“Experimental investigation of scouring around spur dyke using several shapes and sizes”

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This is to certify that the final year project entitled

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I certify that research work titled is my own work. The work has not been presented elsewhere for assessment. Where material from other sources has been used, it is properly endorsed/referenced.

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Abstract

Spur dikes are installed to ensure the main mitigation channel while also preventing erosion on riverbanks. The most dangerous and ultimate threat to spur dike failure is the scour around spur dike. To lessen scouring around spur dikes, various supplementary constructions like "collars" are used. It is difficult to navigate the River banks around spur dikes, particularly when they are in the straight position. In this study several experiments were conducted using variously shaped collars as well as inclinations (45°, 90°, and 135°) to reduce scouring around the spur dike. The results show that when the inclination of the spur dike increases, the minimum scour depth, as well as the volume and dimensions of the scour hole, decrease. Additionally, when collared spur dykes are used, scouring depth is decreased in comparison to non-collared SDs with inclination. The Rectangular Spur Dyke with 45ºC inclination has the deepest scour levels. Compared to spur dyke without inclination, scouring for 135ºC inclination showed a maximum 53% reduction after equilibrium. The outcome demonstrated that collars used along with spur dike can lessen the severity of the flow features and the depth of the scour. It has also been observed during several experiments that the shape of collar has notable effect on the reduction of scouring because the values of maximum scour are minimum in case of spur with circular collar and maximum in case of trapezoidal shaped collar.

Keywords: Collar, Local Scouring Spur dykes (SDs), Spur inclinations

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Introduction

1.1 General

To stop river banks from eroding and to support the aquatic habitat, spur dikes, a type of stream construction built from the river bank into the stream flow, are used (Atarodi et al., 2021). Spur embankments, a type of stream development constructed from the waterway bank into the stream, play a vital role in preventing the damage of channel banks and fostering the marine ecology (Atarodi et al., 2021). Scouring close to a spur nose is a major problem that contributes to the deficiencies of these designs. High flow water hits the spur that are prone to erosion. Near stream structures, characteristics of the stream typically change, creating a descending stream. Then, at the tips of the such structures, a few vortexes known as vortex tubes appear individually. These vortexes and the erodible bed silt work closely together to produce the strange scouring pattern around the structure (Copeland, 1983). Scouring of the inflow occurs frequently on surfaces that are prone to erosion. Inflow speed and strain values typically change in close proximity of stream structures, resulting in an unfavorable inflow. The whirlpool's serious activity with the alluvium in the erodible bed causes the scouring impact (Ghiassi and Abbasnia, 2013). Scouring can be classified into three types, which are local scour, contracting scour and aggradation or degradation.

Scouring around obstructions in Channel is known as local scouring. Local scouring occurs due to the formation of vortices around obstacles when unidirectional flow changes to three-dimensional flow within the erodible channel. On the other hand, scouring caused by channel contraction is called contraction scouring.

Figure 1.1: Spur dike fields; Odra River in Poland

A third type of scour, called aggradation or degradation, also known as general scour, occurs on movable bed. General scour occurred mainly due to natural phenomena such as climate change and land activity, or due to human activities such as mining river bed materials and building reservoirs.

The local scouring creates a hole around the tip of the spur dike that causes the failure of such structures. Localized scour at the nose of the spur is primarily caused by downward flow generated along the upstream side of the spur, resulting in the formation of a horseshoe vortex and wake vortex at the base of the spur as shown in figure 1.2. Equilibrium scour depths around spurs have been determined by numerous laboratory and computer experiments. Much of the work focuses on the depth at which alluvial sand beds reach equilibrium scour.

Consequently, the design methodology and some example scenarios are provided for illustration. There is no better way to calculate the uniform deposition limit condition for than the Shields diagram. Time-dependent scouring depths have been estimated by various researchers. Bed armoring and inflow alteration are the two straightforward countermeasure approaches that can stop or lessen local scouring around in-conduit structures. In order to stop erosion, the bed of the channel is typically covered with riprap or other hard materials. Further, in order to reduce scour depth, a definitive methodology adjusts the inflow bearing by using a careful design similar to a protective spur embankment and collar (Karami et al., 2018). Many academics have promoted the use of projections, lowered vanes, and collars around spurs as scouring retarder which can act as a barrier to the depressing influx (Gupta et al., 2010). Comparing restoration works like structures with a collar to other countermeasure methods like riprap would be wiser given that riprap basics are less effective against various setbacks and removals during cutting-edge releases than the plan release, which is the point at which the collar would be steady. According to the literature, it is practical to use collars, and perfect cutting-edge plates can only be placed around the design during the construction of the in-stream structure. Several studies have been completed on the use of collars to guard spur dikes and projections against scouring. Actually, the use of the types and shapes of collars on embankments has not been investigated.

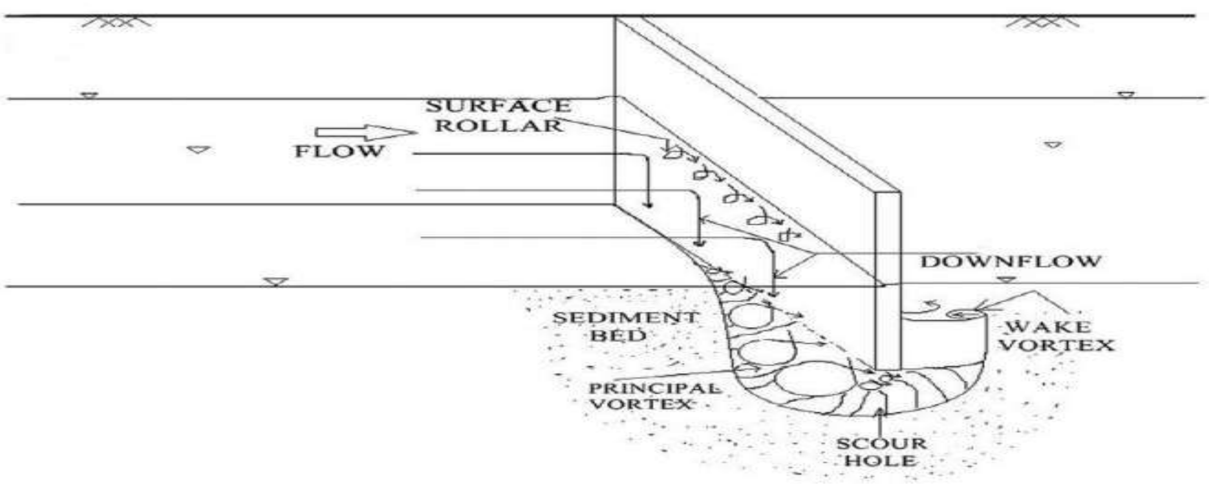

Figure 1.2: scouring around spur dike

Many researches therefore aim to (1) examine the effects of collar, region, size, and height to find an ideal collar execution condition and, (2) evaluate the functionality of the Taguchi framework to brush preliminary elements, and (3) consider the collar performance unidirectional (Kumcu et al., 2014). Researchers encouraged a movement of estimated techniques to check the scour depth at various formed barriers under various stream elements, size, and separation.

Numerous exploratory analysis of the hydraulic structures in alluvial streams have been conducted. A series of tests were completed to examine the scouring technique from various angles in relation to the stream hub. For hydraulics engineers, the bed erosion caused by stream inflows is generally an inconvenience and dangerous problem. The form and tendency of the flow, as well as the state of the collar attached, and the location of scour depth, have all been determined by previous assessments to have a significant impact on the scouring around spurs that draw water toward it and streams downstream is said to be engaged. The angle of the downstream divergence varies. It is pertinent to mention that spurs can be classified into major 3 types. The attracting spike directs the waterway's whole force toward its upstream side, which should unquestionably be fully protected. The downstream inclination does not require any additional safety measures. It works even better when integrated into a general arrangement. Construction along the riverside stops the scour opening.

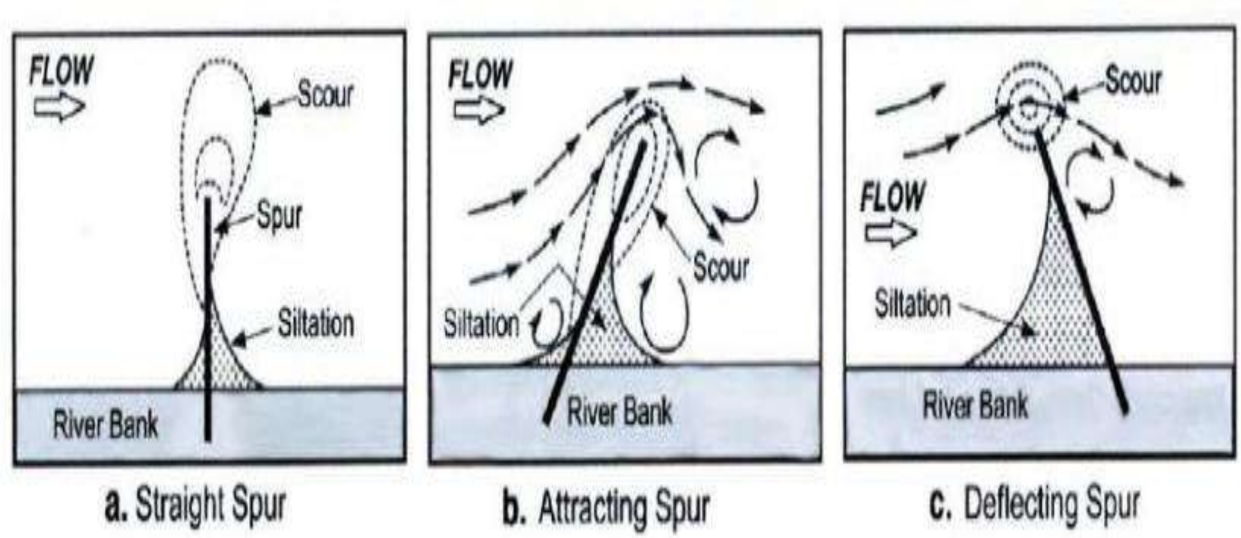

Figure 1.3: Types of spur dikes

A short, upstream spur known as a deflecting spur modifies the direction of the flow without repelling it. It indubitably increases the banks safety. A typical occurrence on substrates that are prone to erosion is scouring. When in stream structures are hit by the flow speed and strain values frequently exchange, resulting in a vortex flow. Areas of strength for the vortexes with erodible bed textures are what cause the scouring characteristic surrounding the structure (Ghiassi and Abbasnia 2013). The most serious concern that could lead to their failure is the placement of obstruction in the middle of a flood stream. The soil disintegration caused by water is the primary cause of the pinnacle's collapse. The vast majority of streams on earth have numerous branches. The effect of turbulence on scouring is still a major problem and point of discussion which need to be discussed and researched in the future.

