. Utilizing these slot configurations can lead to more resilient and sustainable infrastructure designs, better equipped to withstand the erosive forces of water flow.

5.2 Recommendations

Based on the findings and implications of this study on the effectiveness of different slot configurations in reducing scour depth around circular piers, several recommendations can be made for future research:

- The study examined T-shaped, Y-shaped, Rectangular-shaped, and sigma-shaped slots and their impact on reducing scour depth. However, the researchers suggest that there are many other slot configurations to be explored. Future research should investigate different slot shapes, sizes, and orientations to determine the most effective configurations for specific flow conditions and sediment characteristics. This will enhance our understanding of optimal slot designs to mitigate scour depth.
- Explore Combined Slot Configurations: It would be valuable to investigate the potential benefits of combining multiple slot configurations. For example, studying the impact of a T-shaped slot in conjunction with a sigma-shaped slot or exploring the effectiveness of hybrid slot designs. This research could assess whether combining different slot configurations enhances scour reduction and flow modification around circular piers.
- Evaluate the real-world performance of various slot configurations by conducting field studies. By measuring scour depth and flow characteristics around circular piers with different slot designs, researchers can gain valuable insights into the effectiveness of these countermeasures. Additionally, such field studies would allow for an assessment of the long-term performance and durability of slot configurations under different environmental conditions.

- By addressing these areas of future research, we can enhance our understanding of the effectiveness, design optimization, and broader implications of slot configurations in reducing scour depth around circular piers. This knowledge will contribute to the development of more robust and efficient scour mitigation strategies in the field of hydraulic engineering.

REFERENCES

Akhlaghi, E., Babarsad, M. S., Derikvand, E., & Abedini, M. (2020). Assessment the effects of different parameters to rate scour around single piers and pile groups: a review. Archives of Computational Methods in Engineering, **27(1)**, 183-197

Aksoy, A. O., Bombar, G., Arkis, T., and Guney, M. S. (2017). Study of the time-dependent clear water scour around circular bridge piers. *Journal of hydrology and hydromechanics*, ***65*(1)**, 26-34.

Alabi, P. D. (2006). *Time development of local scour at a bridge pier fitted with a collar*

Anzlin, A., Prendergast, L., Gavin, K., and Limongelli, M. G. (2018). The effect of local scour of a single pier on the vibration parameters of a multi-span bridge under seismic excitation. In *Maintenance, Safety, Risk, Management and Life-Cycle Performance of Bridges* (pp. 992-999).

Brethour, J. (2001). Transient 3-D model for lifting, transporting and depositing solid material. 2001 International Symposium on Environmental Hydraulics, Tempe, Arizona (http://flow3d.info/pdfs/tp/wat_env_tp/FloSci-Bib28-01. pdf).

Breusers, H., Nicollet, G., and Shen, H. (1977). Local scour around cylindrical piers. *journal of hydraulic research*, ***15*(3)**, 211-252.

Breusers, H., Raudkivi, A. J. (1991). *Scouring*. Balkema Rotterdam.

Chabert, J., Engeldinger, P. (1956). Study of scour around bridge piers. *Rep. Prepared for the Laboratoire National d'Hydraulique*.

Chiew, Y.-M. (1992). Scour protection at bridge piers. *Journal of hydraulic engineering*, ***118*(9)**, 1260-1269.

Chiew, Y.-M., Melville, B. W. (1987). Local scour around bridge piers. *journal of hydraulic research*, ***25*(1)**, 15-26.

Chiew, Y., Lim, S. (2003). Protection of bridge piers using a sacrificial sill. Proceedings of the Institution of Civil Engineers-Water and Maritime Engineering,

Chiew, Y. M. (1984). *Local scour at bridge piers* ResearchSpace at University of Auckland.

Dailey, L. D., Meng, N., and Pletcher, R. H. (2003). Large eddy simulation of constant heat flux turbulent channel flow with property variations: quasi-developed model and mean flow results. *J. heat transfer*, ***125*****(1)**, 27-38.

Dargahi, B. (1990). Controlling mechanism of local scouring. *Journal of hydraulic engineering*, ***116*****(10)**, 1197-1214.

Dey, S. (1999). Sediment threshold. *Applied Mathematical Modelling*, ***23*****(5)**, 399-417.

Dey, S., Bose, S. K., and Sastry, G. L. (1995). Clear water scour at circular piers: a model. *Journal of hydraulic engineering*, ***121*****(12)**, 869-876.

