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CHAPTER I

INTRODUCTION

1.1 General

Spur dikes are river-training structures built out from one bank into the flow. Depending on the material used, they may be solid or permeable, and they serve to guide the flow along a desired course, protect the bank from attack and erosion, reclaim land adjoining the bank by encouraging siltation, and improve the channel for navigation, among other functions (Kumar & Ojha, 2021a). Permeable spur dikes suit wide, shallow, aggrading rivers particularly well. By altering the local flow field, spur dikes generate flow separation, a mobile boundary, and horseshoe vortices, which ultimately produce scour around them (Nandhini et al., 2024); left unchecked, this scour can lead to structural failure or collapse. A sound understanding of the scour and flow mechanism is therefore essential for the safe, economical design of spur dikes.

1.2 Brief description of spur dikes

Alluvial rivers in plains and torrents in the headwater regions frequently change their course and cause considerable land damage and bank erosion. The extent of such land damage in India has been estimated at approximately 2.73 million hectares (Ministry of Agriculture 1995). The earliest form of river control consisted of embankments, known as levees, to prevent flooding. At a later stage, control was affected through spur dikes and revetments. Spur dikes, in particular, are structures, solid or permeable, constructed transverse to river flow, extending from one of the banks at an angle to the flow. The angle of spur dikes usually ranges from 45° to 135°, depending on the design and water flow conditions (Hussein et al., 2025). They are also known as spur dikes, groynes, transverse dikes, jetties, etc. Spur dikes may be constructed either individually or in series. Single structures deflect water currents, creating stagnation zones downstream where sediment settles. On the other hand, a series of structures traps silt in the spaces between them, reinforcing and stabilizing the bank line over time. Additionally, the spur dikes alter the flow conditions by modifying the hydraulic

conditions near the bank. These approaches effectively control erosion and promote sediment deposition.

1.2.1 Functions of spur dikes

Spur dikes may be constructed singly or in series. If single, they deflect the incoming current away, which again reattaches on the downstream side, forming stagnation pockets and causing sedimentation. If in series, they hold the bank line in place by accumulating silt in the spaces between them. The major functions of spur dikes are listed below:

1. **Flow Deflection:** Spur dikes redirect the flow of water away from the riverbank, reducing the erosive forces acting on the bank.
2. **Velocity Reduction:** By creating zones of relatively slower-moving water, spur dikes encourage sediment deposition along the riverbank.
3. **Turbulence Control:** Permeable spur dikes can reduce turbulence intensity and bed shear stress, minimize erosion and promoting stable sediment accumulation.
4. **Sediment Trapping:** Spur dikes trap sediment carried by the river, which helps build up the riverbank and stabilize the shoreline (Kumar & Ojha, 2021a).

1.3 Types of spur dikes

Spur dikes may vary considerably in type, material, and design. Thus, they may be classified by permeability, submergence, orientation, and head shape (Chakravarty et al., 2024).

1. **Permeability:** spur dikes may be permeable or impermeable. Permeable spur dikes let water pass through, creating only a partial obstruction and a corresponding reduction in velocity, whereas impermeable spur dikes are solid and block the flow entirely, forcing it to change direction and so generating strong vortices and higher shear stress; of the two, impermeable spur dikes cause more scour. Figure 1.1 shows the layout of these spur dikes.
2. **Submergence:** Based on the submergence, the spur dikes may be classified as submerged or unsubmerged types. In submerged spur dikes, the water flows over

the crest level of spur dikes, whereas in unsubmerged spur dikes, the crest level of the structures remains above the water level. These spur dikes are shown in Figure 1.2.

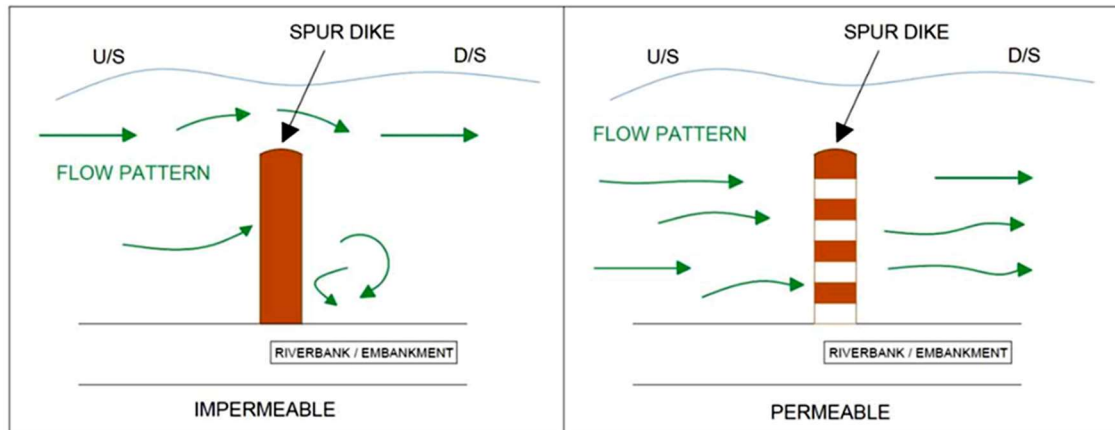


Figure 1.1: Permeable and impermeable types of spur dikes (Chakravarty et al., 2024)

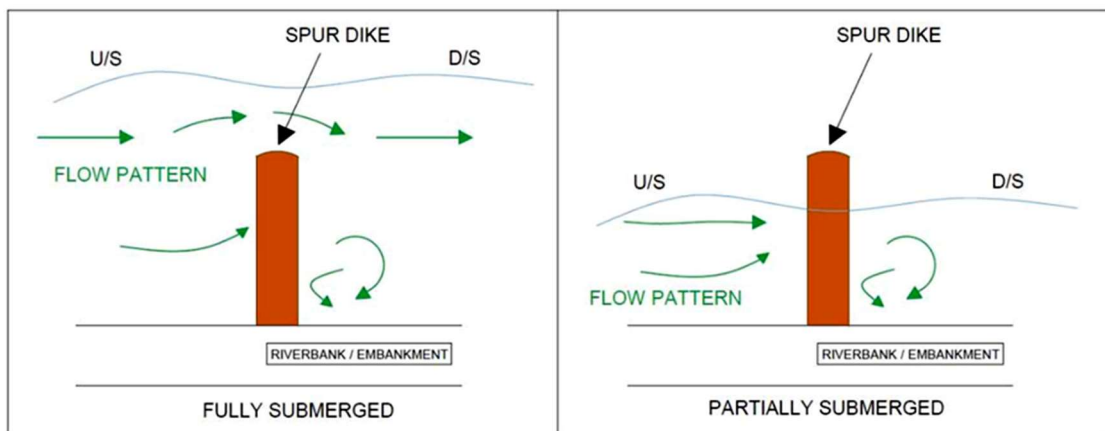


Figure 1.2: Submerged and unsubmerged types of spur dikes (Chakravarty et al., 2024)

3. **Orientation:** On the basis of orientation, the spur dikes are attracting, deflecting, and repelling. The attracting spur dikes are the spur dikes that are inclined at an angle of greater than 90° to the flow direction. For deflecting spur dikes, the angle is 90° , whereas repelling dikes have an angle less than 90° with the flow. Figure 1.3 illustrates the plan view of these spur dikes.

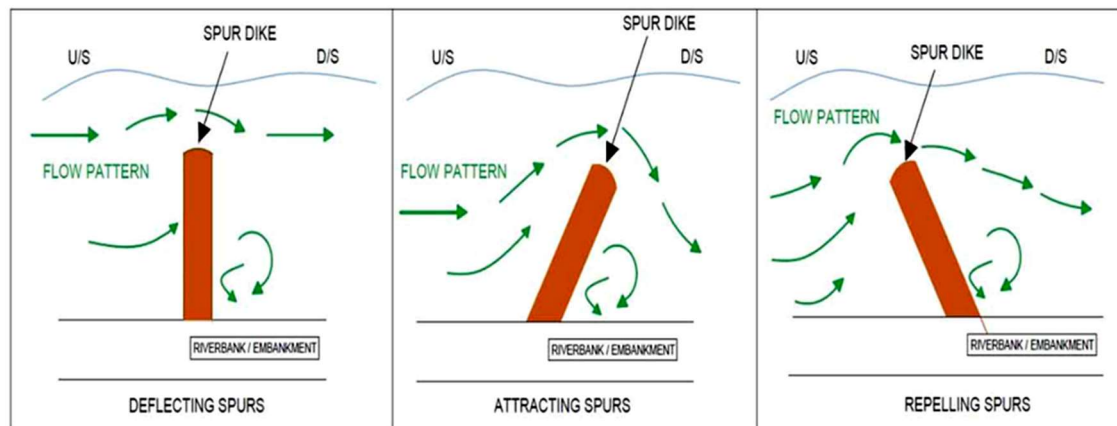


Figure 1.3: Deflecting, attracting, and repelling types of spur dikes (Chakravarty et al., 2024)

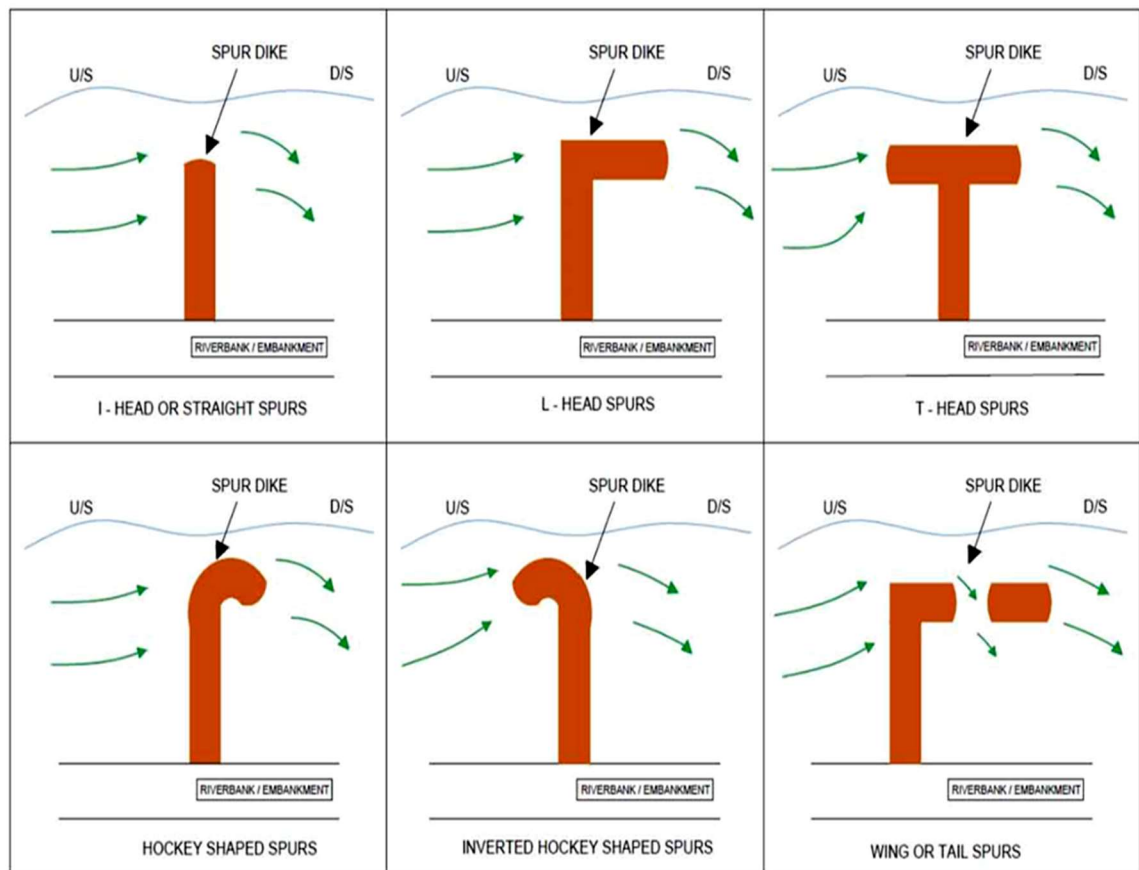


Figure 1.4: I-, L-, T-, hockey- and tail-head spur dikes (Chakravarty et al., 2024)

4. **Head shapes:** The spur dikes are also classified on the basis of head shape as I-, L-, T-, hockey-, and tail shape spur dikes. These head shapes are shown in Figure 1.4.

1.4 Scour depth

Scour is the localised erosion produced when flow velocity, bed shear stress, or turbulence increases over a short stretch of channel, and is conventionally divided into three types: general, contraction, and local. General scour follows from natural morphological change in the riverbed; contraction scour follows from a structure narrowing the watercourse or re-channelling flow across the berm or floodplain; local scour results directly from a structure's own effect on the flow (Wang et al., 2017). Local scour is superimposed on the other two and depends on the characteristics of the structure itself.

Local scour is generally classified into two types: (i) clear-water scour and (ii) live-bed scour. In clear-water scour, the bed material upstream of the scour region remains stationary, since the bed shear stress there stays at or below the critical (threshold) value needed to initiate particle motion, and the hole stops deepening once the flow can no longer entrain further particles from it. Live-bed scour, sometimes called scour with sediment transport, instead occurs when the stream is actively transporting bed material, i.e., the shear stress generally exceeds the critical value (Toth & Brandimarte, 2011). In either case, equilibrium is reached once the volume of material removed from the hole by the flow balances, over time, the volume supplied to it from upstream.

1.5 Scour around spur dikes

As noted above, when an alluvial stream is partially obstructed by a structure such as a spur, erosion occurs in its vicinity - termed 'local scour'. Because excessive local scour can expose or undermine the foundation and lead to structural failure, and because spur failure is often traced to scouring at the nose, the term scour is used here to mean local scour unless stated otherwise. This scour is driven by complex vortex patterns, most notably a horseshoe vortex, that develop as water flows around the structure (Pandey et al., 2018), causing localised erosion at its base and tip and

removing sediment from the bed; Figure 1.5 illustrates this process and the associated vortices.

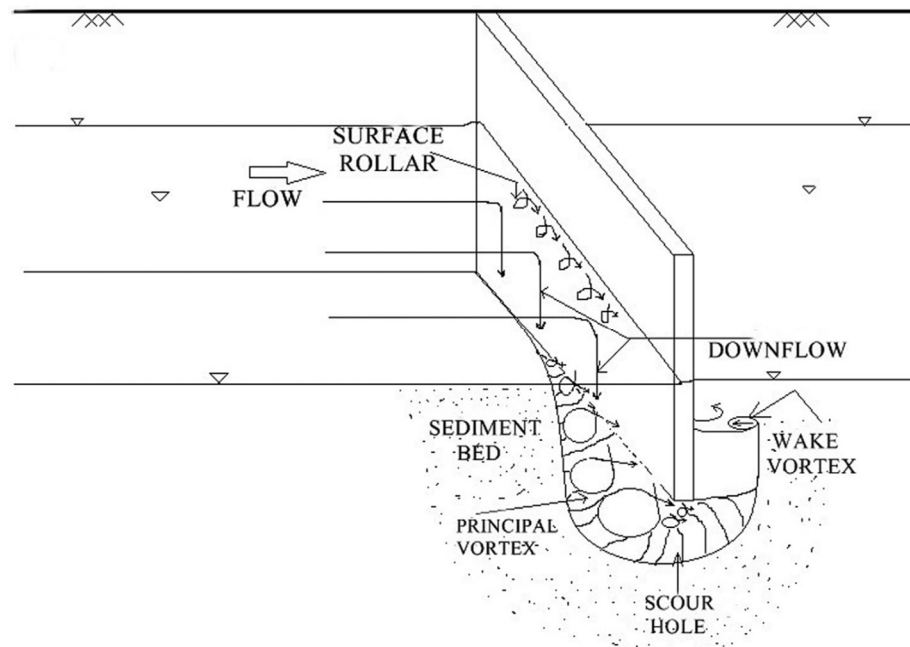


Figure 1.5: Flow structures around a spur dike showing horseshoe vortex, wake vortices, flow separation, and local scour development (Pandey et al., 2018)

A realistic estimate of the maximum equilibrium scour depth around a spur dike therefore matters for both its performance and its economical design. This remains difficult because of the complex way the flow around a spur interacts with the surrounding erodible bed, a problem involving numerous stream-related variables (flow rate, depth, flow condition, bed slope, constriction), obstruction properties (size, shape, geometry), and bed-material properties (size, gradation, layering, cohesiveness).