1.2 Problem Statement:

Scouring around spur dike which are popular guide banks structures is a major concern for hydraulic Engineers. In spite of widespread work being done on the local scouring around spur dikes, and different methods being initiated to control scouring like collars, protective spur dikes and armoring, a little work has been done on finding the collars effects on scour depth around spur dike. This research focuses on investigating combined effects of collar shapes and junction angles on scour depth around spur dikes and thus determining an optimal condition for the best collar performance against local scour under different flow condition.

1.3 Objectives

The main objectives of this investigation are:

- .

1.4 Utilization and scope

Spur dikes are structures made to direct water away from an erodible banks and make a suitable channel for flow diversion, flood management, outdoor wall protection, and other purposes. A weir is a form of canal modification that scour the channel and narrows the water pass-phase, increasing flow rate. At the same time, it enhances river ecosystems and safeguards natural range. Earth center dikes are upstream-facing spurs with a submerged stone tip and a middle section of stone-armored soil. Stone spurs known as "live surges" have an earthen prism on top that is reinforced with living fascines. Numerous investigations on spur dykes with various collar widths were done in earlier works. Testing was done to focus on the scouring process from around spike embankment at various positions relative to the stream axis. For engineers working with water, bed failure caused by stream force is a common source of difficulty and danger. The location of the maximum scour depth is greatly influenced by the spur dike's angle of inclination, shape of the collar attached, and scouring has been shown to be significantly influenced by the shape and inclination of spurs. Spur length and collar length are more important in preventing spur dyke scour than collar shape. Our study focuses on scouring evaluation with different collar designs and spur dyke inclinations at different angles (45^o, 90^o, 135^o).

1.5 Thesis Layout

This thesis comprises of five chapters and their overview is explained below.

- The arrangements are such as the first chapter includes an introduction about purpose of the project and objectives to achieve.
- Chapter two deals with the literature review. The second chapter includes a brief literature review on Experimental investigation of the effects of collars on scour depth around spur dike. It shows a comprehensive study of what kind of research work has been carried out so far in the field of investigating the effects of collars on scour depth around spur dike.
- The third chapter explains the research plan as well as methodology explaining how to accomplish the objectives of the study.
- The fourth chapter includes the results and analysis of results obtained experimentally for the scour reduction around spur dikes using several collars and changing the junction angle.
- The fifth chapter presents the summary, conclusion and final recommendations of the research.

Chapter 2

Literature review

Bank disintegration is considered one of the world's most critical problems. Scour is one of the phenomena which occurs because of high flowing water due to obstruction or hindrance raised in the path of flow and other hydraulic structure in river or stream. When high flow water passes through or near the obstructions, the vortex flow creating vortices is created at the nose and sides of that obstruction because of velocity of mean flow. This vortices phenomena is what causes scoring. The flow level at the front of the spur is increased which creates a hole around the obstruction or spur. Different countermeasures, such as linings made of various materials, the construction of extremely durable areas (heavy banks), and the placement of penetrable and impermeable structures are typically used to protect riverbanks (Ghaderi and Abbasi, 2019). According to previous research, nearly all frameworks degrade completely or partially when exposed to the main channel.

Construction of hydraulic structures in the middle of rivers and aquatic environments affects natural flow, altering flow and sediment movements, leading to local scour. Flow obstruction by spurs can be either caused by the flow changing its natural state or by following the principle of ``moveable'' boundary hydraulics (Khaple, Hanmaiahgari, and Dey 2018),or by the three-dimensional inflow around spur dike ultimately leading to local scour.

Local scour can be divided into two categories such as clear-water scour and live bed scour. Erosion of bed material plays an important role as it disturbs and damages the base of the structure. The creation of scour holes around spur specially at the tip and the relation between the scour depth and flow velocity is affected by sediment transport such as bed material load.

2.1 Detailed Summary of Literature Study

Following literature has been studied and mentioned in tabular format for the study of scouring around spur dikes.

Sr. No.	Paper/ Author	Summary
01	Three Dimensional Flow Characteristics in Slit-Type Permeable Spur Dike Fields/(Hasegawa, Nakagawa, Takebayashi, & Kawaike, 2020)	In order to be used in morphologically dynamic alluvial rivers, this work aims to develop efficient methods for building high-permeability pile spur (or slot) dike fields. The findings demonstrate that the approach speed of the flow within the spur area can be greatly reduced by employing a sequence of slotted spurs. This kind of spur dam has the ability to lower backside shear stress, turbulence depth, and near-shore longitudinal speed. The findings demonstrate that the suggested development produces less scour (low bed shear strain) and float intensification when compared to a desired impermeable spur.
02	Reduction of Bend Scour by Setting Spurs in a Curved Channel/(Shih & Lai, 2020)	In addition to having a high float during storm season, Taiwan's rivers are also rapidly eroding their beds. In order to study erosion brought on by indirect flow, the observer conducted a smaller-scale laboratory experiment. Long-term speed encourages lateral erosion, as seen by the flow's effects on a nearby attitude at the concave financial institution. After the spurs are constructed, the velocity at the downstream spurs is decreased. Even while the cost of abrasion

		mitigation and the protective effect diminish as velocity increases, a good defensive impact is nevertheless usually present. The effects of setting the spurs are as follows: the front spur develops with the highest degree of abrasion.
03	Experimental Investigation of Scour Reduction Around Spur Dikes by Collar Using Taguchi Method **(2021)**	In first stage of this research, experimental data was gathered based on a Taguchi mixed experiment design (L18). Through Taguchi analysis, optimal situation of collar performance had been obtained. Further, analysis of factors showed that collar elevation, area and spur inclination had prominent effects on the scour depth reduction.
04	Numerical Simulation of the effect of L-shaped spur dike wing length on scouring at a 90° bend/(Rasaei, 2022)	The organization and management of erosion along a riverbank frequently involve the usage of spur dams. When powerful currents are diverted from the coast and channeled toward the river axis, the flow pattern and forward leap through the dam are also changed. This study aims to numerically investigate the impact of modifying the period of the L-formed Spur wing on the strength of the 90° bend inside the channel. The 3-dimensional numerical model SSIIM was utilized for simulation. The maximum depth and length of scour across the spur dike were reported at an angle of 90° with a period to internet ratio of 0.50 after comparing the numerical version outputs to laboratory data.
05	Stream bank stabilization	Skim adjustment strategies have been utilized for many years and are

	design, research, and monitoring: The current state and future needs/(Bigham, 2020)	as yet an incessant waterway control approach utilized with the help of global trained professionals. They increment confined shear energy as well as diminish dire tensions at the development monetary organization. The objective of this writing audit is to recognize normal early course adjustment monetary foundation draws near. The accompanying exploration objectives were distinguished to work on the plan and execution of stream bank adjustment methods: I to gauge and measure the spatiotemporal impacts of settling procedure on bank disintegration, power through pressure, dregs conveyance, and environments, and (ii) to keep on further developing mathematical riverbank adjustment configuration approaches to research and control those impacts totally. It is recommended that future seminars on stream dependability address these exploration necessities. (i) utilize a predictable strategy terminology, (ii) describe the philosophies and channels explored, (iii) give support for the trial plan, and (iv) make sense of how the outcomes will work on the plan of circling monetary organization adjustment.
06	Study of Scour and Flow Patterns Around Triangular-Shaped Spur Dikes **(2020)**	In the present study, the scour patterns developed around triangular spur dikes were examined under different hydraulic conditions and compared these patterns with those obtained for common type of spur dikes (rectangular spur dikes). The three-dimensional velocity components around triangular and rectangular spur dikes were also measured.

07	Evaluation and forecasting of the depth of temporal scour along a spur dike.	Because of the erosive activity of enacted water, scouring is a typical phenomenon that occurs in streams. Throughout a development, prod embankments are erected to prevent disintegration and make it easier to divert the stream away from the bank. Due to the disintegration and disintegration of the stream bed, a spike levee is deteriorating, and as a result, many specialists have been unable to determine the cause of the washing peculiarity and to predict the time and most critical investigation close to prod embankments. This email provides a convincing high-level overview of the trips across the spike dykes, complete with all relevant capacity credits, such as washing time and power, float example, and boundaries affecting scouring the anomaly.
08	Experimental study of local scour around T-shaped spur dike in a meandering channel.	A prod dam is basically used to forestall bank disintegration and is molded like a waterway preparing shape. At the point when a barrier is raised in a channel twist, scour turns out to be more extreme. Subsequently, an exploratory review was done to assess the neighborhood scour process encompassing a T-formed prod barrier introduced at different areas along the external bank (or inward). A retrogressive wandering channel. To process the timing and most extreme power of neighborhood forward leap as a component of the strategy drift's Froude assortment and the place of the prod weir, no-layered exact conditions were made. Nearby scour has been believed to increment with expanded Froude number and situating along the dam. Wander (the distance between the entrance and the wander)

		(estimated from the entryway to the wander).
09	Flow behavior concerning bank stability in the presence of spur dike- a review/(Pandey, Ahmad, & Sharma, 2018).	Stream in streams and waterways dissolves the banks consistently, bringing about channel bank removal horizontally and an absence of encompassing area. A spike barrier is a water powered creation that projects outward from the channel bank to coordinate or divert the float away from the bank, shielding it from disintegration. These choppiness boundaries, not entirely set in stone, are basic to dregs transport along the waterway base and from its banks. Prod dams are enormous stream preparing gadgets that are worked along waterway banks to forestall disintegration. This work examines various uses of spike weirs, including their calculation, actual properties, plan components, stream rate, and washing designs. How much writing regarding the matter of tempestuous elements and leakage profundity encompassing a barrier, The area of vegetation and the effect of drainage encompassing the dyke stay obscure subjects
10	Investigation of Scour and Stream Examples around Three-sided Molded Prod Barriers/ (Bahrami-Yarahmadi, Pagliara, Yabarehpour, & Najafi, 2020)	Dams are water structures built perpendicular to erodible riverbanks to divert float toward the centre channel in order to reduce and regulate river financial institution erosion. A blow-through hollow near the tip of the spur dam might cause structural failure. There are constraints in the layout guidelines for this newly proposed shape. In this work, scour patterns formed around triangular spur levees were investigated and compared to those obtained for typical types of spur dikes under various hydraulic conditions (square spur dikes). In terms

		of numbers, the most intense and volume of the common drilled hole It was 44% and 70% lower in the first example than in the second.