Dey, S., Sumer, B. M., and Fredsøe, J. (2006). Control of scour at vertical circular piles under waves and current. *Journal of hydraulic engineering*, ***132*****(3)**, 270-279.

Esmaeili, T., Sumi, T., Chang, W., and Vakili, A. (2013). Application of steady flows for simulating the local scour depth under time varying flows. Proc. of the 12th ISRS Conf,

Ettema, R. (1976). *Influence of bed material gradation on local scour*. University of Auckland.

Ettema, R. (1980). Scour at Bridge Piers. University of Auckland, School of Engineering, Auckland, New Zealand, Rep. No. 216.

Flow Science, I. (2008). FLOW-3D User Manual V. 9.3. In: Flow Sci. Inc.

Ghorbani, B., Kells, J. (2008). Effect of submerged vanes on the scour occurring at a cylindrical pier. *journal of hydraulic research*, ***46*****(5)**, 610-619.

Graf, W. H., Altinakar, M. S. (2017). Local scour. *River System Analysis and Management*, 145-166.

Grimaldi, C., Gaudio, R., Calomino, F., and Cardoso, A. H. (2009). Control of scour at bridge piers by a downstream bed sill. *Journal of hydraulic engineering*, ***135*****(1)**, 13-21.

Ismael, A., Gunal, M., Hussein, H. (2015). Effect of bridge pier position on scour reduction according to flow direction. *Arabian Journal for Science and Engineering*, **40(6)**, 1579-1590.

Keshavarzi, A., Shrestha, C. K., Zahedani, M. R., Ball, J., and Khabbaz, H. (2018). *Experimental study of flow structure around two in-line bridge piers.* Proceedings of the institution of civil engineers-water management,

Khademi, U., Wahab, A. K. B. (2005). mechanism of local scour and reduction of this phenomenon around hydraulic structures.

Kim, U.-Y., Kim, J.-S., AHN, S.-J., and hahm, C.-H. (2005). Scour countermeasure using additional facility in front of bridge pier.1289-1290.

Kirby, A. M., Roca, M, Kitchen, A, Escarameia, M, and Chesterton. (2015). Manual on scour at bridges and other hydraulic structures. *Second edition. ciria c742, rp987.*

Kumar, V., Raju, K. G. R., and Vittal, N. (1999). Reduction of local scour around bridge piers using slots and collars. *Journal of hydraulic engineering*, ***125*(12)**, 1302-1305.

Lagasse, P., Schall, J., and Richardson, E. (2001). Stream stability at highway structures: Hydraulic Engineering Circular No. 20. In: FHWA NHI.

Lagasse, P. F., Richardson, E. V. (2001). ASCE compendium of stream stability and bridge scour papers. *Journal of hydraulic engineering*, ***127*(7)**, 531-533.
Landers, M. N. (1992). Bridge scour data management. *USGS Staff--Published Research*, 141.

Laursen, E. (1958). Scour at Bridge Crossings, Iowa Highway Research Board. *Bulletin*, *8*.

Laursen, E. M. (1962). Scour at bridge crossings. *Transactions of the American Society of Civil Engineers*, ***127*(1)**, 166-180.

Laursen, E. M., Toch, A. (1956). *Scour around bridge piers and abutments* (Vol. 4). Iowa Highway Research Board Ames, IA.

Lee, G. C., Mohan, S., Huang, C., and Fard, B. N. (2013). *A study of US bridge failures (1980-2012)*. mceer Buffalo, NY.

Lichtenstein, A. G. (1993). The silver bridge collapse recounted. *Journal of performance of constructed facilities*, ***7*(4)**, 249-261.

Lu, J.-Y., Su, C.-C., Hong, J.-H., and Chen, E.-J. (2012). Prediction of maximum general scour depth during a flood for intermittent rivers. Proc. of 6th International Conference on Scour and Erosion,

Mashair, M., Zarrati, A. R., and Rezayi, A. (2004). Time development of scouring around a bridge pier protected by collar. 2nd International Conference on Scour and Erosion, ICSE-2, Singapore,

McIntosh, J. (1989). Use of scour prediction formulae. Proceedings of the Bridge Scour Symposium, McLean, VA, Federal Highway Administration Research Report FHWA-RD-90-035,

Melville, B. W. (1975). *Local scour at bridge sites* researchspace@ auckland].