1.6 Present state of knowledge

Scour around spur dikes is difficult to predict because of the intricate mechanisms involved: separation zones, flow acceleration, and vortex formation interact in the flow field around the structure to produce it, leaving both the scour process itself and the flow field driving it as persistent challenges for researchers. Scour depth around spur

dikes has been studied for four decades (Garde et al., 1961; Zaghloul, 1983; Przedwojski, 1995; Kothiyari & Ranga Raju, 2001; Breusers, 2020; Li et al., 2023), generally through experiments on spur dikes of different lengths, shapes, and alignments under varying velocity, flow depth, and sediment conditions. Most of this work has focused on I-, L-, and T-shape spur dikes, with T-shape found most effective at limiting scour, L-shape best for riverbank stability, and I-shape the most economical (Chakravarty et al., 2024); the concentration of research on just these three shapes points to a need for a new spur-dike geometry that can further reduce scour and improve bank protection.

In the past few decades, scholars have used machine learning models, including artificial neural network (ANN), random forest (RF), reduced error pruned tree (REPT), M5P tree, & support vector regression (SVR), and computational fluid dynamics (CFD) software, including FLUENT, FLOW3D, and REEF3D, to investigate the scour phenomena around spur dikes (Zhang et al., 2009; Acharya, 2011; Wei et al., 2018; Ning et al., 2019; Vaghefi et al., 2020; Shampa et al., 2020; Liao et al., 2021; Pandey et al., 2022; Gupta et al., 2025; Tabassum et al., 2024; Liu et al., 2024). Machine learning offers several advantages, such as handling complex relationships, time savings, scalability, cost efficiency, eliminating scaling issues, broad input parameter integration, customizable and adaptive predictions, and environmental and safety benefits, while CFD also has several advantages, such as being cost-effective, time efficient, flexible in scenario analysis, detailed flow visualization, and handling complex geometries over traditional experimental methods. Owing to their advantages, the application of machine learning and CFD in hydraulic engineering has increased significantly in recent years.

1.7 Objectives of the study

The present study aims to design a new spur-dike shape, the curved T-shape, by modifying the existing head geometry, and to test its performance against conventional I- and T-shape spur dikes. Its objectives are as follows:

1. To design and optimize the curvature of newly designed curved T-shape spur dikes.

2. To compare the performance of curved T-shape spur dikes with existing I- and T-shape spur dikes and investigate the flow mechanism around the curved T-shape spur dikes
3. To optimize the spacing between two curved T-shape spur dikes for stream bank protection.
4. Estimation of scour depth around spur dikes using suitable hybrid machine learning models.

1.8 Organization of the thesis

The thesis comprises five chapters, which are summarized below:

Chapter I introduces riverbank erosion and channel instability in alluvial rivers and the importance of river-training structures in addressing them, discussing the function, classification, and significance of spur dikes in river engineering. It pays particular attention to local scour, given its bearing on the structural safety and service life of spur dikes, and closes with the objectives of the present study.

Chapter II surveys the published literature on scour around spur dikes and related river-training structures. It draws on earlier experimental, numerical, and analytical work to explain how hydraulic, sediment, and geometric factors govern scour development, and reviews studies of different head shapes and spacing arrangements. It also outlines how Computational Fluid Dynamics (CFD) has been applied to flow around hydraulic structures, and surveys recent machine-learning and hybrid machine-learning approaches to scour-depth prediction, noting their capacity to capture complex hydraulic behaviour. It closes by identifying the shortcomings of the existing literature and the case these make for the present study.

Chapter III describes the methodology adopted for the experimental, numerical, and machine learning investigations. The laboratory flume, sediment characteristics, flow conditions, and measurement instruments are presented in detail. The procedures used to measure scour depth around conventional I- and T-shape spur dikes, as well as the proposed curved T-shape spur dike, are explained. The chapter also describes the details of 16 geometric configurations of curved T-shape spur dikes used to optimize

curvature and minimize scour depth around the structure. In addition, the methodology employed to investigate the effect of spacing between spur dikes installed in series is presented. The CFD modeling procedure, including geometry creation, mesh generation, boundary conditions, and turbulence modeling, is also detailed. Finally, the chapter covers the development of hybrid machine learning models and regression equations for predicting scour depth.

Chapter IV sets out the results of the experiments, CFD simulations, and machine-learning analyses. It reports the temporal and equilibrium scour depths recorded for the different spur-dike configurations and flow conditions, and examines how flow depth, flow intensity, and geometry govern scour development. The sixteen curved T-shape configurations are compared to find the geometry that reduces scour most, and the spacing between spur dikes in series is examined to identify the arrangement that minimises downstream scour. CFD results are used to interpret the flow mechanisms behind scour, covering velocity distribution, turbulence, flow separation, vortex formation, and bed shear stress, and three regression equations together with hybrid machine-learning models are developed and compared using the **coefficient of correlation (COC)**, **coefficient of determination (R-Square)**, **root mean square error (RMSE)**, and **Nash-Sutcliffe efficiency (NSE)** to identify the most accurate predictor. The chapter closes with the uncertainty in these results and their applicability to real rivers.

Chapter V summarizes the major findings of the study and presents the conclusions drawn from the experimental, numerical, and machine learning investigations. This chapter discusses the effectiveness of the proposed curved T-shape spur dike in reducing scour, the influence of hydraulic and geometric factors on scour development, and the importance of optimal spacing in improving riverbank protection. Key insights obtained from the CFD simulations and machine learning analyses are also highlighted. Potential areas for further investigation include studies under live-bed conditions, field-scale validation, advanced numerical modeling approaches, and the application of emerging artificial intelligence techniques for scour prediction and other river engineering applications.

CHAPTER II

LITERATURE REVIEW

2.1 General

Spur dikes are hydraulic structures built out laterally into a river, offering benefits such as erosion control, bank protection, and better channel navigability, though not without drawbacks: the altered flow pattern they create can accelerate erosion immediately upstream and downstream of the structure, amplifying erosion in unprotected neighbouring reaches (Klingeman et al., 1984). Scour around bridge piers has received considerably more attention in the literature than scour around spur dikes, though recent years have seen growing efforts to identify the parameters governing scour depth at spur dikes and to understand the underlying mechanism, through flume studies of scour, sediment transport, flow characteristics, and bed topography (Li et al., 2024a, b; Akbar et al., 2024; Hu et al., 2022; Pandey et al., 2019; Vaghefi et al., 2012; Kuhnle et al., 2002; Kothyari and Ranga Raju, 2001; Przedwojski, 1995). Most such work has used I-shape (rectangular or straight) spur dikes, though researchers have increasingly turned to L- and T-shape spur dikes to cut scour depth further (Pradhan et al., 2024; Sumi et al., 2021; Mehraein et al., 2017; Vaghefi et al., 2015; Ghodsian & Vaghefi, 2009); Chakravarty et al. (2024) and Patel & Kumar (2024), for instance, found L- and T-shape spur dikes to reduce velocity and redirect flow more effectively, significantly cutting scour around them.

This chapter describes spur dikes as river training works, drawing on past literature. The discussion then shifted to the head shape and scour mechanism around spur dikes. It explicitly discusses the various factors that affect the scour geometry. It is further described how the minimum distance between the spur dikes in series effectively protects the entire riverbank. Finally, the developments and findings of numerical investigation and machine learning are discussed to model the scour depth around spur dikes.

2.2 Spur dikes as river training works

Bank-protection techniques have been used across Asia and the Far East for thousands of years, with the earliest recorded embankment breach dated to 111 B.C. and the earliest recorded use of stone-filled woven bamboo sausages to 3 B.C. (United Nations Commission for Asia and Far East, 1953). The type of spur dike adopted has varied with local needs, the materials available, and cost. A brief regional overview of spur dikes as part of river-training practice follows:

- In ancient India, different types of spur dikes were used, such as bandalling, pile spur dikes, tree spur dikes, porcupine spur dikes, and gabion spur dikes. Banding is an ingenious system of river training practiced since ancient times to confine low-flow water to a single channel (Singh, 1993). In eastern India, bandals are made from bamboo, measuring 15-18 m in length and 2.5-7.5 cm in diameter. These spur dikes are placed at 30° to 40° inclined downstream to slacken the flow and induce silt deposition. Pile spur dikes, made of piles and cross-timbers, have been successfully used in India due to their low cost and ability to be built in stages. Tree spur dikes consist of a thick wire rope anchored at one end to the bank and a heavy-duty or concrete block tied at the other. Porcupine spur dikes, made of bamboo porcupines, have been used to induce siltation along the scouring banks. Gabion spur dikes, made of stone-filled wire mesh crates, have successfully confined river flow along a desired course and reclaimed excess land. Wire mesh crate construction has many advantages over other types, such as flexibility, ease of handling and construction, ease of repair and replacement, and low cost (Palmer, 2020).
- In China, the Yellow River has faced constant bank caving for thousands of years, especially after the construction of its embankment system. Various river works, including spur dikes, have been attempted to protect the river, including the unique indigenous system known as "Sao," which uses sorghum stalks (United Nations Commission for Asia and Far East, 1953). However, sausages or cylinders made of willow bushes and stones are now more commonly used. Brushwood fascines were used to build permeable spur dikes that accumulated silt in bays formed by the spur dikes.

- In Burma, bamboo fences are used to train small flashy streams and reclaim land for crop production. Stake fences consist of 1.5 to 1.8 long bamboo, spaced 25 cm apart, driven parallel to the selected center lines at a predetermined distance (United Nations Commission for Asia and Far East, 1953). Banks form after floods over these fences, and a second fence is added at the top of the new bank. The same type of construction is used to close breaches and build spur dikes.
- In Japan, bank protection methods have been developed since the eighth century, with various permeable spur dikes in use. Wire mesh has been successfully recognized for swift river currents, cheap cobbles, and stones. Spur dikes are placed either perpendicular to the bank or inclined upstream at an angle of about 15 degrees.
- In the United States, a single design of permeable spur dike was used successfully for river-training work on the Missouri and the Middle Mississippi (Corps of Engineers, US Army, 1914). These structures were built from runs of timber piles driven in clumps spaced 4.5-5.5 m apart. To keep the pile foundations from being undermined, woven willow or lumber mattresses, weighted with ballast stone, were sunk into place at the base of the piles before driving.
- European river training was mostly done by constructing spur dikes at both banks, with the angle between the spur dikes and the axis of the rivers varying somewhat in different localities. Several types of solid spur dikes are constructed on European rivers, including fascine, fascine stone, sand and gravel mounds, and rubble mounds.
- In New Zealand and Australia, two special types of spur dikes have been built: low-level spur dikes and willow spur dikes. Low-level spur dikes are submerged stone-mesh spur dikes built up strongly from the river bed, while willow spur dikes are built where conditions favor vigorous willow growth.

2.3 Head shape of spur dikes

Scholars have described spur dikes in the literature as I-, L-, and T-shape. Each shape has its own advantages and disadvantages (Chakravarty et al., 2024). The details of these shapes are discussed in the following subsections.

2.3.1 I-shape spur dikes

Ahmad (1953) was the earliest scholar to study scour phenomena around spur dikes and described the various factors, such as spur geometry, spur dike length, flow conditions, etc., that affected scour depth. Later, many scholars investigated scour and the flow mechanisms around spur dikes and similar hydraulic structures, such as abutments. Barbhuiya and Dey, (2004), Pandey et al., (2018), and Tripathi & Pandey, (2022) reviewed these investigations in their research. Table 2.1 presents a literature survey of I-shape spur dikes, and the findings explain the scour mechanisms and behaviours around these structures.

2.3.2 L- and T-shape spur dikes

L- and T-shape spur dikes offer several advantages over the conventional I-shape, including better hydraulic performance and greater scour reduction: they lower turbulence, improve flow diversion and sediment deposition, raise hydraulic efficiency, adapt well to site conditions, and need less frequent maintenance and repair, making them an attractive choice for river training and scour control (Chakravarty et al., 2024). Fewer studies exist of these shapes than of the I-shape, and those that do exist concentrate mainly on scour characteristics such as its dimensions, features, and behaviour; Table 2.2 reviews this literature on L- and T-shape spur dikes. It shows L- and T-shape spur dikes to give better results by altering the flow structure, though their performance still depends chiefly on geometry, hydraulic conditions, and placement.

2.4 Scour mechanism

Scour around river structures such as piers, abutments, and spur dikes involves complex three-dimensional flow and sediment transport, with both the rate of scouring and the flow pattern evolving until equilibrium is re-established (Patel et al., 2023). It

originates in an adverse pressure gradient that forces three-dimensional separation of the boundary layer a short distance upstream of the structure; the separated flow rolls up to form the horseshoe vortex (Figure 2.1), and scour begins once the shear stress this vortex generates exceeds the threshold for entraining the bed material (Sumer et al., 1995). This mechanism at spur dikes is now well documented (Nandhini et al., 2024; Gupta et al., 2025; Kuhnle & Alonso, 2013; Koken & Constantinescu, 2008; Melville, 1992), and a parallel body of work covers the closely related case of abutments, which behave hydraulically like short spur dikes (Mohammadpour et al., 2021; Mohamed et al., 2016; Lim, 1997). Acting as a bluff body, the upstream face of a spur dike generates stagnation pressure that weakens toward the bed, producing a downflow that strikes the bed as a vertical jet and is important in initiating scour. Once a hole has formed, this downflow turns to run parallel to its base and joins the oncoming flow to form the principal vortex (Li et al., 2024a).

Figure 2.2 reproduces the vortex system that Kwan (1987) measured at a wing-wall abutment, a flow structure believed to carry over to other abutments and flow conditions. His measurements showed the primary vortex to be roughly elliptical in cross-section, its major axis parallel to the scour-hole surface, with its core located 0.5-1.0 D below the original bed and 1.5-2.0 D from the abutment edge (D being the approach-flow depth), rotating at 0.5 rev/s. Tangential-velocity measurements further indicated an inner core behaving like a forced vortex and an outer core like a free vortex, together resembling a Rankine vortex. This primary vortex is balanced by vortices generated at the bed and abutment edge, and to a lesser extent by the surrounding flow; the field also contains a counter-rotating secondary vortex driven by the primary one, together with wake vortices from flow separation at the abutment - unstable shear layers that break into eddies and are carried downstream into regions of lower pressure.

Table 2.1: Summary of the most relevant research on I-shape spur dikes

Studies	Title	Focus of Study	Key Findings
Gill, (1972)	Erosion of sand beds around spur dikes	Laboratory experiments on straight spur dikes under clear-water conditions	Modified Straub's kinematic erosion model, developed originally for a long contraction, for application to spur dikes, and showed equilibrium scour depth to depend on sediment size and the flow depth upstream of the structure
Garde et al., (1961)	Study of scour around spur dikes	Flume experiments on rigid rectangular spur dikes	Showed scour depth increases with flow intensity and spur length
Rajaratnam & Nwachukwu, (1983)	Flow near groin-like structures	Experimental investigation of flow structure around straight groynes	Analysed the deflected flow as a three-dimensional turbulent boundary layer and shear layer, and described the amplified bed shear stress near the groyne tip on a fixed bed
Kuhnle et al., (2002)	Local scour associated with angled spur dikes	Laboratory scour experiments on straight spur dikes at different alignment angles	Demonstrated alignment angle strongly influences scour depth and scour-hole location

Studies	Title	Focus of Study	Key Findings
Uijtewaal, (2005)	Effects of groyne layout on the flow in groyne fields: laboratory experiments	Laboratory experiments on straight groyne fields	Showed groynes significantly alter near-bank velocity distribution and turbulence
Dey & Barbhuiya, (2005)	Time variation of scour at abutments	Time-dependent scour experiments applicable to straight spur dikes	Identified rapid initial scour followed by a slow approach to equilibrium
Kuhnle & Alonso, (2013)	Flow near a model spur dike with a fixed scoured bed	Laboratory experiments over a pre-scoured bed around a straight spur dike	Demonstrated feedback between scour geometry and near-bed flow structure
Rashak & Khassaf, (2020)	Study the local scour around different shapes of single submerged groyne	Flume experiments including straight single submerged groyne	Reported scour depth increases with submergence and flow intensity
Bahrami-Yarahmadi et al., (2020)	Study of scour and flow patterns around triangular-shaped spur dikes	Experimental comparison with rectangular spur dike as reference	Showed modified shapes reduce scour relative to rectangular spur dikes
Özyaman et al., (2022)	Experimental investigation of scouring around a single spur under clear water conditions	Clear-water laboratory experiments on a straight spur dike	Identified effects of sediment gradation, flow depth, spur angle, and spur length on scour depth and volume

Studies	Title	Focus of Study	Key Findings
Farshad et al., (2022)	Temporal scour variations at permeable and angled spur dikes under steady and unsteady flows	Laboratory experiments on permeable and angled spur dikes under steady flow and flood hydrographs of different duration	Permeability reduced scour more effectively than a favourable orientation angle; proposed an empirical model for time-dependent scour depth
Esmaeli et al., (2022)	Experimental investigation of permeability and length of a series of spur dikes effects on the control of bank erosion in the meandering channel	Series of straight spur dikes in a meandering flume	Showed spur length and permeability significantly influence erosion control
Xu et al., (2023)	Experimental study on the local scour of submerged spur dike heads under the protection of soft mattress in plain sand-bed rivers	Laboratory experiments on submerged spur dike heads with soft-mattress bed protection	Derived formulas for the maximum local scour depth of a submerged spur dike and its distance from the dam axis
Qi et al., (2024)	Characteristics and mechanism of local scour reduction around spur dike using the collar in clear water	Flume experiments on straight spur dike with collar	Reported significant scour reduction and downstream shift of maximum scour