Past exploration has shown that a wide range of frameworks experience incomplete or complete breaking down when presented to the fundamental channel. Nearby washing is worked with by incline float, posterior structure removal, speedy silting, or downstream disintegration. The discoveries show that the proposed development significantly decreases scour (low bed shear), stream heightening, and strain when contrasted with a run of the mill impermeable spike (Han et al., 2022).

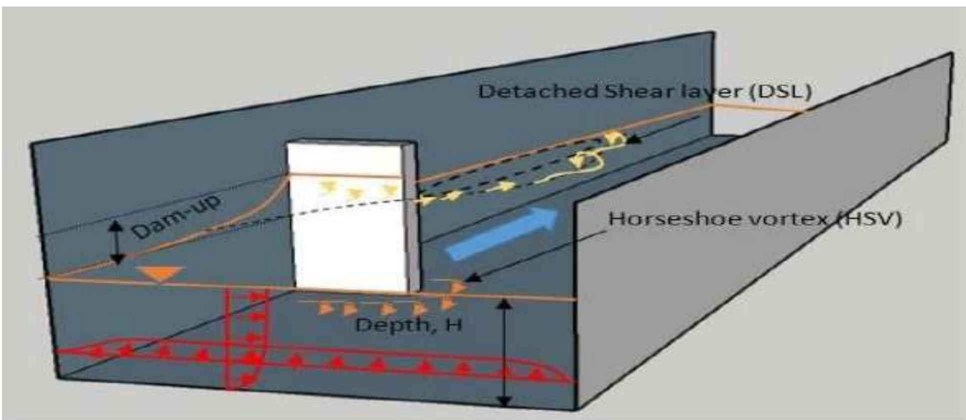

Figure 2.1: Conceptual description of flow around spur dike

The front of a tsunami is characterized by rapidly enlarging tide stages and beat variants. It is caused under specific conditions by non-direct tsunami contortion. The unsettled water stretch can be more noticeable than 10 m due to a steep bend in the stream or obstruction by homes. This study used field assessments and mathematical analyses to examine the characteristics of washing caused by sea surges over a coastal levee. The scours surrounding the spike dam can be classified as upstream feature scour and dam head panning, according to the discoveries. The weir head and upstream wrinkle's power were properly defined using the least squares approach. Because of the steep terrain and abundant rainfall, Taiwan's rivers run quickly and release a lot of water. Rivers ruin many watersheds with steep slopes due to free dirt during the rainy season. Following the installation of the spurs, the speed at the spurs along the glide path decreases, and the element with higher velocity ascends. Furthermore, the price of washout volume reduction after installing spurs is 7.97% of the 10-year go back time and 4.65% of the 20-year duration, respectively. The front spur is employed while the most cleaning posture is retained a distance from the shore. Ultimately, when compared to the unique go with the flow subject, the waft can be reduced by 35%-40%.

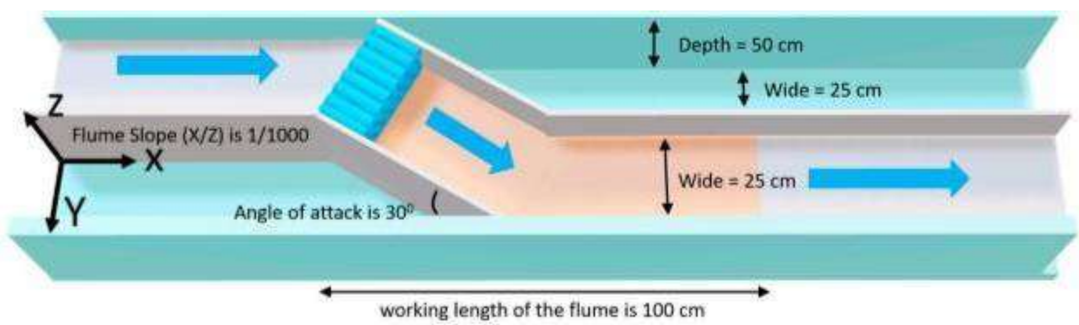

Figure 2.2: Schematic diagram of experimental channel

A tidal bore is the front of tidal waves with rapidly increasing tide stages and tempo variations. Under certain conditions, it is miles caused by non-linear tidal wave distortion. In the case of a sharp bend in the river or obstruction by houses, the agitated water column can be greater than 10 m. This study explored the characteristics of washing around a spur levee caused by tidal bores using field measurements and model experiments. According to the findings, the scours around the spur dike can be classified as dike head panning and upstream facet scour. The least squares method produced an appropriate formulation for the intensity of the weir head and upstream furrow.

A spur dam is a common structure used to control and organize erosion on the Flask River. This phenomenon must be considered and, in some way, stabilized and protected by utilizing the river financial institution. The goal of this study was to conduct a numerical investigation. The effect of adjusting the length of the L-formed Spur wing at the penetration depth in a 90° bent channel. In

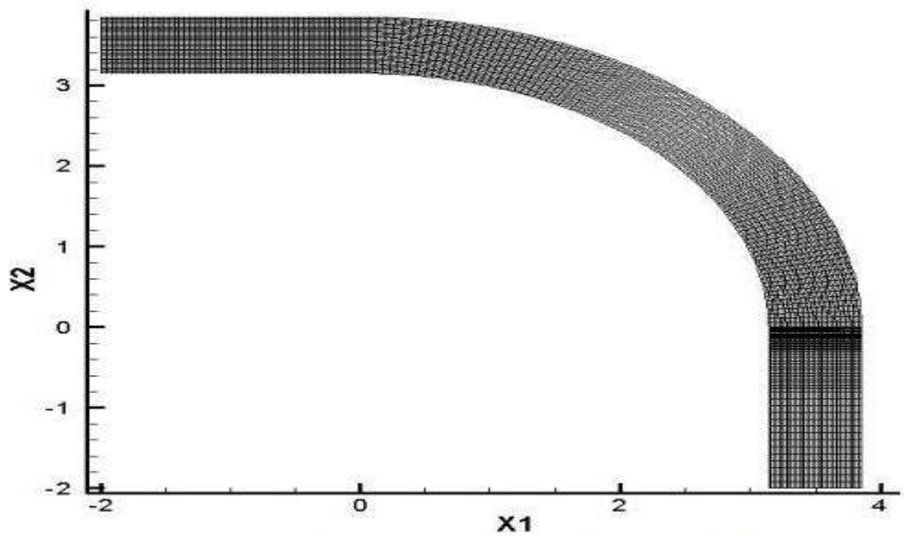

Figure 2.3: Local Scouring around spur dike

Figure 2.3: M. Rasaei Chanel Mesh Network

this situation, the 3-dimensional numerical model SSIIM was used for simulation. Maximum scour severity and extent have also been measured along the 90° spur dike, with a duration-to-internet ratio of 0.5.

Stream bank erosion is a natural and significant geomorphic process that dissipates flow strength while simultaneously supplying sediments and organic detritus required for the development, repair, and diversification of aquatic habitats. The stream erosion is influenced by the shear strength of the stream as well as the gravitational and hydraulic forces acting on it. Stabilization of circulation financial institutions is a method for accelerating recovery. Stream financial institution stabilization is defined as a single approach or collection of strategies that maximizes the shear energy of circulate banks and/or reduces the forces acting on the circulate bank in order to prevent or lessen lateral retreat Stream financial institution stabilization structures are the most ancient and widely used river control tool, with practitioners assessing and quantifying the spatiotemporal effects of circulation financial institution stabilization practices on bank erosion, hydraulics, sediment delivery, and habitat.

Figure 2.4: Spur dikes for stabilizing purpose

Spur dams are hydraulic constructions that help rivers learn and defend banks. The enticing dam is placed parallel to or at an angle to the drift direction within the channels. A tow barrage has two functions: it slows glide velocity and protects channel banks. Spur dikes might vary in shape, height, and construction material, but they all serve the same purpose: to offer coast protection within a specific canal reach.

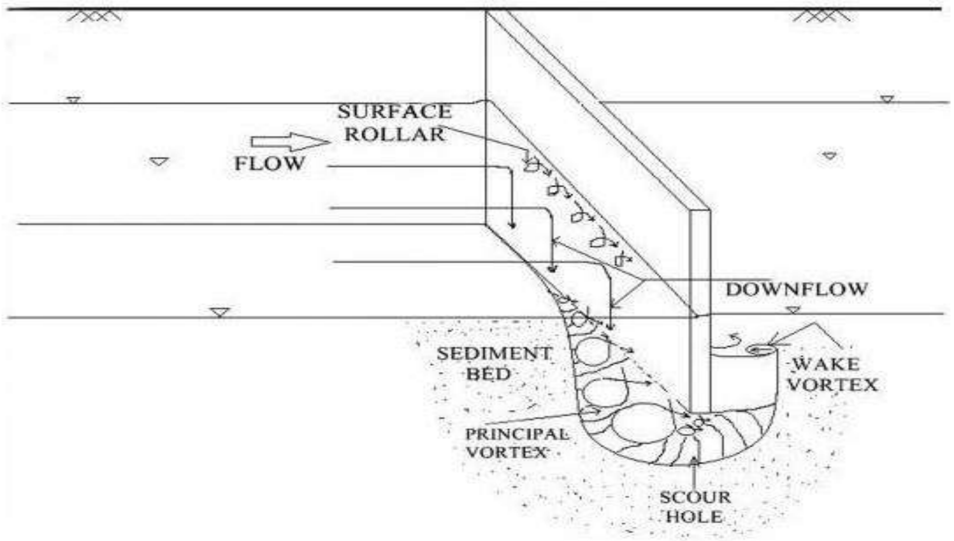

Figure 2.5: Diagrammatic representation of flow processes around spur dike

The failure of spur levees due to local erosion has prompted numerous academics to examine the cause of the erosion phenomenon and forecast the temporal and maximum breaching depth close to dikes. Washing time and depth, waft pattern, and washing parameters are all viable aspects. The incidence became briefly mentioned. The primary issues that must be addressed effectively on erosion approaches on the bed and banks of natural rivers, as well as artificial canal irrigation or navigation channels

There to ensure effective water control. Spur weirs are hydraulic structures that are commonly used to deflect drift and protect canal banks from erosion. The investigation of scouring methods around spur dams is critical for river training because it can provide practical recommendations for hydro engineers and practitioners to employ for the most advantageous operation and management. In fluvial hydraulics, adjacent scour is defined as the removal of sediment debris from alluvial streams. The scientists conducted physical tests in a flume-based completely study to collect new data with the goal of building and comparing a brand new predictive model for spur die scour with others discovered in the literature.