Melville, B. W., Chiew, Y.-M. (1999). Time scale for local scour at bridge piers. *Journal of hydraulic engineering*, ***125*(1)**, 59-65.

Melville, B. W., Coleman, S. E. (2000). *Bridge scour*. Water Resources Publication.

Mia, M. F., Nago, H. (2003). Design method of time-dependent local scour at circular bridge pier. *Journal of hydraulic engineering*, ***129*****(6)**, 420-427.

Molinas, A. (2004). *Bridge scour in nonuniform sediment mixtures and in cohesive materials: Synthesis report*.

Morgese, M., Ansari, F., Domaneschi, M., and Cimellaro, G. P. (2020). Post-collapse analysis of Morandi's Polcevera viaduct in Genoa Italy. *Journal of Civil Structural Health Monitoring*, *10*, 69-85.

Neill, C. R. (1973). Guide to bridge hydraulics. University of Toronto Press, Toronto, ON, Canada

Nuti, C., Briseghella, B., Chen, A., Lavorato, D., Iori, T., and Vanzi, I. (2020). Relevant outcomes from the history of Polcevera Viaduct in Genova, from design to nowadays failure. *Journal of Civil Structural Health Monitoring*, *10*, 87-107.

Palau-Salvador, G., Stoesser, T., Fröhlich, J., Kappler, M., and Rodi, W. (2010). Large eddy simulations and experiments of flow around finite-height cylinders. *Flow, turbulence and combustion*, *84*, 239-275.

Parker, G., Toro-Escobar, C., and Voigt Jr, R. L. (1998). Countermeasures to protect bridge piers from scour.

Pearson, C., Delatte, N. (2006). Collapse of the Quebec bridge, 1907. *Journal of performance of constructed facilities*, *20*(1), 84-91.

Peng, K. (2019). Risk evaluation for bridge engineering based on cloud-clustering group decision method. *Journal of performance of constructed facilities*, *33*(1), 04018105.

Raleigh, A. (2015). How to mitigate the effects of scour on bridge piers through the use of combined countermeasures.

Rambabu, M., Rao, S. N., and Sundar, V. (2003). Current-induced scour around a vertical pile in cohesive soil. *Ocean Engineering*, ***30*****(7)**, 893-920.

Richardson, E. V., and Davis, S. R. (1995). *Evaluating scour at bridges*.

Shen, H. W., Schneider, V., and Karaki, S. (1966). Mechanics of local scour.

Shen, H. W., Schneider, V. R., and Karaki, S. (1969). Local scour around bridge piers. *Journal of the Hydraulics Division*, *95*(6), 1919-1940.

Singh, C., Setia, B., and Verma, D. (2001). Collar-sleeve combination as a scour protection device around a circular pier. Proceedings of the congress-international association for hydraulic research,

Stevens, M. A., Gasser, M. M., and Saad, M. B. (1991). Wake vortex scour at bridge piers. *Journal of hydraulic engineering*, *117*(7), 891-904.

Tafarojnoruz, A., Gaudio, R., and Dey, S. (2010). Flow-altering countermeasures against scour at bridge piers: a review. *journal of hydraulic research*, *48*(4), 441-452.

Tison, L. (1961). Local scour in rivers. *Journal of Geophysical Research*, ***66*****(12)**, 4227-4232.

Toth, E., Brath, A., and Montanari, A. (2000). Comparison of short-term rainfall prediction models for real-time flood forecasting. *Journal of hydrology*, ***239*****(1-4)**, 132-147.

Vittal, N., Kothyari, U., and Haghighat, M. (1994). Clear-water scour around bridge pier group. *Journal of hydraulic engineering*, ***120*****(11),** 1309-1318.

Younis, B. A., and Zhou, Y. (2006). Accounting for mean-flow periodicity in turbulence closures. *Physics of Fluids*, ***18*****(1)**.

Zhang, G., Liu, Y., Liu, J., Lan, S., and Yang, J. (2022). Causes and statistical characteristics of bridge failures: A review. *Journal of traffic and transportation engineering (English edition)*.

CURRICULUM VITAE

OBADA RAKIA

YEAR	EDUCATION	GNO
02/2021- 09/2023	**Master Degree in Civil Engineering**	**3.5**
GAZIANTEP UNIVERSITY, GAZIANTEP,	TURKEY	
09/2015 – 01/2021	**Bachelor Degree in Civil Engineering**	**2.42**
GAZIANTEP UNIVERSITY, GAZIANTEP,	TURKEY	