Studies	Title	Focus of Study	Key Findings
Al-Awadi et al., (2025)	Investigating the morphological changes of scour hole around gabion spur dikes	Experimental study on rectangular gabion spur dikes	Quantified scour-hole geometry and proposed empirical relationships

Table 2.2: Summary of the most relevant research on L- and T-shape spur dikes

Studies	Title	Focus of Study	Key Findings
Ghodsian & Vaghefi, (2009)	Experimental study on scour and flow field in a scour hole around a T-shape spur dike in a 90° bend	Flume study of T-shape spur dike in a bend; measured scour geometry + flow field	Reported that bend-induced secondary currents interact with the T-head to intensify local turbulence and control scour-hole shape and position
Vaghefi et al., (2012)	Experimental study on scour around a T-shaped spur dike in a channel bend	Physical modeling of unsubmerged T-shape spur dike in a bend; bed topography/scour geometry	Showed T-head modifies approach flow and shifts maximum scour location; provided scour patterns for bend placement and flow intensity
Dehghani et al., (2013)	Local scouring around L-head groynes	Extensive flume tests comparing straight vs L-head groynes; included dye visualization	Found L-head geometry can reduce maximum scour compared with a straight spur; identified how orientation affects scour depth and deposition zones

Studies	Title	Focus of Study	Key Findings
Kumar & Ojha, (2021a)	Near-bed turbulence around an unsubmerged L-head groyne	Laboratory ADV/near-bed turbulence study around unsubmerged L-head	Reported turbulence structure (TKE/Reynolds stresses) that explains scour initiation near the groyne head and deposition in the wake
Kumar & Ojha, (2021b)	An investigation on mechanisms of equilibrium-stage scour and deposition process around a submerged L-head groyne	Experiments on submerged L-head; equilibrium scour and deposition mechanisms	Described equilibrium scour-hole geometry and stable deposition region; explained the role of wake circulation under submergence
Tripathi & Pandey, (2021)	Experimental study of local scour around T-shaped spur dike in a meandering channel	Flume experiments in a meandering/curved planform; T-shape spur dike location effect	Demonstrated scour magnitude depends strongly on T-dike placement; suggested preferred zones for minimizing maximum scour
Akbari et al., (2021)	Effect of T-shaped spur dike length on mean flow characteristics along a 180-degree sharp bend	Physical model in 180° bend; T-head length variation; ADV velocity measurements	Showed increasing T-length changes flow redistribution and secondary currents, influencing likely scour intensity around the head

Studies	Title	Focus of Study	Key Findings
Patel & Kumar, (2023)	Hydro-morphological behavior around T-shaped spur dikes with downward seepage	Experiments on T-shape spur dike field with different seepage levels	Reported seepage increases erosion tendency and alters bed response; upstream elements often govern maximum scour in a spur field
Patel et al., (2024)	Downward seepage effects on flow near a L-shape spur dike and bed morphology	Flume study on L-shape spur dike under downward seepage	Showed seepage modifies near-bed flow and enhances scour depth; documented corresponding changes in bed topography
Pradhan et al., (2024)	Investigation on scouring and turbulence characteristics around T-head spur dike	Experimental study varying T-head geometric parameters (length/wing)	Quantified sensitivity of scour depth to head dimensions; linked scour reduction/increase trends to measured turbulence parameters
Patel & Kumar, (2024)	Experimental study on the optimal spur dike shape under downward seepage	Physical modeling comparing spur shapes (includes L and T among candidate shapes) with seepage	Compared shapes under identical seepage/hydraulic conditions; identified which geometry better limits scour while maintaining flow deflection

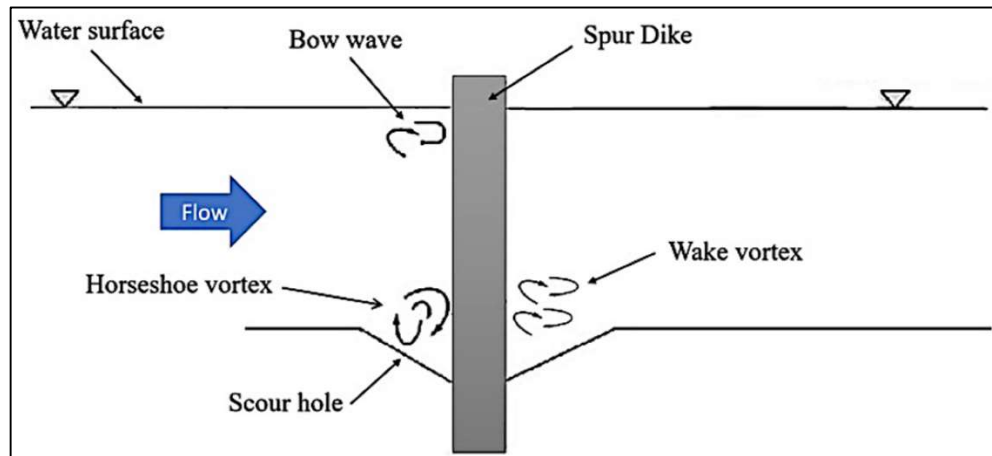


Figure 2.1: Formation of vortex around spur dikes (Ghaderi & Abbasi, 2019)

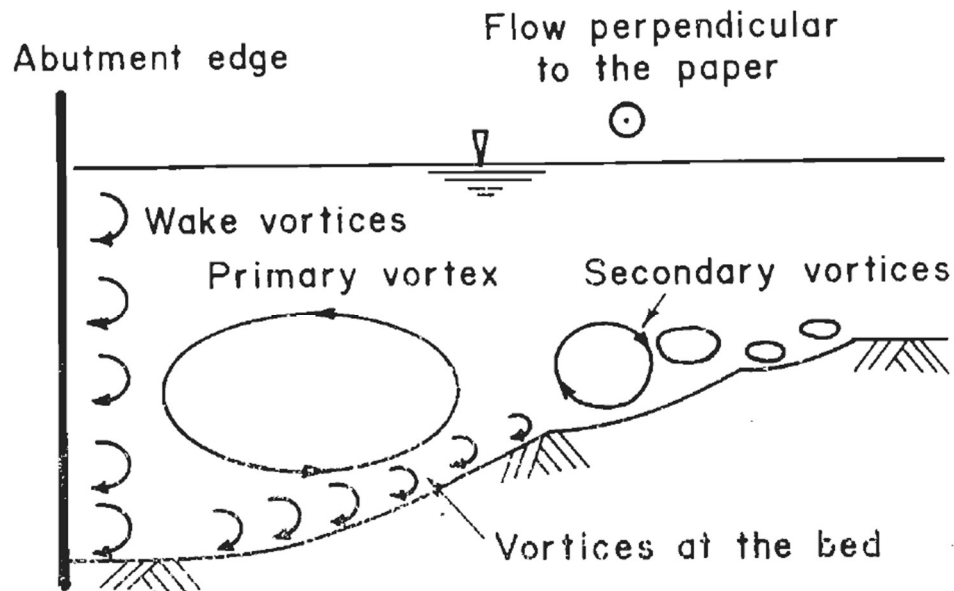


Figure 2.2: Phenomenon of vortex system (Kwan, 1987)

Several other scholars - Copeland (1983), Dongguang et al. (1998), Koken & Constantinescu (2008), Koken & Gogus (2015), Jeon et al. (2018), and Kang et al. (2023) - reported the same vortex pattern Kwan (1987) observed. Jeon et al. (2018) identified two distinct vortex systems around a spur dike: a horseshoe vortex upstream that intensified lateral turbulent mixing, particularly near the bed, and a second, oppositely rotating vortex that raised the free-surface elevation and its fluctuations.

Koken & Gogus (2015) further observed a vortex undergoing bimodal oscillation, raising turbulent kinetic energy and pressure fluctuation along its axis. Understanding how these vortices form is central to designing spur dikes that limit the resulting scour.

2.4.1 Force field and energy dissipation in the scour process

The removal of bed material near a spur dike follows from the balance of forces on an individual particle resting on the bed: drag and lift from the near-bed flow tend to dislodge it, while its submerged weight and the friction of surrounding grains resist this (Dey, 2014). A particle is entrained once the moment of the destabilising forces about its point of support exceeds that of the resisting forces, a balance that defines the critical shear stress (τ_c) and critical velocity (U_c). The obstruction a spur dike poses raises the destabilising forces locally well above their approach-flow values, so scour can start even when U/U_c is below unity. This local intensification stems from three flow features the obstruction itself generates. The first is the stagnation pressure on the spur dike's upstream face, and the downflow it produces, striking the bed as a vertical jet at the base of the structure. The second is the horseshoe vortex, formed as the approaching boundary layer separates ahead of the structure and rolls into the developing hole; its coherent, highly unsteady structures raise bed shear stress within the hole above the approach-flow value (Kirkil et al., 2008). The third is the set of wake vortices shed from the tip of the spur dike, nearly vertical in axis, which lift sediment from the bed and carry it downstream (Melville & Coleman, 2000).

Particle entrainment depends not just on the size of the instantaneous force but also on how long it acts, since the near-bed flow around a spur dike is turbulent and the drag and lift on a particle fluctuate continuously. Diplas et al. (2008) showed experimentally that a large force of very short duration may fail to move a particle where a smaller, longer-acting one succeeds, and proposed impulse, the product of force and the time it acts, as the criterion for the onset of particle motion. Here, this implies that sediment removal near the spur-dike nose is governed by the impulse delivered by the energetic vortex structures, not merely by the time-averaged shear stress.

The scour process can equally be viewed in terms of energy dissipation. As flow approaches a spur dike, part of its mechanical energy is dissipated in the separated flow, the vortices, and the turbulence around the structure. Annandale (1995, 2006) linked the erosion of an earth material to the rate of energy dissipation at its boundary with the flow, expressed as stream power, showing that erosion occurs only once this rate exceeds a material-dependent threshold. On this basis, a scour hole forms because the rate of energy dissipation at the bed initially exceeds the threshold of the bed material, and continues to deepen until its geometry spreads the flow enough to bring that dissipation back down to the threshold - the equilibrium SD being the point at which the erosive power of the flow and the resistance of the sediment are in balance. Melville & Raudkivi (1977) observed that, as the hole deepens, the flow's attack on the bed near the structure's base weakens, slowing the rate of scouring with time, and Hoffmans & Verheij (1997) described the growth of scour holes in the same terms, as a progressive reduction in the flow's attack on the bed as the hole deepens.

2.5 Factors affecting scour around spur dikes

Several variables affect scour around a spur, and the interaction between the flow around a spur dike and the erodible bed material surrounding it is complex. Some of the important factors associated with the scour process, viz., the geometry of the spur dike, bed material, stream flow conditions, and time, are discussed below.

2.5.1 Influence of spur geometry on scour

Spur dikes can be built in many sizes and shapes. Their geometry is generally described through the size of the obstruction (its projected length), a shape factor capturing differences in head form, the permeability of the structure, the angle it makes with the approach flow (its alignment), its position relative to the stream, and its degree of submergence. Each is discussed below:

2.5.1.1 Length of spur dikes

For a given channel, an increase in projected spur dike length (b) corresponds to a greater contraction of the flow section and, hence, a direct increase in the blockage

(constriction) ratio (b/B). Laursen (1952), Laursen & Toch (1953), Garde et al. (1961), and Hedman (1965) found that the blockage ratio is the most important term characterizing the spur/abutment geometry. In their study, with the approach velocity held constant, they observed that the maximum scour depth increased with increasing blockage ratio.

Kandasamy (1989) presented the streamline patterns around short, medium, and long abutments in Figure 2.3. As abutment length grows, more of the upstream flow is intercepted, but the angle of attack of that flow falls as the dead-water region expands, so scour depth keeps rising but at a diminishing rate. Kuhnle et al. (1999), studying two spur dikes, found longer ones to scour more than shorter ones, while Garde & Chandra (1969) argued that the blockage ratio of a spur should be kept small - below about 0.30 - to minimise its interference with the river's flow regime. Kondap & Prayag (1989) similarly found a blockage ratio near 0.2 to give the smallest rise in discharge intensity at the spur nose, with scour depth rising sharply beyond that value; their plot of blockage ratio against discharge density (Figure 2.4) showed the latter increasing with the former. Short spur dikes in high flows may therefore scour back to their root, threatening their stability, and bed shear stress likewise rises with blockage ratio (Rajaratnam & Nwachukwu, 1983).

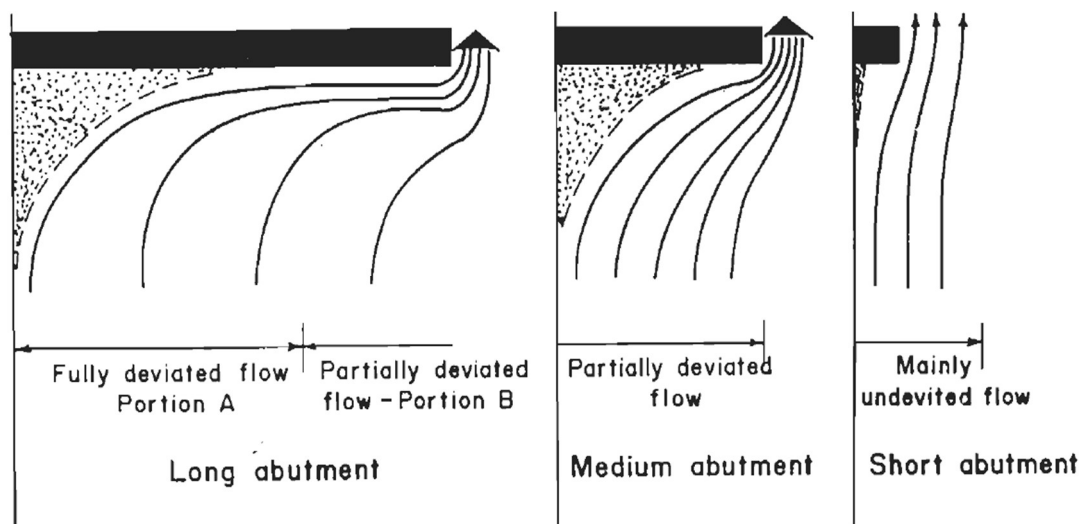


**Figure 2.3: Streamlines pattern of flow moving past different abutments
(Kandasamy, 1989)**

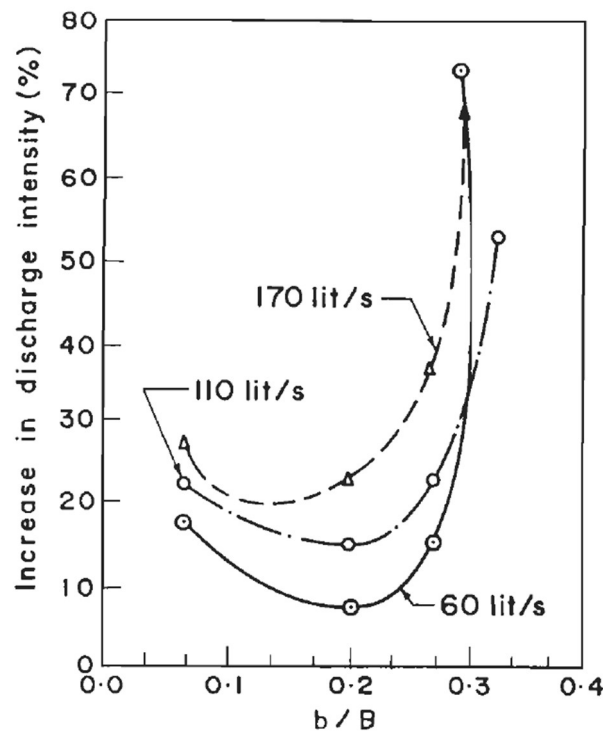


**Figure 2.4: Effect of blockage ratio of spur dikes on discharge density
(Rajaratnam & Nwachukwu, 1983)**

2.5.1.2 Spur alignment

Spur-dike alignment is defined by the angle (θ) the spur makes with the flow direction, measured from downstream. Relative to a perpendicular spur ($\theta = 90^\circ$), upstream-pointing spur dikes give deeper scour - up to 10% more at angles between 150° and 180° - while scour depth falls as θ decreases, reaching a maximum reduction of 17% for a spur pointed downstream at 30° (Melville, 1992).