Figure 2.6: Spur dikes in series

A spur we *Figure 2.6: Schematic diagram of spur weir* ypically used for river education. It directs the circulation or flow away from the bank, protecting it from erosion. A spur weir limits the waft in the channel, disrupting the cutting-edge field surrounding it. This turbulence surrounding the structure is caused by a distortion within the flow discipline (or drift area). As a result, an experimental study to evaluate the adjacent scour method surrounding a T-shaped weir located at various points along the outer bank (or concave) of an opposing meander channel was completed. The maximum washing depth was also examined using experimental facts from the literature addressing the one hundred eighty bend, and it became determined that the application of the offered equation is fairly constrained.

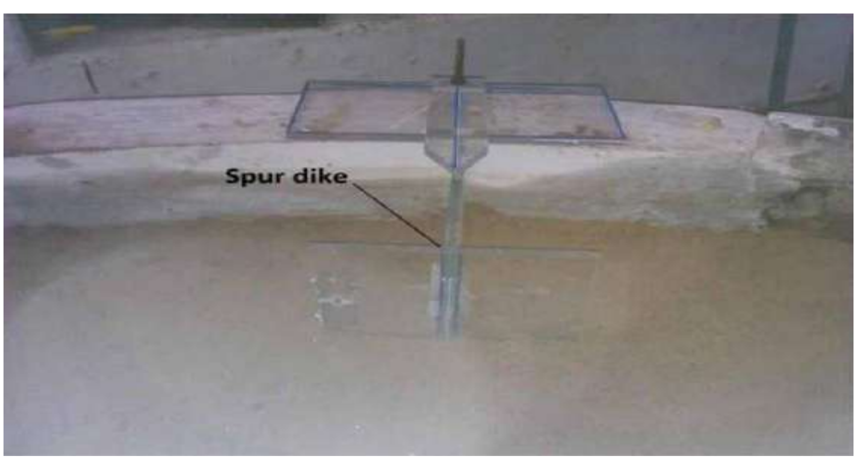

Figure 2.7: Experimental setup of spur dike located at 60º

Deposition widens the Channel while financial institution erosion widens it. A few in-flow structures, such as dams, levees, and dams, are constructed to preserve channel width and protect river banks from erosion. Turbulent properties, such as 3-dimensional velocity distribution, turbulent kinetic energy, Reynolds shear stress, turbulence intensity, and bottom shear strain, all have an effect on bed and bank balance. These turbulence factors, according to the researchers, are critical to sediment migration along the canal's bottom and from its banks.

Figure 2.8: Spur dike protection at Gamka River, South Africa

Spur dams are built on river banks to prevent bank erosion. Many studies of spur leves in straight and meandering rivers have been conducted in order to determine float, scour, and deposition processes around these structures. The layout standards of this newly added shape are restricted. This study looked at the scour patterns created by triangular spur levees. These styles were compared to those discovered for a common shape of spur weir under various hydraulic conditions (square spur weirs). The enlargement of the flush hole at the spur dam's apex can result in structural failure. It is strongly advised that the distance between triangular spur dikes not exceed five times the effective length of the shape.

One way to reduce the local scour and to control it is to put large stones and making a riprap protection which can breakdown the mighty down flows and horseshoe vortices. (Chiew 2004; Chew and Lim 2000). In the process of bed armoring, the primary objective is to reduce and control the erosive action of scour by adapting physical protections such as riprap made of rocks. Use of riprap is one the major provision in controlling the scour. Placing a riprap sheet in the region of the spur increases the resistance against erosion around and in the vicinity of the spur. Bed armoring can be classified into two types, revetments and local armoring. The both techniques are provided in the form of blankets which can cover the whole region and can reduce the scouring.

The both methods can be adapted by the use of both rigid and flexible materials. The revetments mostly made of rigid materials are impervious by nature and can suddenly fail upon the high thrust of the flowing water. The others made of flexible material can go upto equilibrium and can altered after the erosion. The major objective of these armoring process is to lessen the effect of high velocity and to reduce the high energy of the channel. These can be placed in many forms such as rock riprap, concrete unit, pavements, wall pier, pile bent, column bent, wing walls etc.

Figure 2.9: Riverbed armoring

(A R Zarrati, Nazariha, and Mashahir 2006) inspected the riprap technique at the base of a pier with collars and deduced that there was a handsome reduction in bed movement. But is pertinent to mention that such techniques when used alone are not enough to control the scour completely.

Application of collars is one of the latest modification used in controlling and reducing the bed erosion and scour. (Fotherby and Jones 1993) defined collar as a tool, which acts as an obstruction against downwards flows to retard the strength of horseshoe vortex, so as to stop the removal of sediments and bed material at the pier. (Bruce W Melville and Coleman 2000) intimated that collars with varying dimensions and different shapes were experienced around the bridge piers acting as protective plates against the removal of bed material.

(Amir R Zarrati, Gholami, and Mashahir 2004) through their research found the effect of the width of the collar on bed erosion and deduced the optimum collar width to be 3-D (D representing the diameter). Application of collars have been a vital tool to mitigate cannels flows since 80s (Ettema 1980). (Dargahi 1990) examined the various geometries to find collar performance but found a little effect on desiring results. (V. Kumar, Raju, and Vittal 1999) derived an equation which can predict the scour depth resulting due to the presence of collar.

A latest study by (Khosravinia et al. 2018), created an innovation by using trapezoidal collar instead of circular collar. A series of experiments with varying Froude number and Reynolds number were performed with impressive results. Scour occurred at higher rate initially when no collars were used and then declined after the development of scour hole. Approximately 70%of the scour occurred in less than 2 hours but after the application of collar scour occurred upto eighty minutes from the beginning of the experiment and negligible increment was noted for the next three hours. There was considerable reduction in scour depth when collars were used. Atarodi, A., Karami, H., Ardeshir, A. *et al.* (2021), in first stage of their research, experimental data was gathered based on a Taguchi mixed experiment design (L18). Through Taguchi analysis, optimal situation of collar performance was obtained. Further, analysis of factors showed that collar elevation, area and spur inclination had prominent effects on the scour depth reduction. in increased scouring.

Chapter 3

Materials and Methods

3.1 Hydraulics Channel/Flume

Laboratory Channel:

In the hydraulics laboratory of the civil engineering department at the university of engineering and technology Taxila, several tests were conducted in a channel with dimensions 20.0 m long, 96.5 cm wide, and 75.5 cm deep as shown in Figure 1. Also a 9.5 horsepower centrifugal pump with variable speed control was used to circulate water. 500 USGPM or similar can be discharged per minute using the pump. At the channel's end, a compound trapezoidal rectangular weir was erected to gauge actual discharge.

Figure3.1: Laboratory flume in Hydraulics Lab CED, UET

The Laboratory flume used in the experiment has five major components as given below:

1. Inflow pipe
2. Main flume/channel
3. Settling basin
4. Weir
5. Outflow pipe

3.1.1 Inflow Pipe:

Circular pipe of 15 cm diameter are installed at the start of the channel to deliver the water to the channel. Flow rate is controlled with the help of a controlled valve as shown in figure 3.2. The supply of water is ensured through an underground tank which is file with the help of an electric pump.

3.1.2 Main flume/channel:

The experiments were done in a rectangular channel having length of 20m, width of 75cm and a depth of 1m. The main channel is filled with fine sand having discrete specification which is then levelled. A basin is provided on upstream of the channel to control the turbulences. This is done by providing pvc pipes installed at the start of the channel.

Figure 3.2: Straighter Pipes at the start of the channel

3.1.3 Settling basin:

With the passage of time the flow erodes the bed material. This eroded bed material can lower the capacity of the tank when it enters into the tank. Apart from that these sediments can influence the working of the pump. Therefore, to avoid such circumstances a settling basin is provided before to outflow pipes. The eroded sediments are first go into the basin which are settled at the bottom of the basin. Hence clear water enters the tank without any sediments.

3.1.4 Weir

The Compound weir consisting of rectangular and trapezoidal sections having sharp edges at crest of weir was used. CRTSC weir was used as per specifications provided by ASCE.

3.1.5 Outflow Pipes:

Outflow pipes are installed to dispose off the water and to deliver that water to the tanks. The diameter of such pipes is 15 cm. In order to maintain the uniform flow open valves are used.

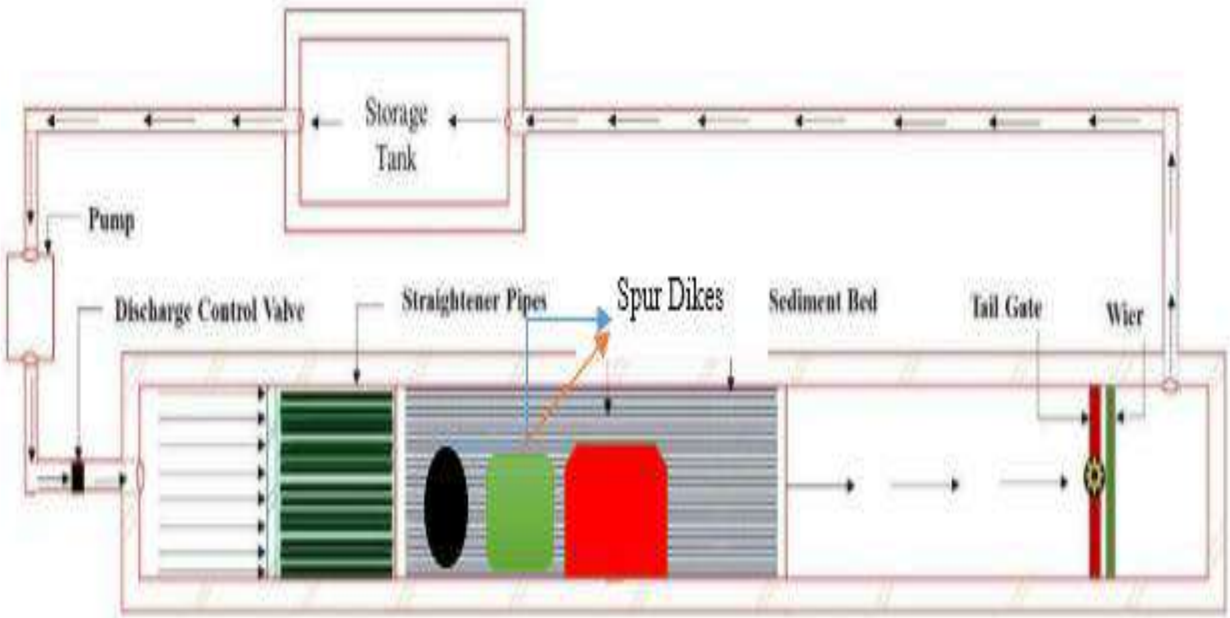

Figure 3.3: Plan View of Open Channel used for Experimental design

Point gauges near the channel's Centre line was used to measure the head of water at several places. The study area's channel bed was fixed with sand, which has a specific gravity of2.65 and a mean sediment diameter of 0.51 mm. Compound Weir equation, which was fixed at the end of the channel, was used to calculate discharge. The slope of the channel bed was kept uniform and having sediments of the average diameter 0.51mm. Scour depth was measured around Different Collar Shapes spur dike with scour gauge.

3.3 Sand Bed Material Analysis

All the tests were performed on a bed of uniform thickness of 15 cm made of sand with mean average diameter of d_{50} = .51 mm which was determined through sieve analysis. The standard deviation of the grain size was 1.19.

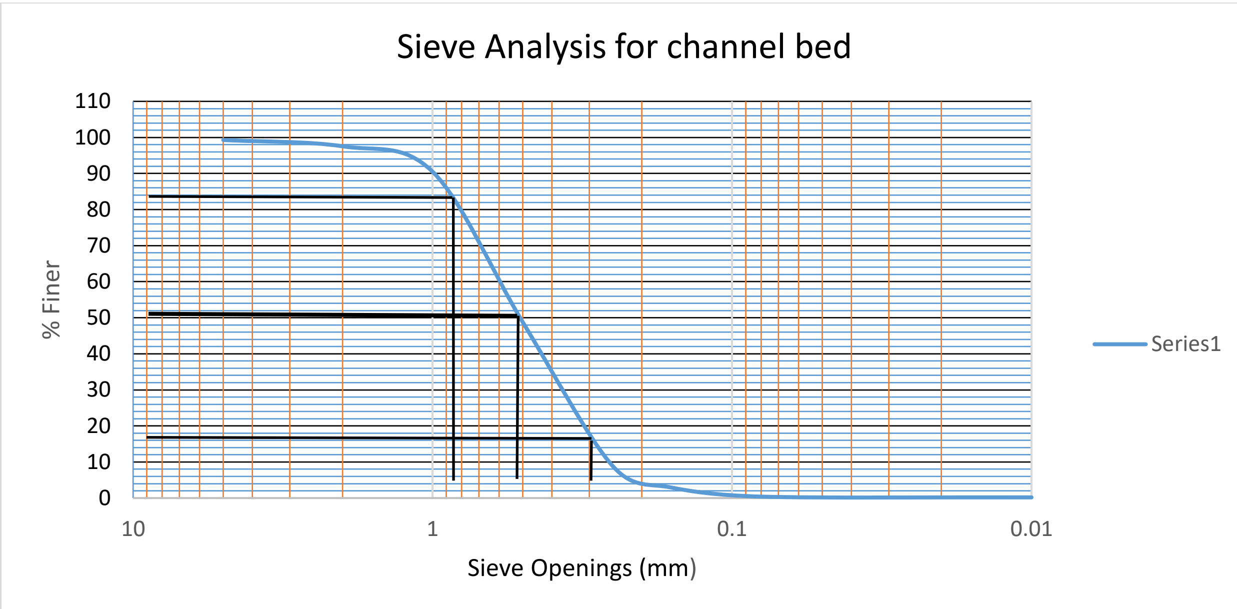

Figure 3.4 Grading diagram of bed material

Discharge	Flow Depth	Median Grain Size	Approach Flow Velocity	Critical Velocity	Flow Intensity	Froude Number
(Q)	(d_f)	(d_{50})	(V)	(V_c)	(V/V_c)	(Fr)
m^3/s	m	m	m/s	m/s	-	-
0.023	0.15	0.00051	0.16	0.3028	0.53	0.131
0.029	0.15	0.00051	0.2	0.3028	0.66	0.164
0.035	0.15	0.00051	0.24	0.3028	0.79	0.197
0.041	0.15	0.00051	0.28	0.3028	0.92	0.23

Table 3.1: Flow parameters

3.4 Flow Condition:

All tests were conducted at four distinct discharges (0.023 m^3/s, 0.029 m^3/s, 0.035 m^3/s, and 0.041 m^3/s). Froude number were calculated against four different velocities (0.131, 0.164, 0.197, and 0.230) using the formula $Fr = V/\sqrt{gy}$, where V is the approach flow velocity, y is the flow depth and g is gravity constant. Different flow parameters used in the experiments are given in table 3.2.

All the tests were done on clear water condition with threshold flow intensity (V/V_c) of less than 0.92, where V represents the approach flow velocity. The critical velocity value was determined from the logarithmic form of the velocity profile as follows (B W Melville and Sutherland,1988).

$$V/Vc = 5.75log(5.53y/d50)$$

Where y is the flow depth and d_{50} is median grain size of sand bed material.

3.5 Spur and Collar:

In the initial configuration, a straightforward wooden spur with no collar was employed in the flow field channel of the CED lab at UET Taxila. The same trials were performed on several types of spur, including rectangular, trapezoidal and circular wooden collar shapes with various spur dike junction angles, such as 45°, 90°, and 135°. The scouring around spur dikes with and without collar conditions was watched using point gauge for varied inflow conditions. The collective effect of different collar shapes and junction angle on scour was also analyzed.

Three shapes of collars are used (Circular, rectangular and trapezoidal) having dimensions of 18 cm. as shown below

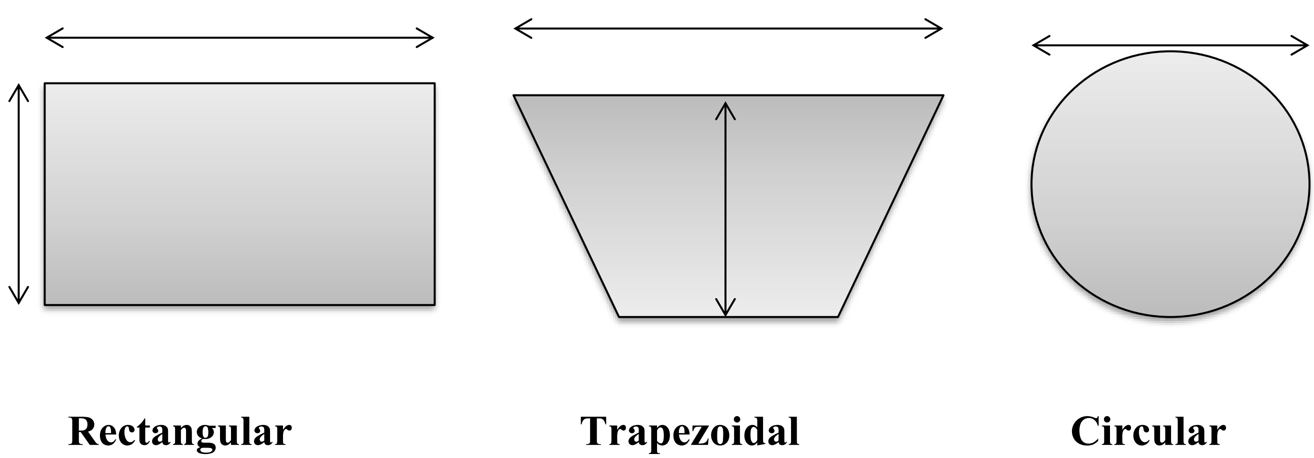

Figure 3.5: Spur dykes with various collars shapes

3.2 Discharge Calculations

A compound trapezoidal rectangular weir is installed on the channel's end to measure actual discharge. The CRTSC equation is used to compute the discharge values (Henderson, 1966).

$$Q = \frac{2}{3} C_{rd2}\sqrt{2g}\, b_2 h_2^{3/2} + \frac{2}{3} C_{rd1}\sqrt{2g}\,(2b_1) h_1^{3/2} + \frac{8}{15} C_{td}\sqrt{2g}\tan(\theta/2)\, h_{1e}^{5/2}$$

Where,

b = weir length;

Crd= discharge coefficient of the rectangular sharp-crested weir

Ctd= discharge coefficient of the trapezoidal sharp-crested weir

g = gravitational acceleration

h = water head on the weir crest

he = effective head

θ = notch angle.

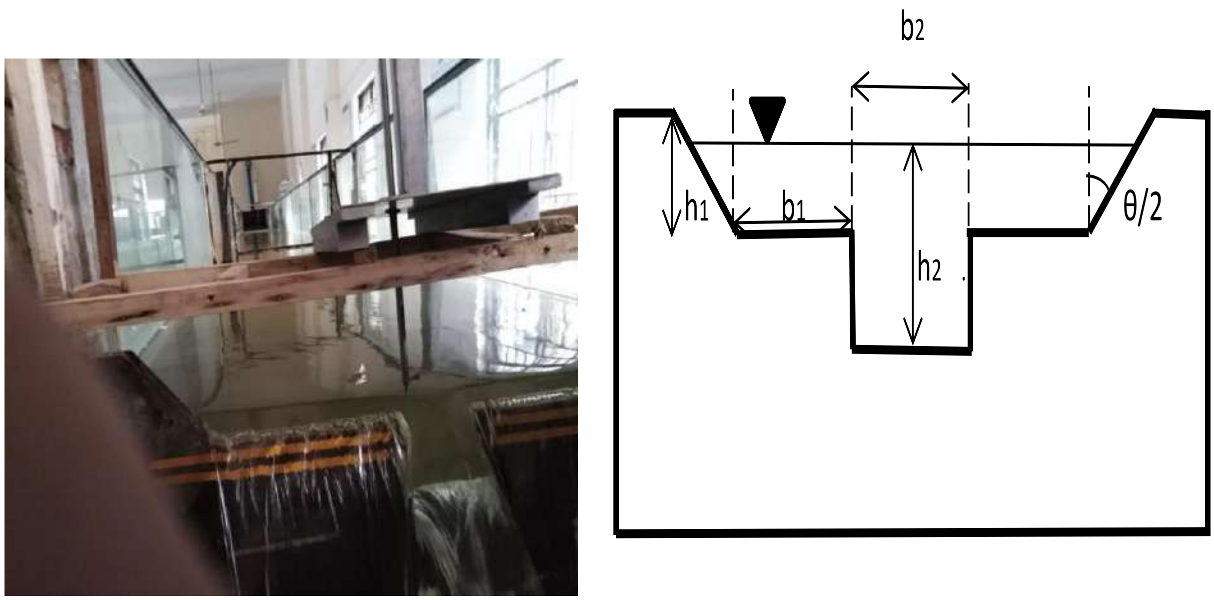

Figure 3.6 Compound weir

3.4 Methodology:

In the present study, following sets of the experiments have been carried out:

- Experiment of the scour around Spur Dike with and without using collars of several shapes were conducted
- Experiment of the scour around Spur Dike with different collar shapes were performed at an equilibrium time of 2 to 3 hours were conducted.
- Experiments of the scour around Spur dikes with straight, attracting and deflecting spur dikes at an angle of 45, 90 and 135 degrees were performed.
- All the experiments have been carried out under clear water condition, so that the flow velocity in the tests could be adjusted for the experiments under threshold movement of the particles.