Ahmad (1953) was among the first to study how the angle of inclination of a spur affects scour, finding the maximum at 130° and 150° (Figure 2.5); the associated flow and siltation patterns are shown in Figure 2.6 (U.S. Department of Agriculture, 1980). Sastry (1962) found scour depth to increase with inclination angle while the scour location shifted progressively upstream, and Singh et al. (1970) found spur dikes deflecting the flow (at 90°) to work well in straight reaches, though protection was still needed against scour near the nose.

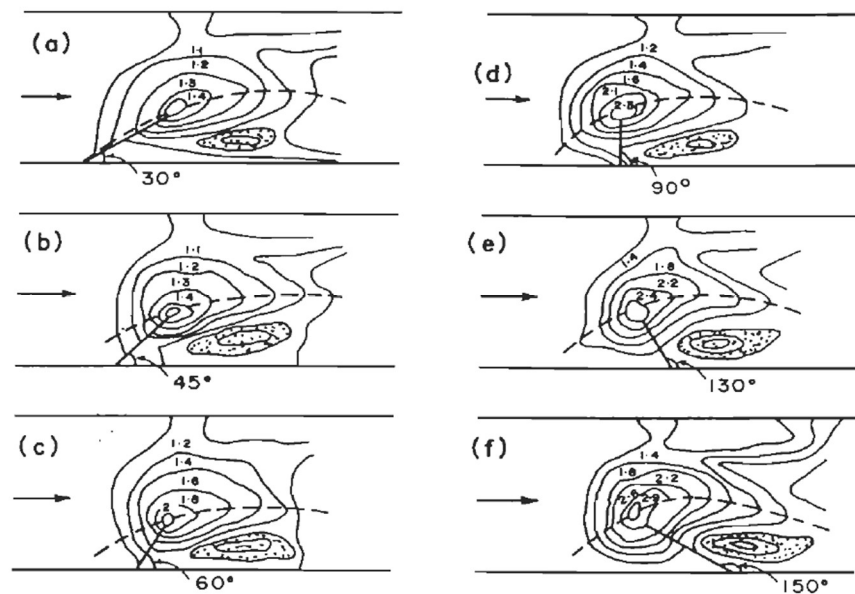


Figure 2.5: Scour pattern around spur dikes with different angles Ahmad (1953)

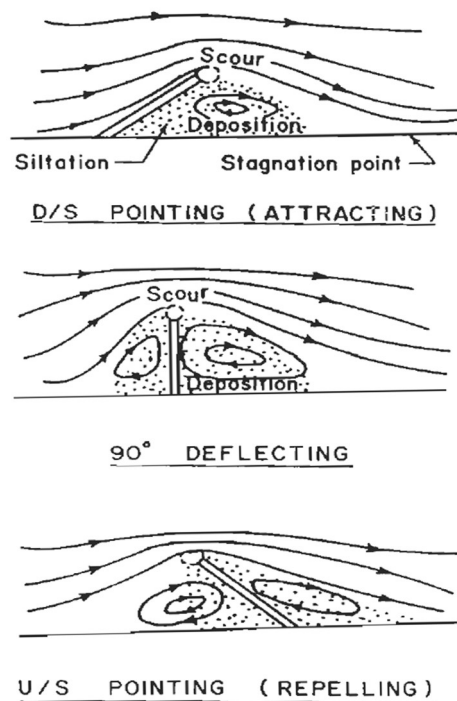


Figure 2.6: Flow and siltation pattern around different types of spur dikes (U.S. Department of Agriculture, 1980)

Kuhnle et al. (2002) found 90° spur dikes to erode the bed least and 135° ones the most, of three angles tested (60°, 90°, 135°), while Giglou et al. (2018), testing 45°, 75°, 90°, 105°, and 120° spur dikes, found that increasing the angle from 90° to 120° substantially enlarged the sedimentation area, widening it by about 71% and lengthening it by about 92%.

2.5.1.3 Shape of spur dikes

Spur-dike shape has a strong bearing on sediment transport, flow pattern, and scour behaviour, and researchers have accordingly developed I-, T-, and L-shape spur dikes to reduce scour. Of these, the traditional I-shape produces the most scour through concentrated vortices, the T-shape redistributes the flow efficiently to reduce scour, and the L-shape lowers erosive forces and thereby encourages sediment deposition (Chakravarty et al., 2024).

A spur dike obstructs flow much as a bridge pier or abutment does, so evidence from those structures on how nose shape affects scour is also relevant. Design equations account for this through a shape factor, with the values Melville (1997) gives for abutments and Melville & Coleman (2000) give for piers both lower for streamlined shapes than for blunt ones. Vijayasree et al. (2019), testing rectangular, oblong, trapezoidal, triangular, and lenticular piers of a common aspect ratio, found upstream scour to be greatest at the leading edge of the rectangular pier and least at the lenticular pier, with the flow bifurcating immediately at the triangular and lenticular noses to give less scour than the other shapes; even so, the horseshoe vortex remained the dominant scour agent across every shape, sharp edges included. Ghaderi & Abbasi (2019), simulating flow around airfoil-shaped piers in FLOW-3D, found the uplift vortices behind the pier almost eliminated, so that no scour occurred there, with the sharp edge facing the flow weakening the horseshoe vortex. This vortex is a secondary flow that develops inside the scour hole (Dey et al., 1995), its coherent structures raising bed shear stress above the approach-flow value (Kirkil et al., 2008), so a nose that divides or gradually turns the approaching flow can be expected to weaken it and reduce scour.

This same principle applies more broadly to river-training structures. Using FLOW-3D, Choufu et al. (2019) numerically studied how the orientation and spatial arrangement of groynes affect flow pattern, bed erosion, and sedimentation, finding that arranging groynes from large to small at 45° cut scour depth by up to 55%, and arranging them from small to large at 135° cut it by up to 72%. Bahrami-Yarahmadi et al. (2020), who inclined the horizontal crest of rectangular spur dikes into a triangular shape, found the resulting maximum scour depth and volume to be, on average, 44% and 70% smaller, respectively, than around equivalent rectangular spur dikes.

These studies indicate that the shape of the part of the structure that faces the flow governs the strength of the vortices and, consequently, the scour. The flange of the conventional T-shape spur dike is straight and presents a blunt face to the approach flow, whereas the curved flange of the proposed spur dike presents a progressively turning face. This is expected to reduce the stagnation pressure gradient, weaken the downflow and the horseshoe vortex, and thereby reduce the scour at the nose of the spur dike

2.5.1.4 Channel geometry

Rafiqii et al., (2024) found that channel geometry significantly affects scour, thereby affecting the design of spur dikes in any river. Key aspects of geometry, such as channel slope, channel width, material of the bed and banks, and cross-sectional shape, influenced current generation and enhanced scour. Narrow channels increase scour depth due to higher flow velocity and restricted flow area, while wide channels distribute flow energy over a larger area (Li et al., 2023). Channel depth can be shallow, deep, or steep, and different interactions between the structure and flow can easily affect the scour depth. Channel slope, flow alignment with channel geometry, channel constriction, and the influence of secondary currents also contribute to determining scour depth.

2.5.2 Sediment size and gradation

Scour occurs locally wherever the shear stress the flow generates around a spur dike exceeds that of the approach flow. Once this exceeds the critical value for incipient

sediment motion, the properties of the bed material become important: channel boundaries are typically a non-homogeneous mix ranging from boulders down to silt and clay, and the resulting deposits can show complex grain-size distributions and stratification.

Alluvial river sediment is most simply described by its median particle size (d_{50}), which is adequate for uniform material but not for non-uniform material (Melville, 1992), since different size fractions resist scour differently and interact in complex ways. Sediment non-uniformity is instead captured by the geometric standard deviation of the particle-size distribution, σ_g , defined as (Breusers & Raudkivi, 1991):

$$\sigma_g = (d_{84}/d_{16})^{1/2} \quad (2.1)$$

$$\text{or } \sigma_g = d_{84}/d_{50} = d_{50}/d_{16} \quad (2.2)$$

Here, σ_g is the geometric standard deviation of the sediment particle-size distribution, d_{84} the particle diameter for which 84% of the sediment is finer by weight, and d_{16} the particle diameter for which 16% is finer by weight.

Laursen, (1952; 1962) stated that the maximum scour depth is independent of the sediment size. Izzard & Bradley, (1958) considered that sediment size and standard deviation affect only the rate of scour, not the maximum scour depth. However, according to Inglis, (1949) and Ahmad, (1953) changes in sediment size affect the maximum scour depth. Iwagaki et al., (1958) emphasized the role of sediment size and noted that the coefficient of drag (CD) is a significant parameter that accounts for both sediment size and specific weight. Garde et al., (1961) and Nambudripad, (1961) also indicated that the sediment size has an influence on the maximum scour depth and that the drag coefficient of the sediment particle can account for its characteristics. Neill, (1962) observed that the drag coefficient is nearly constant for particles coarser than 1.5 mm. Thus, scour is independent of sediment size above 1.5 mm.

Tyagi (1973) found sediment size and specific gravity to affect scour depth. Ettema (1980) and Chiew (1984) analysed, respectively, clear-water and live-bed scour at circular piers in uniform sediment, showing the equilibrium scour depth, D_{sm} , to

increase with relative sediment size (b/d_{50}) up to $b/d_{50} = 50$ and to become independent of sediment size beyond that, a relationship Melville (1997) also observed. Vegas Merino et al. (2005) found sediment characteristics to significantly affect scour depth, while Pandey et al. (2021b) found scour depth to decrease as sediment non-uniformity increased. Muzzammil and Gangadhariah (2003) and Bihs & Olsen (2011) linked the angle of repose of the soil to scour depth, arguing that it reflects the architecture of the scour hole and is relevant to forecasting it and examining local vortex features, and Zhang et al. (2017) found the angle of repose of the sediment to be slightly greater than the slope of the scour hole.

These findings appear contradictory only because they cover different ranges of conditions. Laursen (1952; 1962) and Izzard & Bradley (1958) worked mainly with fine, nearly uniform sand, for which the ratio of obstruction width to median particle size (b/d_{50}) is large, and under these conditions, grain size affects only the rate of scour, not its maximum depth. Inglis (1949) and Ahmad (1953), by contrast, derived their relations from regime theory and field observation on Indian rivers, where the silt factor itself carries the effect of particle size, so a dependence of scour depth on sediment size emerges. The disagreement, therefore, reflects the different ranges of relative sediment size the studies covered, not a difference in the underlying physics.

The results of Ettema (1980), Chiew (1984), and Melville (1997) can be used to reconcile the two positions. According to them, the equilibrium scour depth increases with the relative sediment size up to $b/d_{50} = 50$ and is independent of grain size beyond that value. The studies in which the sediment size had no effect correspond to the range $b/d_{50} > 50$, whereas those in which it had an effect correspond to smaller values of b/d_{50} . The observation of Neill (1962) that the drag coefficient is nearly constant for particles coarser than 1.5 mm leads to the same conclusion from the side of the force field. Since the effect of the sediment on scour was expressed through the drag coefficient by Iwagaki et al. (1958) and Garde et al. (1961), a drag coefficient that no longer varies with the particle size implies that the grain size also ceases to influence the scour depth. The same reasoning applies to the non-uniformity of the sediment. The armouring effect reported by Pandey et al. (2021b), in which the scour depth

decreases with increasing non-uniformity, can operate only when the finer fractions are present in sufficient quantity to be washed out and leave a coarse layer behind (Raudkivi & Ettema, 1983). For a uniform sediment, such as the one used in the present study, no such armour layer forms. The practical consequence is that the range of validity of a scour relation, with respect to b/d_{50} and to the gradation of the sediment, must be checked before the relation is used or before the results of different studies are compared.

2.5.3 Approach flow

The influence of stream flow characteristics such as flow intensity, sediment transport in approach flow, flow depth, velocity, etc., on scour is discussed below:

2.5.3.1 Flow intensity

Scour at spur dikes can occur under either clear-water or live-bed conditions (Raudkivi & Ettema, 1983): the former applies for velocities up to the threshold for general bed movement ($U/U_c < 1$), the latter for $U/U_c > 1$. In the clear-water regime, U/U_c is equivalent to the shear-velocity ratio (u^*/u_{*c}), and either ratio can express the effect of velocity on scour; in the live-bed regime U/U_c is preferred, since u^*/u_{*c} is hard to measure once the bed deforms. Maximum scour at a pier or spur dike coincides with the threshold of sediment motion, the boundary between the two regimes, so design is generally governed by this worst case, with clear-water scour at $U/U_c \approx 1.0$ taken as more critical than live-bed scour. Figure 2.7 plots scour depth as a function of time and approach velocity. Melville (1997) derived the threshold velocity (U_c) from the Shields diagram as:

$$\frac{U_c}{u_{*c}} = 5.75 \log \left(5.53 \frac{D}{d_{50}} \right) \quad (2.3)$$

Where $u_{*c} = 0.0115 + 0.0125 * d_{50}^{1.4}$, if $0.1 \text{ mm} \leq d_{50} \leq 1 \text{ mm}$ and $0.0305 * d_{50}^{0.5} - 0.0065 * d_{50}^{-1}$, if $1 \text{ mm} < d_{50} \leq 100 \text{ mm}$. The u_{*c} is in m/s, and d_{50} is in mm. Lauchlan & Melville, (2001) modified this equation by replacing the d_{50} with k_s . So, the equation becomes:

$$\frac{U_c}{u_{*c}} = 5.75 \log \left(5.53 \frac{D}{k_s} \right) \quad (2.4)$$

Here, k_s is the height of the equivalent roughness, assigned the value $2d_{50}$, as used by Dey & Barbhuiya, (2005).

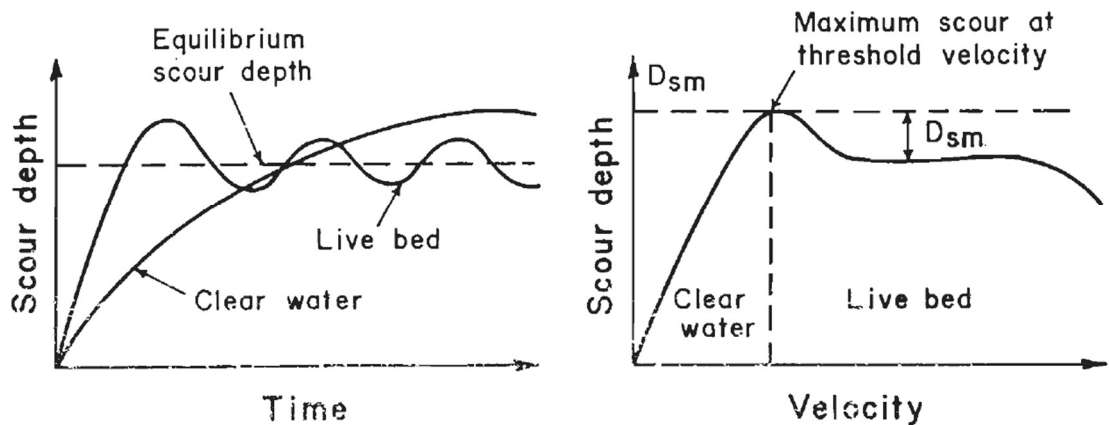


Figure 2.7: Scour depth as a function of time and approach velocity (Raudkivi & Ettema, 1983)

Several researchers, including the early studies of Laursen & Toch (1956), Laursen (1958), and Shen et al. (1966), have stressed that clear-water and live-bed scour differ enough to warrant separate treatment. In clear-water scour, no sediment reaches the hole from upstream, whereas in live-bed scour sediment continues to arrive, and equilibrium is reached once supply matches removal. Melville (1997) examined how flow velocity affects scour depth under each regime, noting that U/U_c determines whether bed grains move at all: for U/U_c below 1.0, clear-water conditions hold for both uniform ($\sigma_g < 1.3$) and non-uniform ($\sigma_g > 1.3$) sediments. Dongol (1994) ran extensive tests on how flow intensity affects abutment scour under live-bed conditions for both sediment types, complementing the earlier work of Chiew (1984) and Baker (1986) on live-bed scour at piers in uniform and non-uniform beds, respectively.

2.5.3.2 Flow depth

Kandasamy (1989), working from a three-dimensional plot of laboratory measurements, mapped the zones in which scour depth depends differently on flow

depth and abutment length. In deep flow relative to the pier or abutment size, he found scour depth to scale with spur length (b) rather than flow depth (D), consistent with earlier pier studies (Ettema, 1980; Raudkivi, 1986; Melville & Sutherland, 1988). Ettema (1980) attributed this, for shallow flow, to a surface roller ahead of the pier that opposes the horseshoe vortex, since the two rotate in opposite senses; as flow depth increases this interference weakens and eventually disappears. Thus, in shallow flow the maximum scour depth (D_{sm}) scales with D and is largely unaffected by b , whereas at intermediate depths D_{sm} depends on both D and b (Kandasamy, 1989). At greater depths, the strength of the equivalent flow features at an abutment is tied to its transverse size, so scour depth again tracks pier or abutment size. Gill (1972) likewise found scour depth around spur dikes to depend on flow depth, a result Tey (1984) also reported for bridge abutments. Other researchers, however, found mean velocity to matter more than depth: Liu et al. (1961) reported that, other conditions being equal, a higher mean velocity produces deeper scour, and Laursen (1962) identified velocity and sediment size as the governing parameters for clear-water scour, treating them as relatively unimportant for live-bed scour beyond determining the mode of sediment transport. Melville (1992) drew on these ideas to classify abutment scour, giving the envelope curves and depth-size expressions below:

$$K_{Db} = 2b, \quad \text{for } \frac{b}{D} \leq 1 \quad (2.5)$$

$$K_{Db} = 2\sqrt{Db} \quad \text{for } 1 < \frac{b}{D} < 25 \quad (2.6)$$

$$K_{Db} = 10D \quad \text{for } \frac{b}{D} \geq 25 \quad (2.7)$$

The equations apply to short, intermediate-length, and long abutments, respectively. According to equations (2.5, 2.6, and 2.7), there are three ranges of scour depth dependence: D_{sm} proportional to b for short abutments, D_{sm} proportional to $(Db)^{0.5}$ for intermediate-length abutments, and D_{sm} proportional to D for long abutments.

2.5.3.3 Froude Number

Garde et al. (1961), Liu et al. (1961), Paintal & Garde (1965), and Tyagi (1973) all showed the Froude number to be a significant parameter capturing the effect of flow characteristics on maximum scour depth. Dehghani et al. (2013), testing spur dikes to examine this effect, found scour depth to increase with Froude number regardless of spur-dike type. Masjedi et al. (2011), testing spur dikes in a 180° bend flume under clear-water flow, examined the time development of scour under four Froude numbers (0.23, 0.25, 0.28, 0.35), with the perpendicular face of the spur set to 15% of the channel width, the parallel face to 50% of the perpendicular face, and the dikes positioned at 75°; they found dimensionless scour depth to increase with Froude number owing to stronger vortex formation near the dikes, a pattern consistent with Abbasi et al. (2011) and Dehghani et al. (2013).

2.6 Spacing of spur dikes

A single spur protects only a limited length of bank, with little effect beyond it, so spur dikes are normally used in series, spaced closely enough that currents cannot attack the bank between them and cause erosion instead of accretion. Ahmad (1951) found a single spur to protect a bank length of 3 to 5 times its own projection, and Kondap & Prayag (1989) recommended an optimum spacing of three times the projected spur length, extendable to at most four times; wider spacing suits convex banks, narrower spacing concave banks, with an intermediate value at crossings. The following equation may also be used to choose spacing:

$$L = \frac{K_1 D^{4/3}}{2gn_s^2} \quad (2.8)$$

Where L = spacing between spur dikes, D = depth of flow, g = acceleration due to gravity, n_s = Manning's roughness coefficient, and K_1 = constant (0.6).

Copeland (1983) tested a sand-bed flume with three bends and found the standard scour-prediction formulae unreliable for spur dikes on concave banks. Suzuki et al. (1987) reported straight-flume tests on uniform sand with a continuous series of impermeable spur dikes aligned along the side walls, while Przedwojski (1995)

presented field data from two concave bends of Poland's Warta River, showing scour depth to vary along the bend: it is greatest at spur dikes downstream of the bend apex and markedly smaller near the entrance and exit of the outer bank. Nakagawa et al. (1995) and Fukuoka et al. (2013) examined the scour mechanisms and flow dynamics of spur dikes in series, expressing spacing as the ratio of the distance between successive dikes to their length. Jian et al. (2018) tested multiple spur dikes at spacings of $2b$, $3b$, and $4b$ and found the least scour at the second dike for spacings of $2b$ to $3b$, while Majeed et al. (2022) found spacing the dikes equal to their own length to minimise scour between them.

2.7 Numerical investigation

Growing computational power has encouraged the use of numerical methods to study flow and scour around spur dikes. Tingsanchali & Maheswaran (1990) simulated the stress and depth-velocity distributions around spur dikes with a k -epsilon turbulence closure, and Ouillon & Dartus (1997) presented a 3D model that successfully and efficiently predicted reattachment length, water depth, and shear stress. Jia & Wang (1999) simulated spur-dike flow with a 2D finite-volume model, using a mixing-length model and a depth-averaged parabolic eddy-viscosity model for the turbulence and finding both to capture the influence of secondary flow and lateral slope.

Choi & Oh (2004) introduced a further 2D numerical model for flow around spur dikes, coupling a constant eddy-viscosity model with the upwind Petrov-Galerkin finite-element method, and found the downstream recirculation zone to be 12.5 and 2 times the spur-dike dimensions in length and breadth, respectively. Duan & Nanda (2006) simulated suspended-silt concentration in spur-dike fields by solving the 2D convection-diffusion equation alongside the 2D shallow-water equations, applying the model to several experimental and field cases and showing spur dikes to be effective at displacing suspended sediment in natural rivers. McCoy et al. (2008) proposed a 3D large-eddy-simulation model for a fully developed spur-dike field with various embankments, finding that the resulting large eddy produces a mixing layer extending into the embayment to a distance comparable with the flow depth, with bed shear stress inside the hollow reaching a maximum at the downstream spur dikes and jet-like fluxes

appearing parallel to them. Zhang et al. (2009), using a 3D non-linear $k-\epsilon$ model to simulate the turbulent flow in a local scour hole at a spur dike, found the simulated results to agree closely with experimental observation.

Yazdi et al. (2010) examined how discharge, direction, and spur-dike length affect the flow parameters around straight spur dikes in a rectangular channel, using a 3D numerical model with the $k-\omega$ turbulence closure. They found the recirculation-zone dimensions to stay fairly consistent across orientations below 200, with longer spur dikes producing larger recirculation zones, and the highest bed shear stress occurring at deflecting spur dikes rather than repelling or attracting ones. Karami et al. (2014) developed two SSIIM-2.0-based turbulence simulation models for scour around spur dikes that reproduced the experimental observations with only minor error, and Albano et al. (2016) modelled the damage spur dikes sustain from floating debris during flash floods, finding this damage could be reduced by choosing the position of the upstream and downstream spur dikes carefully.

Vaghefi et al. (2017) modelled the effect of submergence ratio on flow around T-shape spur dikes using the Navier-Stokes equations with a standard $k-\epsilon$ closure, finding eddy viscosity near the bed to fall by 42% as submergence ratio rose from 0% to 50%. Mirzaei et al. (2019), comparing several turbulence models for spur-dike flow, found large-eddy simulation to perform best and the renormalised-group model worst. Liao et al. (2021) built a repose-angle formula and a bed-geometry adjustment mechanism into a 2D mobile-bed model, improving the accuracy of predicted scour-hole geometry, while Gupta et al. (2025), testing three turbulence models (large-eddy simulation, renormalised-group, and $k-\epsilon$) in Flow-3D, found all three to predict scour depth successfully, with large-eddy simulation again the best performer.

2.8 Machine learning models

Hydraulics engineering, a field in civil and environmental engineering, deals with the behaviour of water flow in natural and man-made streams. Various traditional methods, such as theoretical, empirical, and CFD methods, are complex and time-dependent. To overcome these problems, machine learning methods have emerged as

a powerful tool. The implementation of machine learning methods is increasing day by day, as they efficiently handle large and complex datasets and reduce computational and experimental costs. These models are capable of capturing the non-linear relationship of variables and provide good results. It has been observed that researchers have used machine learning models to predict scour depth around these structures. Earlier investigations used conventional machine learning models, such as ANNs. Later, the researchers began using evolutionary models and ensemble models such as GEP, GMDH, random tree, random forest, and ANFIS, and found that these models demonstrated improved results than conventional machine learning. Various scholars have successfully used these models in their studies (Rahman & Chavan, 2024; Tola et al., 2023; Bonakdari et al., 2020; Pourzangbar et al., 2017; Etemad-Shahidi et al., 2011; Azamathulla et al., 2010; Goel & Pal, 2009).

Azmathullah et al. (2005) found ANN models to outperform traditional equations for predicting scour depth, and Nassar et al. (2009) found an SVM model to outperform other approaches for scour at sluice gates. Kazeminezhad et al. (2010) likewise found an ANN model for scour around submarine pipelines to outperform an empirical one. Such results have drawn spur-dike researchers toward machine-learning methods, and Table 2.3 reviews this literature for spur dikes and abutments.

Table 2.3: Summary of the most relevant machine-learning-based research on predicting scour depth around spur dikes and abutments

Studies	Title	Applied Models	Best Model
Muzzammil, 2008	Application of neural networks to scour depth prediction at the bridge abutments	ANN	ANN
Şarlak & Tiğrek, 2011	Analysis of experimental data sets for local scour depth	ANN	ANN

Studies	Title	Applied Models	Best Model
	around bridge abutments using artificial neural networks		
Azamathulla, 2012	Gene-expression programming to predict scour at a bridge abutment	GEP and ANN	GEP
Najafzadeh et al., 2013	GMDH based back propagation algorithm to predict abutment scour in cohesive soils	GMDH-BP, ANFIS, RBF- NN	GMDH- BP
Basser et al., 2014	Predicting optimum parameters of a protective spur dike using soft computing methodologies – A comparative study	SVR, ANFIS and ANN	SVR
Hosseini et al., 2016	Prediction of time-varying maximum scour depth around short abutments using soft computing methodologies - a comparative study	NLR, ANN and ANFIS	ANFIS
Vaghefi et al., 2020	Application of artificial neural networks to predict flow velocity in a 180° sharp bend with and without a spur dike	ANN	ANN

Studies	Title	Applied Models	Best Model
Pandey et al., 2021a	Prediction of maximum scour depth near spur dikes in uniform bed sediment using stacked generalization ensemble tree-based frameworks	MARS, MGGP, KELM, BRT and BGT	BRT and BGT
Pandey et al., 2022	Assessment of scouring around spur dike in cohesive sediment mixtures: A comparative study on three rigorous machine learning models	GBDT, CFNN and KRR	GBDT
Delavari et al., 2022	Scour depth prediction around bridge abutment protected by spur dike using soft computing tools and regression methods	MLP, GMDH, MLR, and NLR	MLP
Tripathi & Pandey, 2023	Gene-expression programming for scour around spur dike	GEP	GEP
Pandey et al., 2023	A comprehensive experimental and computational investigation on estimation of scour depth at bridge abutment: emerging ensemble intelligent systems	CATBoost, ETR and KNN	CATBoost

Studies	Title	Applied Models	Best Model
Kumar et al., 2023	A novel-tuned Custom ensemble machine learning model to predict abutment scour depth in clear water conditions	DT, AdaBoost, XGBoost, LightBoost, and Custom Ensemble	Custom Ensemble
Sadeghi et al., 2024	Evaluation of the performance of machine learning methods for estimating the maximum scour depth around the bandallike spur-dike	RF, SVR, and GEP	RF
Khan et al., 2024	Advanced prediction models for scouring around bridge abutments: a comparative study of empirical and ai techniques	ANN, ANFIS and RF	ANFIS
Marulasiddappa et al., 2024	Prediction of scour depth around bridge abutments using ensemble machine learning models	ANFIS, GTB, GMDH and MARS	GTB and MARS
Tabassum et al., 2024	Machine learning-based prediction of scour depth evolution around spur dikes	RF, XGBoost, ANN, CNN, LSTM	XGBoost

The abbreviations used are as follows: ANN (artificial neural network), GEP (gene expression programming), GMDH-BP (group method of data handling with back

propagation), ANFIS (adaptive neuro-fuzzy inference system), RBF-NN (radial basis function neural network), SVR (support vector regression), NLR (non-linear regression), MLP (multilayer perceptron), MLR (multiple linear regression), MARS (multivariate adaptive regression splines), MGGP (multi-gene genetic programming), KELM (kernel extreme learning machine), BRT (boosting regression tree), BGT (bagging regression tree), GBDT (gradient boosted decision tree), KRR (kernel ridge regression), ETR (extra trees regressor), KNN (k-nearest neighbors), DT (decision tree), RF (random forest), GTB (gradient tree boosting), CNN (convolutional neural network), and LSTM (long short-term memory).

2.9 Summary and research gaps

This chapter draws together the literature on scour depth around spur dikes: an overview of spur dikes as river-training works, their different head types, the scour mechanism, and the various governing factors, including spur length, alignment, channel geometry, sediment size and gradation, flow characteristics, and spacing between dikes. Scour occurs when flowing water interacts with a hydraulic structure in a channel, disrupting the flow pattern and increasing the force on the bed enough to remove sediment around the structure. Section 2.3 covers scour around I-, L-, and T-shape spur dikes under varying flow and sediment conditions; Section 2.4 details the scour mechanism itself - scour formation, sediment transport, vortex formation, and the mobile boundary - and Section 2.4.1 explains the forces acting on bed particles and the associated energy dissipation. Section 2.5 covers the influence of spur-dike geometry, sediment characteristics, flow depth, and Froude number on scour depth, all of which bear on sediment transport and scour behaviour, and Section 2.5.1.3 reviews evidence from streamlined bridge piers and abutments that underlies the curved head shape studied here. Section 2.6 covers the effective spacing between adjacent spur dikes, and Sections 2.7 and 2.8 cover numerical simulation and machine learning, respectively. Where earlier work has typically used only CFD, machine learning, or regression equations in isolation to estimate scour depth, this study combines all three. On this basis, the following research gaps were identified:

1. A new shape, a curved T-shape, needs to be investigated and compared with the existing shape of spur dikes. The evidence on streamlined noses from pier and abutment studies has not been extended to the head shapes of spur dikes.
2. The flow behavior around the newly designed shape, curved T-shape spur dikes, needs to be investigated.
3. Spacing of newly curved T-shape spur dikes needs to be optimized.
4. A comparative review showed that till now, ANN, GEP, SVR, and ANFIS have been mainly used for the prediction of scour depth, so more machine learning models, such as hybrid machine learning models, need to be developed.

During the study, all efforts were directed to address the above gaps, which are discussed in detail in subsequent chapters.

CHAPTER III

METHODOLOGY

3.1 General

Scour studies on spur dikes are difficult because flows are complex and data collection is challenging. Laboratory studies in a hydraulic flume are convenient under controlled flow and controlled bed-material conditions. In line with the objectives of the present study, there is a need to design a new type of spur dike that provides good stability and reduces scour depth around these structures. Additionally, to determine the optimal spacing between multiple spur dikes to protect the riverbank, reduce erosion, and control river flow direction. Finally, develop a CFD simulation model and a machine learning prediction model to analyze the flow behavior and predict scour depth, respectively, without conducting experiments.

With this in mind, the experimental programme was designed to determine scour depth under clear-water conditions while optimising the curvature of the new curved T-shape spur dike, with a smaller number of runs also carried out on I- and T-shape spur dikes for comparison. All testing took place in the Hydraulics Laboratory of Delhi Technological University (DTU), Delhi, India; the equipment and procedure used are described in this chapter.

3.2 Experimental setup

3.2.1 Flume

The experiments were carried out in a recirculating masonry flume at the University Hydraulics Laboratory, Delhi Technological University, Delhi, shown schematically in Figure 3.1. The flume is 14 m long, 1.1 m wide, and 0.8 m deep, with glass side walls that allow direct observation of the 4 m working section positioned 5 m downstream of the inlet (Figure 3.2). It comprises three parts: an inlet tank that dissipates turbulence from the incoming supply, a test section holding the sediment bed and spur dike, and an outlet tank where discharge is collected and measured over

a V-notch. The glass wall along the working section gives a clear view of the developing scour. A 0.3 m depth of uniformly graded sand fills the working area, while the remaining flume bed is built up in brick and finished flush with the sand surface in concrete, so that no level discontinuity can trigger additional turbulence or scour.

The entire experimental setup operates as a closed-loop recirculating system. Water is drawn from a sump tank and supplied to the flume inlet via a centrifugal pump, with suction and delivery pipes fitted with a venturimeter and a gate valve for discharge regulation. The water flows through the inlet section, passes over the sediment bed in the working section, and finally exits through the outlet tank over the V-notch weir, after which it is returned to the sump tank. Flow discharge is continuously monitored and measured using a V-notch weir.