The experiment was carried out with a 10 m sediment bed having a thickness of 27 cm, and the upstream Spur was installed in one third of the zone to confirm the formation of a fully developed velocity profile at the working section. The Spur was aligned at zero angle with respect to the centerline of the flume. In the initial configuration, a straightforward wooden spur with no collar is employed in the flow field channel of the CED lab at UET Taxila. The same trials are performed on several types of spur, including rectangular, trapezoidal and circular wooden collar shapes with various spur dike junction angles, such as 45°, 90°, and 135°. The scouring around spur dikes with and without collar conditions is watched using point gauge for varied inflow conditions. The collective effect of different collar shapes and junction angle on scour is also analyzed. For the testing with the other velocity ratios, the best settings were chosen. Scour depth, discharge (m/s), velocity, Froude No, scour depth average percentage reduction around each main Spur are among the results of a total of main tests. A 2-hour equilibrium time was maintained for each test (Karimi et al. 2017). Melville and Chew (1999) defined the equilibrium time as the time when the scouring depth is not changed by more than five percent of the Spur diameter. The flume was gradually drained out and the geometry of the scour hole was measured at the end of every test. The scour dimensions of the scour effected area (length and width) were also measured and recorded. The sediment bed was again leveled, and the experiments were repeated for a new discharge.

Figure 3.7: Experimental Setup of Spur dikes (a) Rectangular Collared Spur (b) Circular collared spur

Figure 3.8: Experimental Setup of Spur dikes (a) Spur without collar(b) trapezoidal collared spur

Chapter 4

Results and Discussion

For the testing with the other velocity ratios, the best settings were chosen. Scour depth, discharge (m/s), velocity, Froude No. reduction, and average percentages of scour depth reduction around each main Spur dyke are among the results of a total of 48 main tests. The local scouring of the bed channel is affected by the geometry, inclination as well as the shape of collared spur dike. Scouring depth is maximum where spur dikes are used without any collar and minimum values due to varying shapes of collar attached to spur dike. Similar to this, the relationship between the Froude number and depth of scouring is seen with various spur dike inclinations. Experimental research demonstrates an inverse relationship between flow condition and local scouring of spur dikes. For spur dikes with the highest inclination for each Froude number, the scouring depth is at its lowest, and vice versa. According to the chart, the maximum scouring depth for spur dikes is at 45° inclinations. The goal of this study is to prevent channel bed scouring following the installation of various Collar-shaped spur dikes and installing them at 45°, 90°, and 135°inclinations.

Comparing the streamlines at the horizontal plane for both tests with and without a protective SD made it clear that the flow field had improved as a result of the protective SD. When compared to non-collared SDs with inclination, scouring depth is reduced when collared spur dykes are used. The detailed calculations are shown in Table 4.1.

Table 4.1: Experimental Calculations under several conditions

Test No.	Dyke inclination	Dyke Collar Shape	Q (m^3/s)	T (hr)	h (m)	ys_f (cm)	ys_ f/D
Sp1	45^0C	Without Collar	0.023	2	0.20	7.2	0.91
Sp2	45^0C	Rectangular			0.20	7.8	0.93
Sp3	45^0C	Trapezoidal			0.20	8.4	0.91
Sp4	45^0C	Circular			0.20	5.3	0.89
Sp5	90^0C	Without Collar			0.20	6.0	0.85
Sp6	90^0C	Rectangular			0.20	6.7	0.90
Sp7	90^0C	Trapezoidal			0.20	6.1	0.76
Sp8	90^0C	Circular			0.20	6.6	0.80
Sp9	135^0C	Without Collar			0.20	7.2	0.75
Sp10	135^0C	Rectangular			0.20	6.7	0.90
Sp11	135^0C	Trapezoidal			0.20	6.1	0.86
Sp12	135^0C	Circular			0.20	8.4	0.91
Sp1	45^0C	Without Collar			0.20	6.3	0.81
Sp2	45^0C	Rectangular			0.20	6.8	0.83

Sp3	45^{0}C	Trapezoidal			0.20	7.4	0.81
Sp4	45^{0}C	Circular			0.20	4.3	0.89
Sp5	90^{0}C	Without Collar			0.20	5.0	0.95
Sp6	90^{0}C	Rectangular			0.20	5.7	0.90
Sp7	90^{0}C	Trapezoidal			0.20	5.1	0.76
Sp8	90^{0}C	Circular			0.20	5.6	0.75
Sp9	135^{0}C	Without Collar			0.20	6.2	0.65
Sp10	135^{0}C	Rectangular			0.20	5.7	0.90
Sp11	135^{0}C	Trapezoidal	0.029	2	0.20	5.1	0.76
Sp12	135^{0}C	Circular			0.20	7.4	0.81
Sp1	45^{0}C	Without Collar			0.20	6.3	0.71
Sp2	45^{0}C	Rectangular			0.20	6.8	0.73
Sp3	45^{0}C	Trapezoidal			0.20	7.4	0.71
Sp4	45^{0}C	Circular			0.20	4.3	0.79
Sp5	90^{0}C	Without Collar	0.035	2	0.20	5.0	0.85
Sp6	90^{0}C	Rectangular			0.20	5.7	0.70
Sp7	90^{0}C	Trapezoidal			0.20	5.1	0.77

Sp8	90^0C	Circular			0.20	5.6	0.85
Sp9	135^0C	Without Collar			0.20	6.2	0.75
Sp10	135^0C	Rectangular			0.20	5.7	0.93
Sp11	135^0C	Trapezoidal			0.20	5.1	0.78
Sp12	135^0C	Circular			0.20	7.4	0.86

4.2 Effects of different shapes of collars on scour depth:

The values of d_s/D for spur dike without collar case and the spur with three shapes of collar (i.e., circular, trapezoidal, and rectangular) are shown in Figure 4.2 for flow intensity of (0.53, 0.66,0.79 and 0.92). From the figure, it is shown that as the value of flow intensity increases from 0.53 to 0.92, the value of d_s/D increases.

The spur dike without collar has maximum value of ds/D and the spur with circular collar has minimum value of ds/D as compared to rectangular shaped collar, trapezoidal shaped collar and the spur without collar.

To summarize the observations on flow pattern around Collared and without Collar Spur dikes, the measurements of scour depths made around each of the Spur models at different vertical planes exhibit almost similar profiles along the flow depth. It is observed that the non-dimensional scouring depth varies directly with increase in Froude No. values.

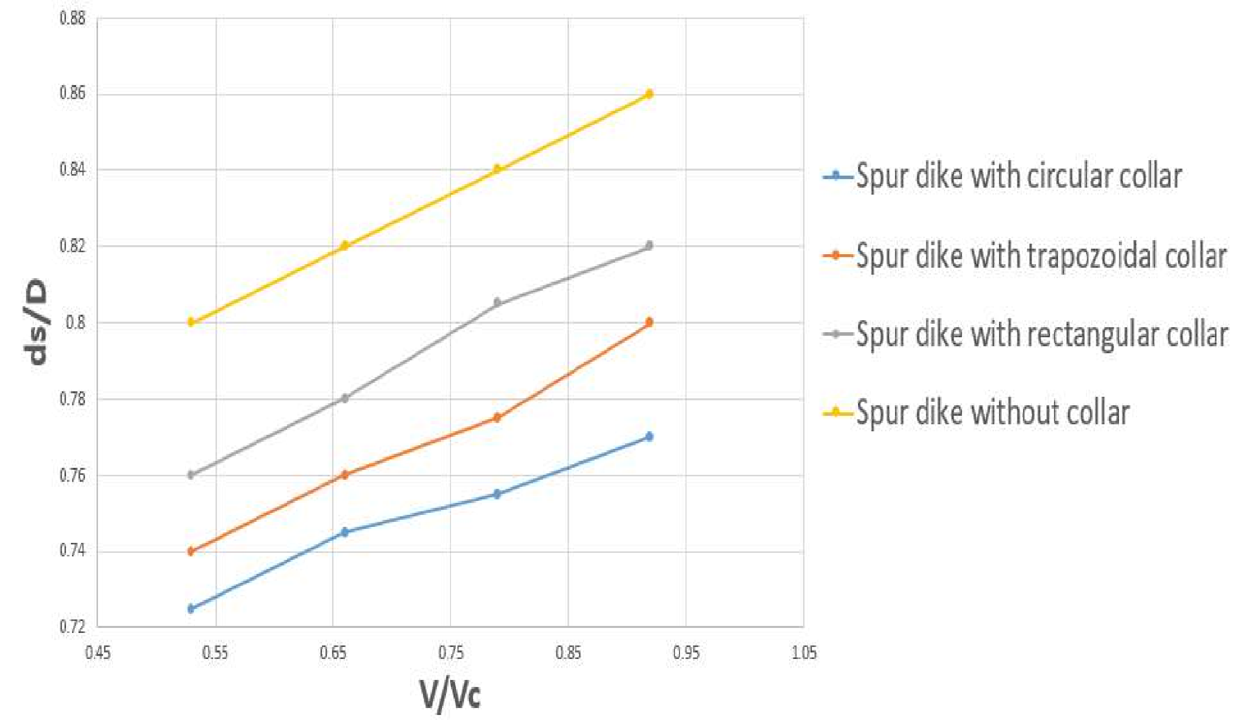

Figure 4.1: Relationship between Non-Dimensional Scour depth and Flow intensity for different Collared spur dikes

4.3 Effect of Junction angle:

The values of maximum scour for collared spur dikes with different junction angles i.e. 45^0, 90^0 , and 135^0 are shown in figure 4.2, figure 4.3, figure 4.4 respectively. From the figures it is shown that the ds value is minimum when the junction angle of spur is 135^0 and the ds value is maximum when the junction angle of the spur is 450. The value of ds for spur with 90^0 angle lie between those of the 45^0 and 135^0 . It is also shown from graphs that the values of ds are minimum in case of spur with circular collar and maximum in case of trapezoidal collar.