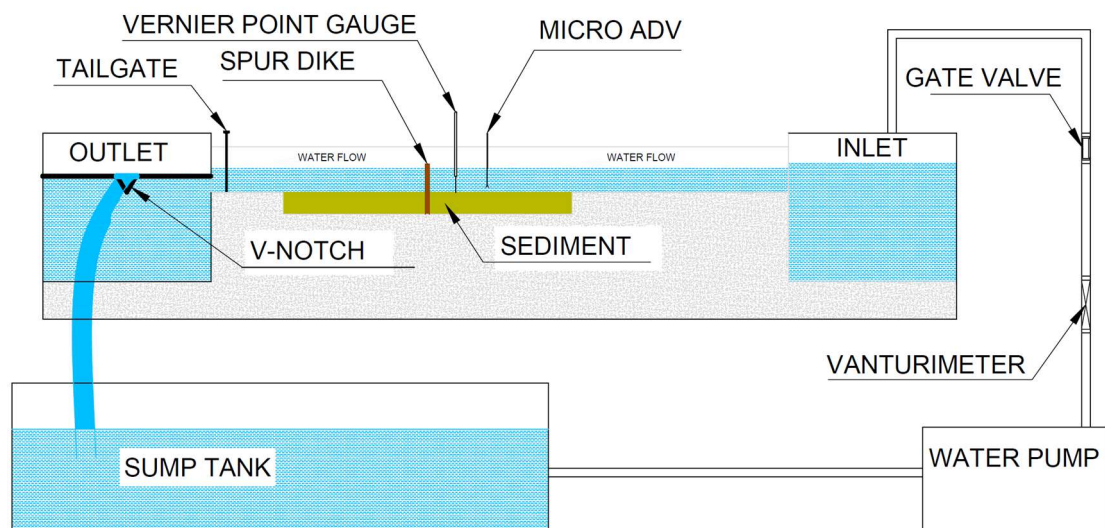


Figure 3.1: Systematic diagram of experimentation

A vernier point gauge, accurate to ± 0.1 mm, was used to read the bed and water levels precisely. A tail gate at the downstream end of the flume controlled flow depth, and a gate valve between the pump and delivery pipe regulated the flow rate. Settling chambers in both the inlet and outlet tanks captured floating debris without disturbing the flow. A sump tank and pump maintained continuous circulation: water was drawn from the sump through a venturi meter and gate valve to the inlet tank, across the working section, and into the outlet tank; discharge through the flume was measured

with a venturi meter between the pump and gate valve, and with a V-notch weir at the downstream end.



Figure 3.2: Masonry flume

3.2.2 Sediment size and properties

The bed material used in the current study is a fine river sand, which is collected from the Yamuna River, to assess the scouring condition under realistic alluvial-bed conditions (bed material). The relative density of the sediment is 2.67, and the mean particle size (d_{50}) is 0.22 mm (details of the grain size distribution curve presented in Figure 3.3). It is considered uniform if $d_{95}/d_5 < 4$ and $\sqrt{d_{84.1}/d_{15.9}} < 1.4$, where $d_{84.1}$, $d_{15.9}$, d_{95} , and d_5 are the median sizes of used sediment for which 84.1%, 15.9%, 95%,

and 5% of the sample, are finer by weight than this size (Raudkivi, 1986). In the current study, the values of d_{95}/d_5 and $\sqrt{d_{84.1}/d_{15.9}}$ were 2.7 and 1.35, respectively, indicating that the sediment is uniform in nature.

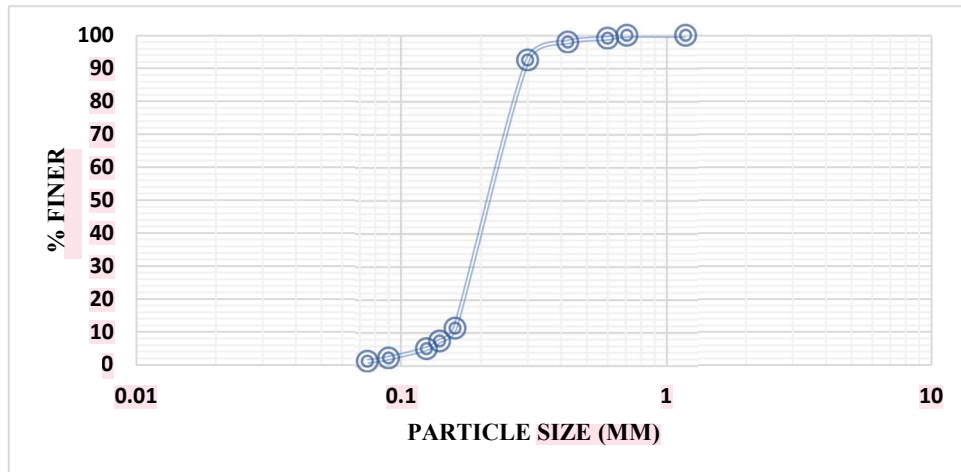


Figure 3.3: Particle size distribution curve

3.2.3 Spur dikes

In this study, three different shapes of spur dikes were experimentally analyzed to measure scour depth. Three shapes are I-, T-, and a newly designed curved T-shape. The length of all spur dikes was kept constant at 20% of the channel width (0.22 m). For optimising the curvature of the newly designed curved T-shape spur dikes, a total of 16 geometric configurations were generated by varying the values of the length of the flange (X) and the crest width of the spur dikes (Y). As per Safarzadeh et al. (2016), the values of X must lie between half the length of the spur dikes and the full length, so four values of X have been selected ($b/2$, $2b/3$, $5b/6$, and b). Additionally, the values of Y were divided into four intervals: $b/10$, $3b/20$, $b/5$, and $b/4$, as the crest width of spur dikes must be 0.1 to 0.25 times b . The details of the spur dikes are summarized in Table 3.1). The crest width used for I- and T-shape spur dikes was 0.044 m ($b/5$). For the T-shape spur dikes, the flange length, i.e., 0.22 m, was equal to the length of the spur dikes.

Table 3.1: Details of the newly designed curved T-shape spur dikes

Sr. No.	X (m)		Y(m)	
R1	b/2	0.11	b/10	0.022
R2	b/2	0.11	3b/20	0.033
R3	b/2	0.11	b/5	0.044
R4	b/2	0.11	b/4	0.055
R5	2b/3	0.147	b/10	0.022
R6	2b/3	0.147	3b/20	0.033
R7	2b/3	0.147	b/5	0.044
R8	2b/3	0.147	b/4	0.055
R9	5b/6	0.183	b/10	0.022
R10	5b/6	0.183	3b/20	0.033
R11	5b/6	0.183	b/5	0.044
R12	5b/6	0.183	b/4	0.055
R13	b	0.22	b/10	0.022
R14	b	0.22	3b/20	0.033
R15	b	0.22	b/5	0.044
R16	b	0.22	b/4	0.055

3.3 Measuring devices

3.3.1 Discharge measurement

Discharge was measured with a V-notch fixed at the downstream end of the flume (Figure 3.4) and calibrated against the flow rate in the channel, giving a coefficient of discharge (C_d) of 0.595; the theoretical discharge equation was adjusted accordingly for use in measuring discharge.

$$Q_{Act} = \frac{8}{15} 0.595 \sqrt{2g} \tan \frac{\theta}{2} H_d^{5/2} \quad (3.1)$$

$$Q_{Act} = 1.406 H_d^{5/2} \quad (3.2)$$

Here, Q_{theor} is the theoretical discharge (m^3/s), Q_{Act} the actual discharge (m^3/s), C_d the (dimensionless) coefficient of discharge for the V-notch, the crest angle of the V-notch (degrees), and H_d the head over the notch crest (m). The discharge obtained from the V-notch was also cross-checked against the approach velocity recorded by the ADV, and the two measurements were in close agreement.



Figure 3.4: V-notch used for flow measurement

3.3.2 Scour depth and water depth measurement

A point gauge fitted with a vernier scale (least count 0.1 mm), mounted on a sliding trolley, recorded scour depth around the spur dikes and the water level before, during, and after each run; the gauge used is shown in Figure 3.5.

3.3.3 Velocity measurement

Flow velocities were recorded with a Micro Acoustic Doppler Velocimeter (ADV), which resolves instantaneous velocity components at a fixed point with high temporal resolution by applying the Doppler shift principle to acoustic signals scattered from suspended particles. Its high operating frequency (16 MHz) makes it well suited to laboratory-scale hydraulic work; the velocity-measurement setup is shown in Figure 3.6.



Figure 3.5: Vernier point gauge



Figure 3.6: SonTek Micro ADV

3.4 Experimental procedure

The experiments used the same recirculating masonry flume (14 m long, 1.1 m wide, 0.8 m deep), water being supplied from the sump tank (capacity about 330 m³) by centrifugal pumps through the delivery pipe, where a gate valve and venturimeter regulated and measured the discharge. From the inlet tanks the water passed through the sediment-filled working section over the spur dike models and left through the outlet tank over a V-notch weir before returning to the sump. All runs were conducted under clear-water conditions, i.e., with bed shear stress below the threshold value ($\tau_b/\tau_c < 1$), equivalently $U/U_c < 1$, over a U/U_c range of 0.76-0.95 that falls within the range commonly used in clear-water scour studies. Keeping to this range makes the results comparable with earlier work and keeps the flow below the sediment-movement threshold, so that the observed scour reflects the interaction between the flow and the spur dike rather than sediment already in transport.

The working section, 4 m long, 1.1 m wide, and 0.8 m deep, was filled with sediment to a height of 0.30 m and leveled flat. The spur dike model was mounted vertically along one flume wall, centered in the working section, and set perpendicular to the flow. For each U/U_c value, the corresponding discharge was released with the tailgate closed and the flow held low enough to avoid washing bed particles out prematurely (Zhang et al., 2012); once the target depth was reached, discharge was raised gradually to the design value and the tailgate opened to hold that depth. Following Setia (2008), each run continued for 8 hours, by which point equilibrium scour depth had clearly been reached. The bed level was then measured with a vernier point gauge (least count 0.1 mm), the maximum scour depth being the difference between the initial and the lowest recorded bed level for that run.

3.4.1 Repeatability of the experimental runs

To check the repeatability of the experimental results, replicate runs were carried out. Six runs were conducted on the curved T-shape spur dike configuration R1 ($X = b/2$, $Y = b/10$) at the constant flow depth of 0.19 m, three at the lowest flow intensity (U/U_c

= 0.83) and three at the highest ($U/U_c = 0.95$). The bed was re-laid, flattened, and levelled before each run, and the procedure described in Section 3.4 was followed.

The replicate runs gave the following results. At $U/U_c = 0.83$, the three runs produced maximum scour depths of 0.158, 0.160, and 0.156 m (mean 0.158 m), with a mean error - the average absolute deviation of the individual runs from this mean - of 0.84% and a maximum departure of 1.27%. At $U/U_c = 0.95$, the runs gave 0.168, 0.165, and 0.170 m (mean 0.1677 m), a mean error of 1.06%, and a maximum departure of 1.59%. The maximum departure from the set mean was thus 1.27% at the lower flow intensity and 1.59% at the higher, small compared with the overall variation in SD across the sixteen configurations (0.142 to 0.168 m at $U/U_c = 0.95$; Table 4.2), though configurations differing by less than this margin cannot be ranked with certainty.

The remaining configurations were tested in single runs. This is in line with the usual practice in scour experiments, in which a limited number of runs is repeated to establish the repeatability of the procedure and the uncertainty of the measurements, instead of replicating every run (Kline & McClintock, 1953; Moffat, 1988).

3.5 Data collected from existing literature

In addition to data collected during the experimentation, scour depth data were obtained from the literature (Ezzeldin et al., 2007; Nasrollahi et al., 2008; Pandey et al., 2016; Zaghoul, 1983). The dataset consists of the length of spur dikes (b) in meters, flow velocity (U) in meters per second, threshold velocity (U_c) in meters per second, flow depth (D) in meters, median particle size diameters (d_{50}) in meters, the width of the flume (B) in meters and scour depth (SD) in meters. Table 3.2 illustrates the range and statistical descriptions of the parameters obtained from the aforementioned studies. In the overall dataset, U ranged from 0.1590 to 0.6700, U_c ranged from 0.1825 to 0.70590, D ranged from 0.0380 to 0.6000, b ranged from 0.0500 to 4.7500, d_{50} ranged from 0.0003 to 0.0031, and SD ranged from 4.7000 to 74.7000.

Table 3.2: Range of the data collected from existing literature

Studies	b	U	D	d ₅₀	Fd ₅₀	B
Zaghloul (1983)	0.045-0.23	0.32-0.43	0.135-0.30	4.49	1.69	0.46
Ezzeldin et al. (2007)	0.04-0.1	0.195-0.31	0.065-0.13	0.60	1.98-3.15	0.40
Nasrollahi et al. (2008)	0.25-0.75	0.3125	0.128	1.3	1.467-2.15	2.0
Pandey et al. (2016)	0.06-0.15	0.21-0.43	0.05-0.53	0.8-1.02	1.78-4.07	1.0

3.6 Dimensional analysis

SD around depends upon the approach velocity (U), critical velocity for initiation of sediment motion (U_c), fluid density (ρ), and sediment densities (ρ_s), spur dike length (b), flow depth (D), median sediment diameter (d_{50}), gravitational acceleration (g), and kinematic viscosity (ν). The SD can be expressed as a function of these parameters (Pandey et al., 2021a).

$$SD = f(U, U_c, \rho, \rho_s, b, g, D, d_{50}, \nu) \quad (3.3)$$

Where SD: [L], U: [LT^{-1}], U_c : [LT^{-1}], ρ, ρ_s : [ML^{-3}], b: [L], D: [L], d_{50} : [L], g: [LT^{-2}], and ν : [L^2T^{-2}].

Using Buckingham π -Theorem, the above relation contains $n = 9$ variables with $k = 3$ fundamental dimensions (M, L, T); therefore, the number of dimensionless parameters is: $n - k = 9 - 3 = 6$.

From equation 3.6, dimensionless parameters are obtained using the Buckingham π dimensional analysis method. Three repeating variables are U, ρ , and b, representing the flow, fluid, and geometric scales, respectively.

By constructing the dimensionless Π terms, there were 9 variables (n) involving 3 fundamental dimensions (k), i.e., M, L, T. Therefore, the number of dimensionless Π -groups was 6 ($n - k = 9 - 3 = 6$).

$$\Pi_1 = \frac{SD}{b}, \Pi_2 = \frac{U}{U_c}, \Pi_3 = \frac{D}{b}, \Pi_4 = \frac{b}{d_{50}}, \Pi_5 = \frac{U}{\sqrt{\Delta g d_{50}}}, \Pi_6 = \frac{UB}{v} \quad (3.4)$$

Where $\Delta = \frac{\rho_s - \rho}{\rho}$ and Π_5 represents the densimetric Froude number, commonly denoted as:

$$Fd_{50} = \frac{U}{\sqrt{\Delta g d_{50}}} \quad (3.5)$$

and Π_6 was the Reynolds number ($Re = \frac{UB}{v}$). For fully turbulent flow conditions, the dependence on Re becomes weak and may be omitted (Dey & Barbhuiya, 2005).

The final non-dimensional expression is as follows:

$$SD/b = f(U/U_c, D/b, b/d_{50}, Fd_{50}) \quad (3.6)$$

3.7 Numerical simulation

This section covers the theoretical and practical aspects of Computational Fluid Dynamics (CFD), a numerical approach that has, over recent decades, made it possible to study complex physical problems that are otherwise analytically intractable for practical engineering and water-resources work. CFD solves the Reynolds Averaged Navier-Stokes (RANS) equations - the second-order partial differential equations governing fluid flow - numerically, since the nonlinearity and unsteadiness of real flows generally rule out an analytical solution. Here, CFD is used to study the flow behaviour around the different spur-dike shapes, with ANSYS Workbench 2024R2 used for the analysis; the governing equations and procedures used are set out below:

3.7.1 Continuity equation (Volume Fraction Equation)

The volume fraction (V_f) of the water in a computational phase is defined as:

$$V_f \text{ of water phase} = \alpha_w = \frac{\text{Volume of water phase in the cell}}{\text{Volume of the cell}} \quad (3.7)$$

Thus, $\alpha_w = 1$ represents the cell is full of water, $\alpha_w = 0$ represents the cell is empty, and $0 < \alpha_w < 1$ represents the cell contains a free surface.

The interface between water and air is tracked by solving the continuity equation for the volume fraction of one or more phases. For the water phase, the governing equation is:

$$\frac{\partial}{\partial t}(\alpha_w \rho_w) + \nabla \cdot (\alpha_w \rho_w u_w) = 0 \quad (3.8)$$

Where, ρ_w is the density of water, t is the time, α_w is the volume fraction of the water, u_w is the velocity vector of the water phase.

The volume fraction equation is not solved for the primary phase. Instead, the primary-phase (air) volume fraction (α_a) is computed as:

$$\alpha_w + \alpha_a = 1 \quad (3.9)$$

The volume fraction equation may be solved either through implicit or explicit temporal discretization.

3.7.2 Momentum equation

In the computational domain, a single momentum equation is solved, and the resulting velocity field is shared among all phases. The equation accounts for the influence of phase volume fractions through the fluid properties, including density (ρ) and dynamic viscosity (μ). The equation is:

$$\frac{\partial(\rho u)}{\partial t} + \nabla \cdot (\rho u u) = -\nabla p + \nabla \cdot [\mu(\nabla u + \nabla u^T)] + \rho g \quad (3.10)$$

Where, p represents the pressure, u represents the velocity vector, and g represents the acceleration vector due to gravity.

The momentum equation can be reformulated using RANS, which accounts for turbulence by averaging flow variables over time. The process keeps the form of the momentum equations unchanged while adding additional terms called Reynolds stresses, which model the momentum transfer due to turbulent velocity fluctuations.

$$\frac{\partial(\rho u)}{\partial t} + \nabla \cdot (\rho u u) = -\nabla p + \nabla \cdot [\mu_{eff}(\nabla u + \nabla u^T)] + \rho g \quad (3.11)$$

Here, μ_{eff} effective viscosity, incorporating both molecular viscosity and turbulent eddy viscosity.

3.7.3 Turbulence model

The flow field around spur dikes is highly complex, marked by strong velocity gradients, flow separation, vortex formation, and a horseshoe vortex near the base of the structure, all of which strongly influence sediment entrainment and hence the development of local scour. The k-omega turbulence model was chosen to simulate this turbulent flow in the computational domain, since it is widely used for its accuracy near solid boundaries. It solves two transport equations, one for the turbulent kinetic energy and one for the specific dissipation rate (Wilcox, 1998), given as:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k \bar{u}_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k - \beta^* \rho k \omega + S_k \quad (3.12)$$

$$\frac{\partial(\rho \omega)}{\partial t} + \frac{\partial(\rho \omega \bar{u}_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\omega} \right) \frac{\partial \omega}{\partial x_j} \right] + \alpha \frac{\omega}{k} G_k - \beta \rho \omega^2 + S_\omega \quad (3.13)$$

where k represents the turbulent kinetic energy, and ω is the specific dissipation rate. The term $\bar{u}_j$ denotes the mean velocity component, μ is the molecular viscosity, and μ_t is the turbulent or eddy viscosity. The terms S_k and S_ω are user-defined source terms, which were taken as zero in the present study. The term G_k represents the production of turbulent kinetic energy due to velocity gradients, and it is calculated as:

$$G_k = \mu_t S^2 \quad (3.14)$$

where S is the magnitude of the mean strain rate, defined as:

$$S = \sqrt{2 S_{ij} S_{ij}} \quad (3.15)$$

The strain-rate tensor S_{ij} is expressed as:

$$S_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \quad (3.16)$$

The turbulent viscosity μ_t in the k- ω model is calculated using:

$$\mu_t = \rho \frac{k}{\omega} \quad (3.17)$$

The $k-\omega$ model offers improved predictions in the near-wall region and is suitable for flows involving boundary-layer separation and recirculation. These characteristics make it useful for studying the turbulent flow behavior around hydraulic structures such as spur dikes.

3.7.4 Grid generation

Grid generation plays a crucial role in determining the accuracy of CFD models, especially in wall-bounded flows. A structured mesh aligned in the wall-normal direction is generally recommended, as it allows for proper resolution of the boundary layer. This structured region should encompass the entire boundary layer and extend beyond its thickness to prevent artificial confinement of boundary layer growth. Although these guidelines are not mandatory, they are considered best practice for boundary layer simulation. It is generally more important to ensure adequate resolution across the boundary layer than to strictly adhere to a specific y^+ value. However, when employing wall functions, y^+ values below 30 should be avoided, as they can lead to inaccurate predictions of wall shear stress and heat transfer. In regions prone to laminar separation, further mesh refinement is necessary to accurately capture the rapid changes associated with separation bubbles.

3.7.5 Mesh quality parameters

In CFD simulations, the computational mesh strongly impacts the stability, accuracy, and convergence of the numerical solution. The main quality indicators used to mesh assessment include aspect ratio, orthogonality, element quality, and skewness (ANSYS Fluent, 2025). Element quality values range from 0 to 1; cells with good geometric shape are indicated by values close to 1, while values near 0 indicate highly distorted elements that can reduce numerical reliability within the computational domain. The orthogonality quality describes the alignment between cell faces and the line joining the centers of neighboring cells. Values approaching 1 produce better cell orientation, whereas very small values may introduce numerical instability; therefore, a minimum acceptable limit is required to maintain stable computations. Aspect ratio reflects the degree of stretching of mesh cells, and sudden changes in cell dimensions

should be avoided, especially in regions with strong velocity or pressure gradients. Skewness is a parameter that indicates the deviation of a cell from its ideal geometric form. Large skewness can lower solution accuracy and slow convergence. For reliable CFD results, skewness values for triangular or tetrahedral elements should remain below 0.95, with average values preferably below about 0.33 to minimize convergence difficulties and excessive solver adjustments.

3.8 Process involved in numerical simulation

The CFD analysis is carried out in three main stages: creation of the flow geometry, discretization of the domain through mesh generation, and definition of suitable boundary conditions. Each stage is essential for properly capturing the flow characteristics, and the details are presented below:

3.8.1 Geometry creation

The first step in computational analysis involves the development of a three-dimensional (3D) Computer-Aided Design (CAD) model representing the computational domain. For this purpose, ANSYS Space Claim, an integrated CAD tool within the ANSYS Workbench environment, was employed. The geometry was meticulously constructed to accurately represent the physical system. The computational domain was designed to facilitate the movement and interaction of the involved fluids within a well-defined control volume.

In the present numerical simulation, the computational channel was set to 3.0 m in length, 1.1 m in width, as shown in Figure 3.7. The spur dikes were installed in the middle of the channel. These domain dimensions were carefully chosen to balance computational accuracy, numerical stability, and efficiency while minimizing the number of computational cells and overall simulation cost.

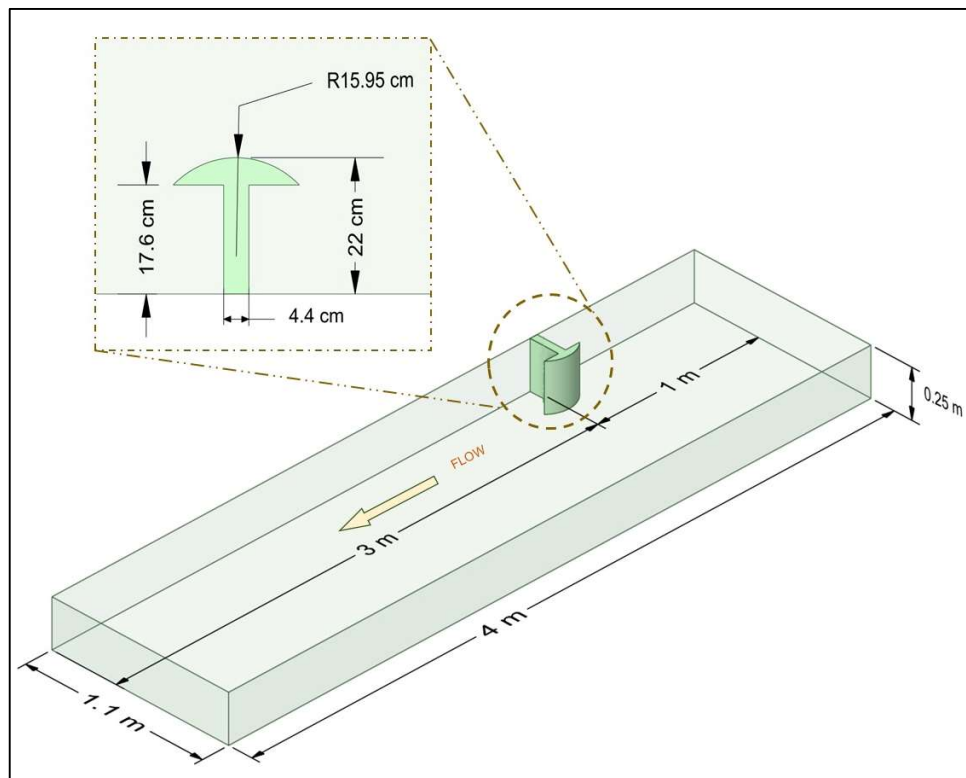


Figure 3.7: Geometry used for the simulation process of curved T-shape spur dikes

3.8.2 Mesh generation

ANSYS Workbench Meshing was used to discretise the computational domain into smaller cells, a process that trades off accuracy against computational cost, the latter shaped by processing time and hardware demands: finer meshes improve accuracy, since fluid properties such as pressure, velocity, and density are computed at every cell, but at greater computational expense. A non-uniform mesh was therefore adopted, coarser away from the spur dikes and finer around them where capturing the flow behaviour mattered most, as shown in Figure 3.8: a base mesh size of 20 mm, refined to 8 mm near the spur to resolve the local flow physics. The resulting domain contained roughly 4 million elements, with an average element quality of 0.8.

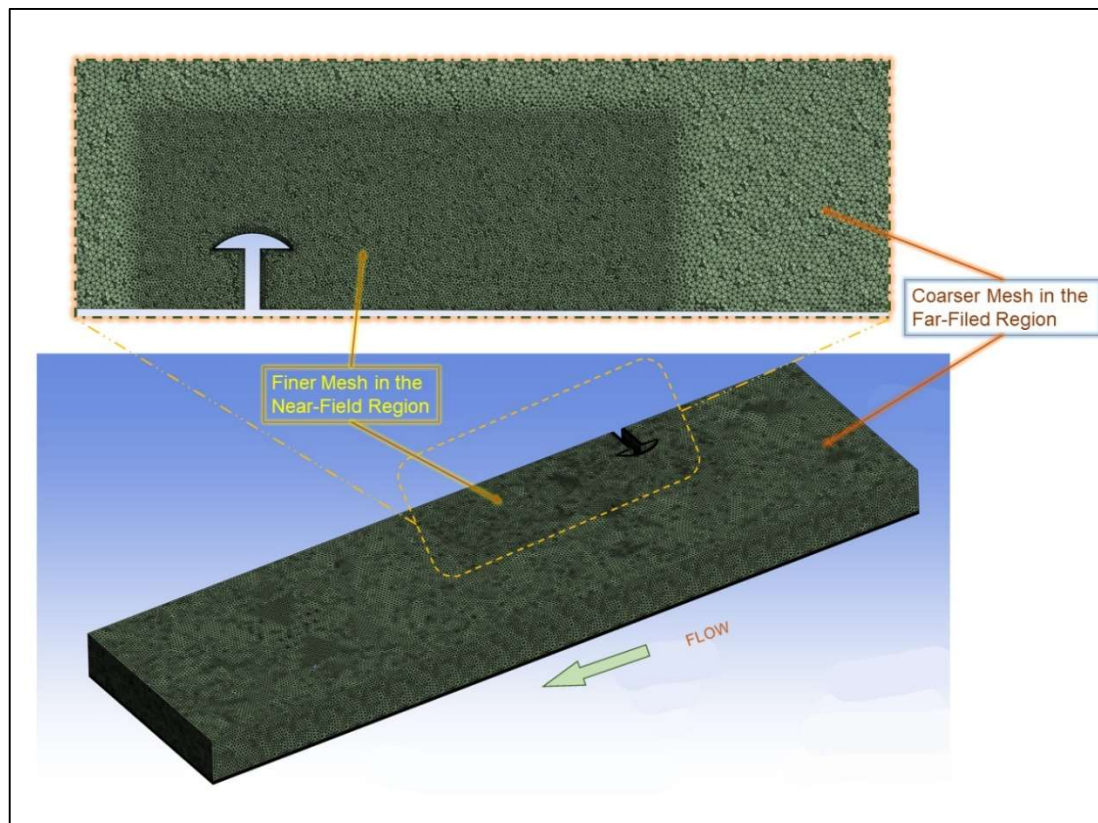


Figure 3.8: Discretised computational domain

3.8.3 Boundary conditions

In the present CFD analysis, a two-phase Volume of Fluid (VOF) model was employed to simulate water–air interactions. The boundary conditions were set based on physical relevance and computational stability. The inlet was defined as a mass flow, the channel outlet was assigned as a pressure outlet, and the top surface was treated as a free surface under atmospheric (zero-shear) conditions to allow water level fluctuations. All solid surfaces, except the top, were modeled using no-slip wall conditions as shown in Figure 3.9.

For turbulence modeling, the $k - \omega$ model with standard wall functions was used, considering the turbulent nature of the flow (based on Reynolds number). The multiphase setup included air as the primary phase and water as the secondary phase, with an implicit body-force formulation and a constant surface tension of 72.86 mN/m (Figure 3.10).