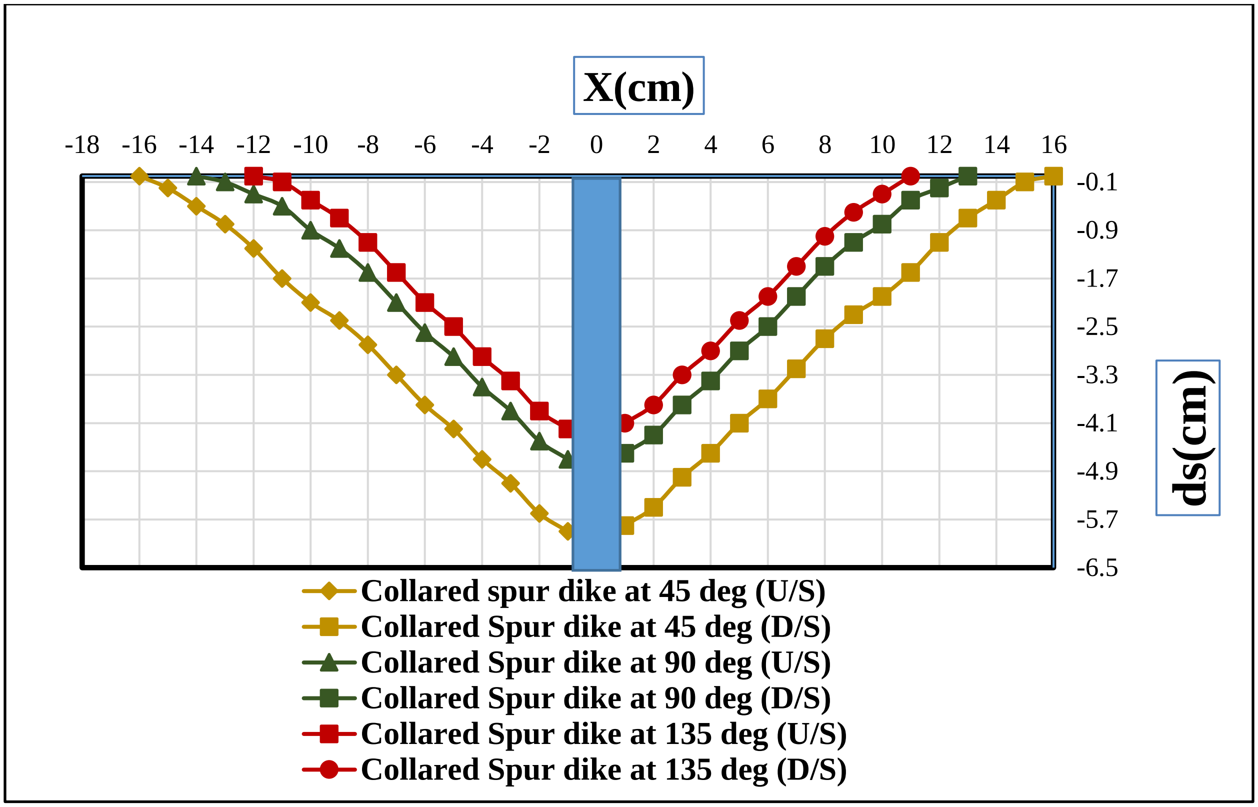

Figure 4.2: Rectangular Collar Spur dike showing Scouring profile at different angles

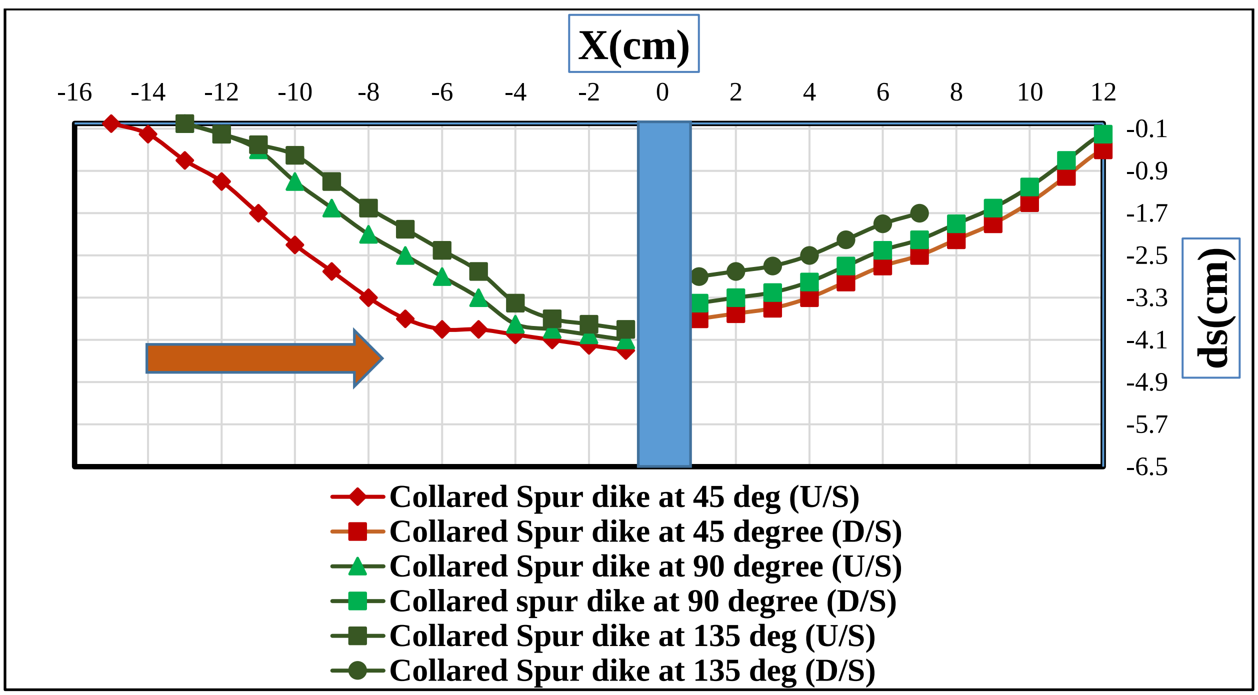

Figure 4.3: Circular Collar Spur dike showing Scouring profile at different angles

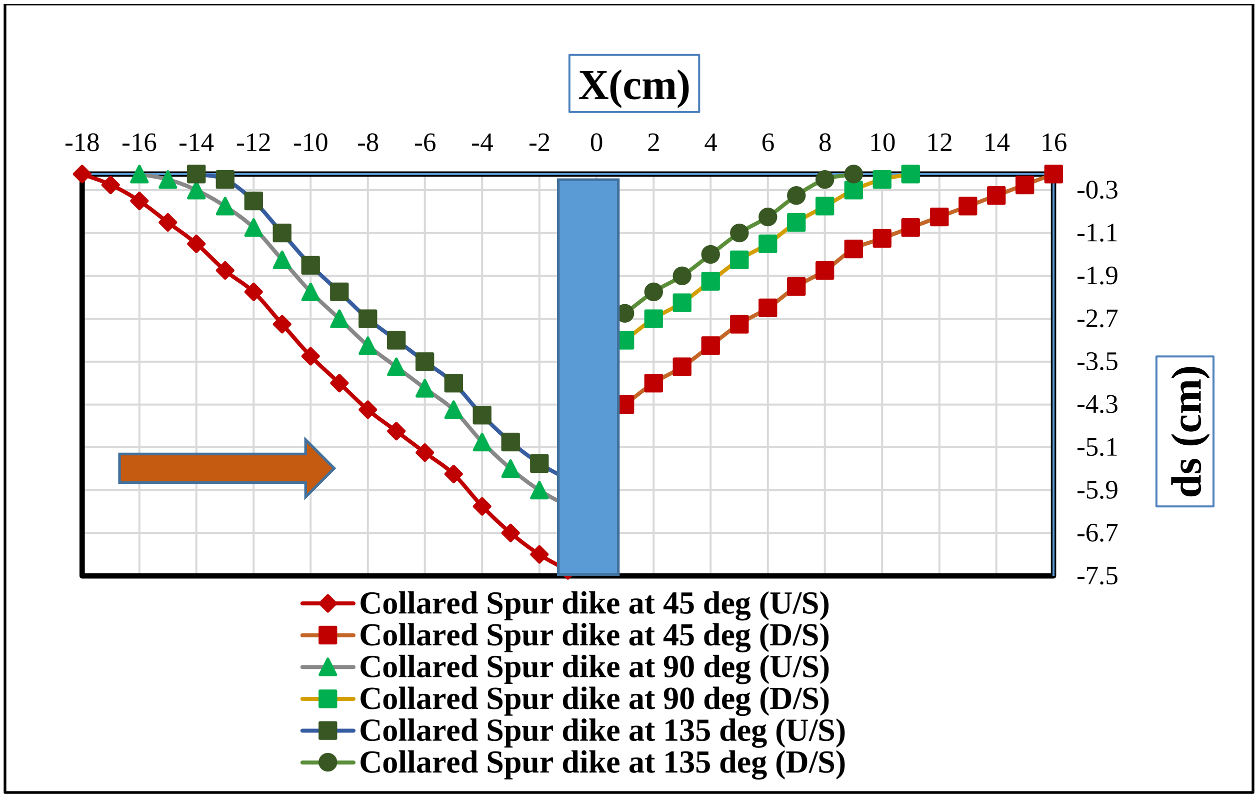

Figure 4.4: Trapezoidal Collar Spur dike showing Scouring profile at different angles

Comparing the streamlines at the horizontal plane for both tests with and without a protective SD made it clear that the flow field had improved as a result of the protective SD. When compared to non-collared SDs with inclination, scouring depth is reduced when collared spur dykes are used.

As the discharge in the channel increased, the scouring around the inclined, collared spur dykes diminished. The most effective spur dykes have 135 inclinations, which reduce scouring by up to 15% when compared to spur dykes without inclinations.

Relationship between Non-Dimensional Scour depth and Flow intensity for different collared spur dikes is shown in the figure 4.1. It has been observed that the spur dike with different collar shapes shows different values of non-dimensional scouring depth. Also the scouring depth decreases by installing collars with the spur dike and vice versa.

The Figure 4.5 shows the average scour reduction in the corresponding maximum scour depth for each shape of the collar that was calculated at the maximum value of discharge. From the figure, it is clear that the circular collar gives maximum percentage reduction (upto 53%) as compared to rectangular and trapezoidal shape of collars.

Analyzing the values of percentage reduction in scour depth the optimal shape of the collar is circular shaped collar as compared to rectangular shaped collar and trapezoidal shaped collar.

Figure 4.5: Comparison of Various scour reduction % for different shapes of collar

To assess the efficiency of different shapes of collars (namely circular, trapezoidal and rectangular), with different inclinations and the combination of collars and inclinations attached with the spur surface as a countermeasure flow altering techniques. The, collars and the combination of spur and collar showed their effectiveness in the reduction of maximum scour depths and volume of the scour hole.

The maximum scour depth for spur attached with three shapes of collar. It is pertinent to note that circular shape collar is the most efficient in reduction of the scour depth as compared to trapezoidal collar and rectangular collar. The percentage of scour reduction for trapezoidal, rectangular and circular were 23, 33 and 53, respectively.

Chapter 5

Conclusions and Recommendations

5.1 Conclusion

In this research, the efficiency of several shaped collared spur dikes is studied with different inclination by placing dikes and performing several experiments in an open flume. Following are the conclusions and outcomes of this experimental research:

- The maximum scour depth for spur attached with three shapes of collar. It is interesting to note that circular shape collar is the most helpful in reduction of the scour depth as compared to trapezoidal collar and rectangular collar. The percentage of scour reduction for trapezoidal, rectangular and circular were 23, 33 and 53, respectively.
- The Scour depth around the collared spur dikes is increased by increasing the Froude Number in clear water conditions.
- The depth of scour hole is increased by increasing the flow velocity.
- Scouring depth decreases with the use of collared spur dikes with Inclination.
- The scouring around the spur dike decreased with increasing the inclination of collared spur dike in channel.
- The circular collared spur dikes with 135deg inclination is the most efficient and optimum that has reduced scouring up to 53% as compared to without using collar and any inclination of spur dike.
- The data presented here it can serve as the base results flow simulation models needed to be tested. These results are also useful in modeling the scour process and developing new measures for protection against scour around the Rectangular, Trapezoidal and circular shaped Spur dike.
- As the discharge in the channel increased, the scouring around the inclined, collared spur dykes is increased.
- The shape of a collar acts an important parameter in the scouring process of spur dike along with other parameters.

5.2 Recommendations and Future Implications

I. The same research may be conducted by using the different shapes and types of spur like J-head spur, Hockey spur etc.

II. The data presented herein can serve as the base results for flow simulation models needed to be tested. These results are also useful in modeling the scour process and developing new measures for protection against scour around Spur Dike. However, this study presents a quantitative analysis of the development of scour depth under restricted conditions.

III. Discrepancies might occur when the proposed conclusions; for example, for high flow intensity or different geometrical shape of spur dike, both d50 and the geometric standard deviation, which characterizes the sediment mixture, needs to be reconsidered.

References

Ahgtam Mena Alsawaf, “Movable-Bed Experiments Using Spur Dike to Concentrate Flow in One Channel of Multithreaded Channel Model”, 2019.

Ashida, K, T Takahashi, and M Michiue. 1983. “River Sediment Disaster and Its’ Treatment**.”** Shen Ba Publish, 255–321.

Atarodi, a., Karami, h., Ardeshir, a., Hosseini, k. & Lampert, d. 2021. Experimental Investigation of Scour Reduction Around Spur Dikes by Collar Using Taguchi Method. Iranian Journal of Science and Technology, Transactions of Civil Engineering, 45, 971-983.

Bozkus, Zafer, and Murat Çeşme. 2010. “Reduction of Scouring Depth by Using Inclined Piers.” Canadian Journal of Civil Engineering 37 (12): 1621–30.

Brandimarte, L., Paron, P. and Di Baldassarre, G., 2012. Bridge pier scour: A review of processes, measurements and estimates. Environmental Engineering and Management Journal, 11(5), pp.975-989. https://doi.org/10.30638/eemj.2012.121

Cardoso, António H, and Cristina M Fael. 2009. “Protecting Vertical-Wall Abutments with Riprap Mattresses.” *Journal of Hydraulic Engineering* 135 (6): 457–65.

Chiew, Yee-Meng, and Foo-Hoat Lim. 2000. “Failure Behavior of Riprap Layer at Bridge Piers under Live-Bed Conditions.” Journal of Hydraulic Engineering 126 (1): 43–55.

Christopher, V., Loan, N., & Colin, R. (2018). Reduction of bridge pier scour through 74 the use of a novel collar design. 6th International Disaster Mitigation Specialty Conference 2018, Held as Part of the Canadian Society for Civil Engineering Annual Conference 2018, 235–244.

Dargahi, Bijan. 1990. “Controlling Mechanism of Local Scouring.” Journal of Hydraulic Engineering 116 (10): 1197–1214.

Debnath, K., & Chaudhuri, S. (2010). Laboratory experiments on local scour around cylinder for clay and clay-sand mixed beds. Engineering Geology**,** 111(1–4), 51–61. https://doi.org/10.1016/j.enggeo.2009.12.003.

Dey, Subhasish, and Arindam Sarkar. 2006. “Scour Downstream of an Apron Due to Submerged Horizontal Jets.” Journal of Hydraulic Engineering 132 (3): 246–57.

Dey, Subhasish, and Arindam Sarkar. 2006. “Scour Downstream of an Apron Due to Submerged Horizontal Jets.” Journal of Hydraulic Engineering 132 (3): 246–57

Elsaeed, Gamal, Hossam Elsersawy, and Mohammad Ibrahim. “Scour Evaluation for the Nile River Bends on Rosetta Branch.” Advances in Research 5, no. 2, January 10, 2015

El-Azab, Esam El-Deen Yousry. 2014. “Minimizing Scour Downstream of Hydraulic Structures Using Single Line of Floor Water Jets.” Ain Shams Engineering Journal 5 (1): 17–28.

Garde, Ramchandra J, and K G Ranga Raju. 2000. Mechanics of Sediment Transportation and Alluvial Stream Problems**.** Taylor & Francis.

Ghaderi, Amir; Abbasi, Saeed (2019). CFD simulation of local scouring around airfoil-shaped bridge piers with and without collar. Sādhanā, 44(10), 216–. doi:10.1007/s12046-019-1196-8

Ghiassi, Reza; Abbasnia, Amir Hosein (2013). Investigation of Vorticity Effects on Local Scouring. Arabian Journal for Science and Engineering, 38(3), 537–548. doi:10.1007/s13369-012-0337-8

Ghodsian, Masoud, and Mohammad Vaghefi. 2009. “Experimental Study on Scour and Flow Field in a Scour Hole around a T-Shape Spur Dike in a 90 Bend.” International Journal of Sediment Research 24 (2): 145–58.

Gupta, Umesh P.; Ojha, C. S. P.; Sharma, Nayan (2010). Enhancing Utility of Submerged Vanes with Collar. Journal of Hydraulic Engineering, 136(9), 651–655. doi:10.1061/(asce)hy.1943-7900.0000212

Hamidifar, H, M Nasrabadi, and M H Omid. 2018. “Using a Bed Sill as a Scour Countermeasure Downstream of an Apron.” Ain Shams Engineering Journal 9 (4): 1663–69.

Han, X., Lin, p. & Parker, G. 2022. Numerical modelling of local scour around a spur dike with porous media method. Journal of Hydraulic Research, 60, 970-995.

Huang, Wei; Creed, Maggie; Chen, Fei; Liu, Huaihan; Ma, Aixing (2018). Scour around Submerged Spur Dikes with Flexible Mattress Protection. Journal of Waterway, Port, Coastal, and Ocean Engineering, 144(5), 04018013–. doi:10.1061/(ASCE)WW.1943-5460.0000466

Jahangirzadeh, Afshin, Hossein Basser, Shatirah Akib, Hojat Karami, Sareh Naji, and Shahaboddin Shamshirband. 2014. “Experimental and Numerical Investigation of the Effect of Different Shapes of Collars on the Reduction of Scour around a Single Bridge Pier.” PloS One 9 (6): e98592.

Karami, Hojat; Ardeshir, Abdollah; Behzadian, Kourosh; Ghodsian, Masoud (2011). Protective spur dike for scour mitigation of existing spur dikes. Journal of Hydraulic Research, 49(6), 809–813. doi:10.1080/00221686.2011.625166

Karami, H., Hosseinjanzadeh, H., Hosseini, k. & Ardeshir, A. 2018. Scour and three-dimensional flow field measurement around short vertical-wall abutment protected by collar. KSCE Journal of Civil Engineering, 22, 141-152.

Khosravinia, Payam, Amir Malekpour, Ali Hosseinzadehdalir, and Davod Farsadizadeh. 2018. "Effect of Trapezoidal Collars as a Scour Countermeasure around Wing-Wall Abutments." Water Science and Engineering 11 (1): 53–60.

Kisi, O., Khosravinia, P., Nikpour, M. R., & Sanikhani, H. (2019). Hydrodynamics of river-channel confluence: toward modeling separation zone using GEP, MARS, M5 Tree and DENFIS techniques. Stochastic Environmental Research and Risk Assessment**,** 33**(**4–6), 1089–1107. https://doi.org/10.1007/s00477-019-01684-0

Kuhnle, Roger A.; Alonso, Carlos V.; Shields, F. Douglas (2002). Local Scour Associated with Angled Spur Dikes. Journal of Hydraulic Engineering, 128(12), 1087–1093. doi:10.1061/(ASCE)0733-9429(2002)128:12(1087)

Kumcu, s. y., Kokpinar, M. a. & Gogus, M. 2014. Scour protection around vertical-wall bridge abutments with collars. KSCE Journal of Civil Engineering, 18, 1884-1895.

Mahtabi, G., & Arvanaghi, H. (2018). Experimental and numerical analysis of flow over a rectangular full-width sharp-crested weir. Water Science and Engineering**,** 11(1), 75–80. https://doi.org/10.1016/j.wse.2018.03.004.

Mashahir, Mohammad B, Amir Reza Zarrati, and M J Rezayi. 2004. "Time Development of 66 Scouring around a Bridge Pier Protected by Collar." In Proceedings 2nd International Conference on Scour and Erosion (ICSE-2). November 14–17., 2004, Singapore**.**

Pandey, M., Azamathulla, H. M., Chaudhuri, S., Pu, J. H., & Pourshahbaz, H. (2020). Reduction of time-dependent scour around piers using collars. Ocean Engineering**,** 213(July), 107692. https://doi.org/10.1016/j.oceaneng.2020.107692.

Pandey, Manish; Valyrakis, Manousos; Qi, Meilan; Sharma, Anurag; Lodhi, Ajay Singh (2020). Experimental assessment and prediction of temporal scour depth around a spur dike. International Journal of Sediment Research, (), S1001627920300378–. doi:10.1016/j.ijsrc.2020.03.015

Raikar, R V, D Nagesh Kumar, and Subhasish Dey. 2004. "End Depth Computation in Inverted Semicircular Channels Using ANNs." Flow Measurement and Instrumentation 15 (5–6): 285–93

Vaghefi, Mohammad; Faraji, Behrooz; Akbari, Maryam; Eghbalzadeh, Afshin (2018). Numerical investigation of flow pattern around a T-shaped spur dike in the vicinity of attractive and repelling protective structures. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 40(2), 93–. doi:10.1007/s40430-017-0954-y