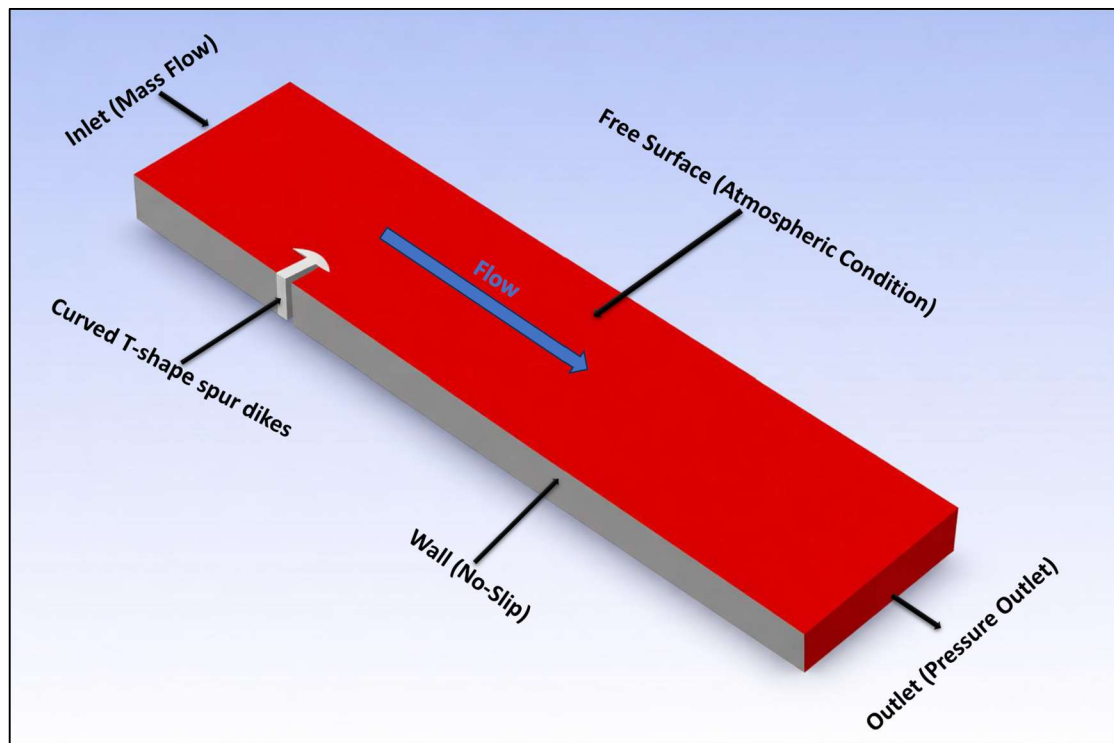


Figure 3.9: Boundary conditions adopted for the simulation

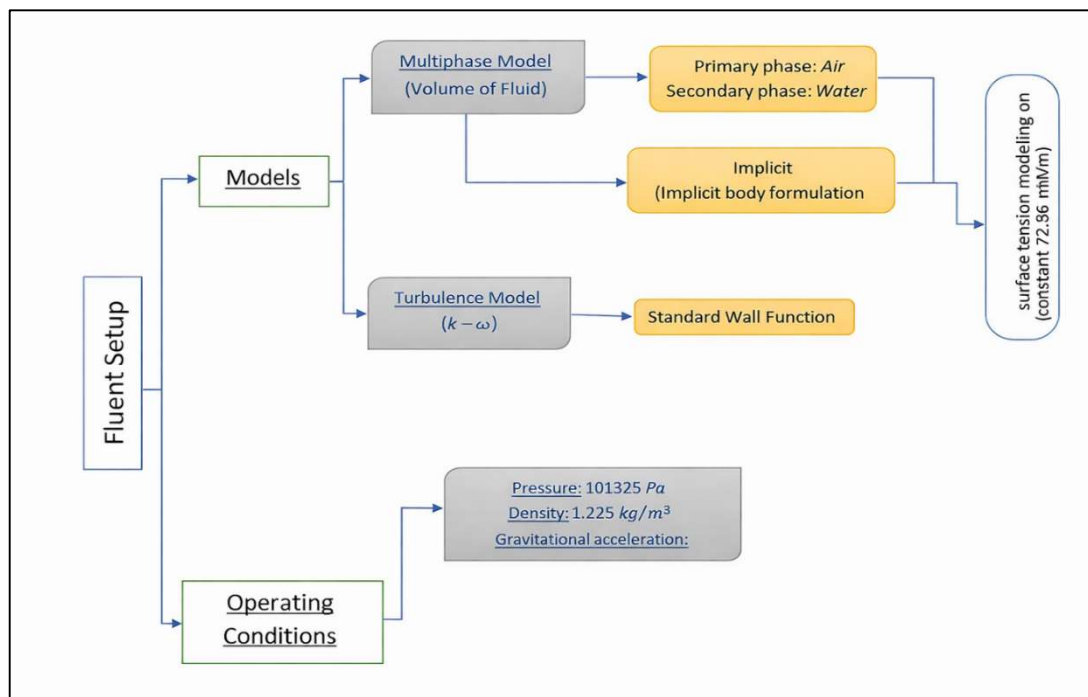


Figure 3.10: Details about the fluent setup for the flow simulation (VOF) model

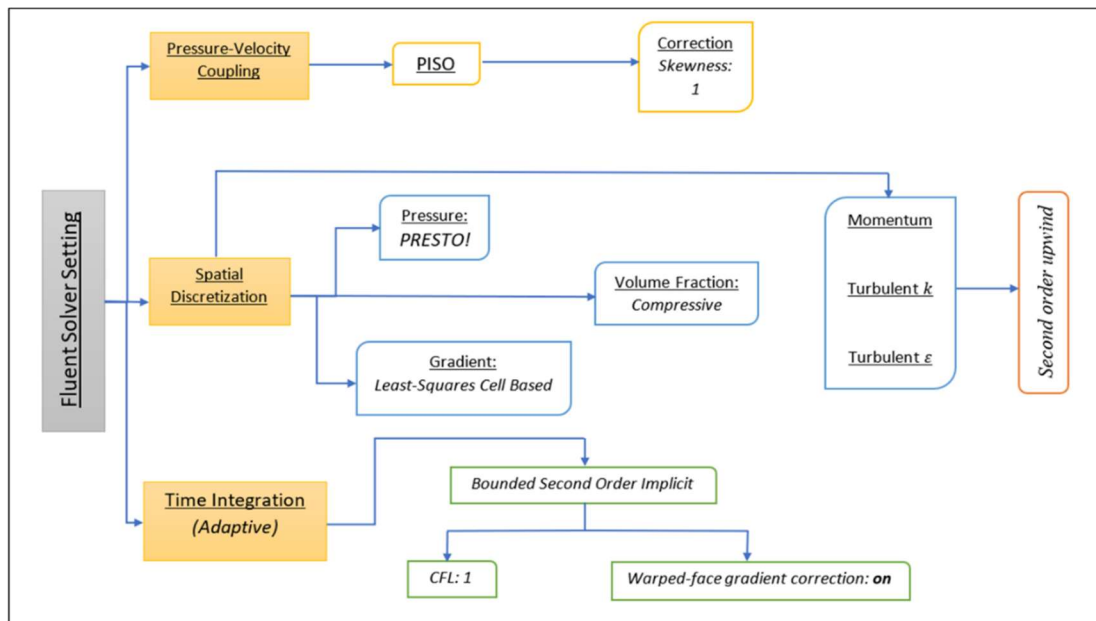


Figure 3.11: Details about Fluent Solver Setting

This section lists the Ansys Fluent solver settings that define the CFD-VOF model, including its boundary conditions. A no-slip condition was imposed on every solid boundary except the top wall, and the turbulence model was chosen for its improved prediction of near-wall turbulence and boundary-layer flow, both important in hydraulic simulation. A **second-order upwind scheme** discretised the momentum, turbulent-kinetic-energy (k), and specific-dissipation-rate equations, and the volume-fraction equation used compressive interface capturing with least-squares cell-based gradient evaluation. Time was discretised with a bounded second-order implicit scheme, adaptive time-stepping, and a Courant number (CFL) of 1.0, with warped-face gradient correction switched on to improve accuracy (Figure 3.11).

3.9 Machine learning

In the past decade, machine learning models have been extensively used to address a wide range of challenging hydraulics and water resource engineering problems. The machine learning models used in the study are discussed below:

3.9.1 Random Tree

The random tree (RT) algorithm addresses classification and regression problems. Aldous (1993) initially established the RT algorithm. It generates a random data collection process for constructing a decision tree. The optimal split of all variables is used to divide each node in a typical tree. Each node is divided using the highest randomly selected subset of predictors in a random forest. The RT node uses bootstrap sampling with replacement to generate sample data. They are using the sample data to develop a tree model. As the tree grows, RT will not sample the data again (Pham et al., 2022). Instead, it randomly selects a subset of predictors and uses the strongest one to divide a tree node. The process is iterated while partitioning each tree node, and constructing a tree in a random forest is based on this fundamental premise.

3.9.2 Additive Regression

The additive regression (AR) algorithm, initially proposed by Breiman & Friedman (1985), is a nonparametric method that plays a vital role in the alternating conditional-expectations algorithm. AR employs a one-dimensional smoother to create a restricted collection of nonparametric regression models that offer greater flexibility than linear models and are easier to comprehend than generic ones. To summarize, the AR algorithm may be defined as follows:

Consider a dataset $Z = \{(Y_h, X_h), h = 1, 2, \dots, N\}$, here Y_h is the output and X_h is the input variables. The AR model will take the form:

$$E[Y|X_1, \dots, X_k] = \beta_0 + \sum_{j=1}^k f_j(X_{ij}) \quad (3.18)$$

The dataset is fitted using unknown smooth functions $f_j(x_{ij})$.

3.9.3 Bagging

Slight modifications in the dataset can lead to instability in data-driven models. In 1996, Breiman proposed a technique called "bagging" to tackle the problem of model instability and improve overall performance. Each predictor is provided with a subset of the primary data set in this approach. In other words, each predictor only has access to a subset of the data and must construct its model using only that subset. Nguyen &

Bui (2019) have demonstrated the use of this method in several studies to improve prediction accuracy.

3.9.4 Random Sub Space

The Random Subspace (RSS) method, like bagging, uses bootstrapping and aggregation to build a predictive model, but draws its bootstrap samples from the feature space rather than the training samples (Tao et al., 2006). As with Random Forest and Bagging, RSS can be applied to both regression and classification. It has four main components: the labelled training dataset (x), the number of subspaces (L), the classifier or regressor (w), and the number of features (D_s) (Skurichina & Duin, 2002). A random number of subgroups is generated from the data structure and stored in subspace L ; separate base regressors or classifiers are then trained on each subset, and these are finally combined into a single ensemble regressor/classifier, E . Further detail on RSS is available in Kuncheva & Plumpton (2010).

3.9.5 Hybrid machine learning models

Machine learning addresses engineering problems by identifying patterns and relationships within data, offering the ability to handle large datasets, deliver fast results economically, and capture non-linear relationships between variables. Used alone, however, such models are prone to overfitting and sensitive to data quality, which hybrid models - built by combining two machine-learning models - address by improving predictive and generalisation ability, lowering result uncertainty, and giving more suitable engineering solutions. Here, the standalone Random Tree (RT) model was hybridised with additive regression (AR), Bagging (B), and random subspace (RSS), giving seven hybrid models in total: AR_RT, B_RT, RSS_RT, RSS_AR_RT, RSS_B_RT, B_AR_RT, and RSS_B_AR_RT. Their performance in predicting scour depth around spur dikes was then compared against that of the standalone RT model.

3.9.6 Data pre-processing

The collected raw data were processed as independent dimensionless variables (U/U_c , D/b , b/d_{50} , and Fd_{50}) as inputs, and the maximum scour depth (SD/b) as the response variable. The total dataset, consisting of 154 observations, was statistically analyzed

and divided into two groups. The larger group included 103 data points used to create the machine learning models (the training subset), and the second group included 51 data points used to test the models (the testing subset). Finally, the results were validated using data from the experimental observations. Table 3.3 provides a statistical description of the input and output variables for the training, testing, and validation subsets. The statistical parameters used to describe data are minimum, maximum, mean, and standard deviation.

Table 3.3: Statistical description of the dimensionless data

Characteristics	Fd_{50}	U/U_c	D/b	b/d_{50}	SD/b
Training					
Minimum	1.467	0.5214	0.0126	19.3548	0.0057
Maximum	4.0695	3.5121	4.1667	5277.78	4.0456
Mean	3.0497	0.9894	2.0229	342.893	1.7319
Standard Deviation	0.459	0.4212	1.1585	790.041	0.7737
Testing					
Minimum	1.7776	0.5105	0.0343	25.8065	0.3041
Maximum	3.9616	2.5257	4.1667	1944.44	3.2293
Mean	3.0485	0.9076	1.676	279.104	1.5992
Standard Deviation	0.5146	0.2678	1.117	318.089	0.7519
Validation					
Minimum	3.2761	0.76	0.5	1000	0.6086
Maximum	4.3788	0.95	0.8636	1000	0.8577
Mean	3.7731	0.846	0.6818	1000	0.7255
Standard Deviation	0.3427	0.0707	0.1917	0	0.078

3.9.7 User-defined parameters

A total of eight machine learning models (one standalone model, RT, and seven hybrid models; AR_RT, B_RT, RSS_RT, RSS_AR_RT, RSS_B_RT, B_AR_RT, RSS_B_AR_RT) are used in this study to predict the scour depth around spur dikes. The performance of the machine learning models strictly depends upon the user-defined parameters (UDFs). Several combinations of UDFs are used; on these sets, the

performance of the machine learning models is checked. The set that gives the best results of models is chosen. These chosen values of UDFs for different machine learning models used for the prediction of scour depth in this study are summarized in Table 3.4, along with the input and output variables.

Table 3.4: UDFs of machine learning models

Models	UDFs	Input and Output Variables
Random Tree	Batch_size=100, max_depth=0, Min_Number=1, Min_variance_proportion=0.001, and random_seed=1	U/U _c , D/b, b/d ₅₀ , Fd ₅₀ , and SD/b
Bagging	Batch_size - 100, bag_Size_percent = 100	
AR	Batch size=100,	
RSS	Batch_size - 100	
Training and testing percentages = 67% and 33%, respectively		

3.10 Performance evaluation

In this research, the performance of the machine learning and hybrid machine learning models was evaluated using the statistical parameters and visual performance indicators. The details of these indicators are as follows:

3.10.1 Statistical parameters

Four statistical parameters are used in this study: Coefficient of Determination (R-Square), Root Mean Square Error (RMSE), Nash-Sutcliffe Efficiency (NSE), and Coefficient of Correlation (COC); their range and ideal values are given in Table 3.5. In this table, A_i and B_i denote the actual and predicted values of SD, $\bar{A}$, $\bar{B}$ denote the mean of actual and predicted values of SD, while t denotes the number of observations.

Table 3.5: Theoretical range of the statistical parameters

Statistical Parameters	Theoretical Range	Ideal Value	Mathematical Formula
R-Square	0 to 1	1	$\left(\frac{\sum_{i=1}^t (A_i - \bar{A})(B_i - \bar{B})}{\sqrt{\sum_{i=1}^t (A_i - \bar{A})^2 \sum_{i=1}^t (B_i - \bar{B})^2}} \right)^2$
RMSE	0 to ∞	0	$\sqrt{\frac{1}{t} \sum_{i=1}^t (A_i - B_i)^2}$
NSE	$-\infty$ to 1	1	$1 - \frac{\sum_{i=1}^t (A_i - B_i)^2}{\sum_{i=1}^t (A_i - \bar{A})^2}$
COC	-1 to +1	1	$\frac{\sum_{i=1}^t (A_i - \bar{A})(B_i - \bar{B})}{\sqrt{\sum_{i=1}^t (A_i - \bar{A})^2 \sum_{i=1}^t (B_i - \bar{B})^2}}$

3.10.2 Visual performance indicators

In this study, the Taylor diagram, box plots, and agreement plots of observed and predicted SD values were used to assess the performance of the developed models. The Taylor diagram (Taylor, 2001) and box plot (Williamson et al., 1989) were also used to facilitate visual evaluation of the models as visual performance indicators. The Taylor diagram comprehensively represents each model's correlations and standard deviations. Greater predictive capacity is achieved when the predicted COC and standard deviation approach the observed values. The box plot comprehensively evaluated the models' capacities using extreme values, medians, and first- and third-quartile predictions. The agreement plot gives the relationship between the actual values and predicted values using machine learning models.

3.11 Regression-based statistical equations

In this study, three regression-based statistical equations were developed to predict the dimensional SD around I-shape spur dikes and the non-dimensional SD around T-shape spur dikes. These three equations were linear, non-linear, and second-order

polynomial regression. The mathematical expressions for these equations are as follows:

Linear regression equation

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \dots \quad (3.19)$$

Non-linear regression equation

$$Y = \beta_0 * (X_1)^{\beta_1} * (X_2)^{\beta_2} * (X_3)^{\beta_3} * \dots \quad (3.20)$$

Second-order polynomial regression equation

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_1^2 + \beta_5 X_2^2 + \beta_6 X_3^2 + \beta_7 X_1 X_2 + \beta_8 X_1 X_3 + \beta_9 X_2 X_3 + \dots \quad (3.21)$$

Where X_1 , X_2 , and X_3 are input variable; β_0 , β_1 , β_2 , β_3 , β_4 , β_5 , β_6 , β_7 , β_8 , and β_9 are regression coefficients; and Y is the output variable.

CHAPTER IV

RESULTS AND DISCUSSIONS

4.1 General

This chapter reports and discusses the results of the experiments on the different spur-dike shapes, together with the machine-learning and CFD findings.

4.2 Curved T-shape spur dikes

To optimize the curvature of the curved T-shape spur dikes, sixteen different configurations were selected for experiments with four values each for the flange length (X) and crest width (Y). For each combination, the scour depth (SD) around these spur dikes was analyzed.

4.2.1 Experimental plan and flow conditions for curved T-shape spur dikes

The experiments used a recirculating masonry flume at the DTU University Hydraulics Laboratory, shown in Figure 4.1. Bed sediment ($d_{50} = 0.22$ mm, specific gravity 2.67) was laid to a depth of 0.3 m; its coefficient of curvature (between 1 and 3) and coefficient of uniformity (below 4) confirmed it to be uniformly graded (Arneson et al., 2012). Wooden spur dike models were centred in the working section, perpendicular to the bank, and the sixteen configurations were tested under three flow conditions ($U/U_c = 0.95, 0.89, 0.83$). To keep the comparison fair, flow depth was held constant at 0.19 m throughout, a constraint of the setup, for which U_c was found to be 0.275 m/s; the corresponding flow details are given in Table 4.1.

To determine the duration of the experiments to attain the equilibrium scour depth, one experiment was conducted for 48 hours. The scour depth was measured using a vernier point gauge at 30-minute intervals for the first 180 minutes and at 60-minute intervals thereafter (Mishra et al., 2025). The temporal variation in scour depth indicated that the equilibrium scour depth was reached within 8 hours for this experimental setup and sediment, with no significant change in scour depth observed beyond this period.

These findings of achieving the equilibrium scour depth within 8 hours are consistent with those of Cardoso & Bettess (1999), Melville and Chiew (1999), and Setia (2008). Therefore, all subsequent experiments in this study were conducted for 8 hours.

Table 4.1: Clear-water flow conditions for measuring scour depth around curved T-shape spur dikes

Flow Velocity (U) (m/s)	U/U _c (--)	Discharge (Q) (m ³ /s)
0.2613	0.95	0.0496
0.2448	0.89	0.0465
0.2283	0.83	0.0434



Figure 4.1: Experimental plan of masonry flume with curved T-shape spur dikes

4.2.2 Experimentally observed scour depth (SD) around various geometric configurations of curved T-shape spur dikes

SD was measured around the various curved T-shape configurations listed in Table 4.1, under the clear-water conditions of Section 4.2.1, with the resulting values given in Table 4.2. The maximum SD occurred at the highest flow condition tested ($U/U_c = 0.95$, $U = 0.2613$ m/s) for every configuration, falling by 2.4-3.4% as flow intensity dropped to $U/U_c = 0.89$ ($U = 0.2448$ m/s), and by a further 3.5-4.9% as it dropped to $U/U_c = 0.83$ ($U = 0.2283$ m/s).

Table 4.2: Scour depth around different curved T-shape spur dikes for three different flow conditions

Sr. No.	X	Y	Scour Depth (m)		
			$U/U_c = 0.95$	$U/U_c = 0.89$	$U/U_c = 0.83$
R1	b/2	b/10	0.168	0.164	0.158
R2	b/2	3b/20	0.161	0.157	0.150
R3	b/2	b/5	0.155	0.151	0.144
R4	b/2	b/4	0.158	0.153	0.147
R5	2b/3	b/10	0.162	0.158	0.151
R6	2b/3	3b/20	0.156	0.152	0.145
R7	2b/3	b/5	0.15	0.146	0.139
R8	2b/3	b/4	0.153	0.149	0.142
R9	5b/6	b/10	0.158	0.153	0.146
R10	5b/6	3b/20	0.152	0.148	0.141
R11	5b/6	b/5	0.147	0.143	0.136
R12	5b/6	b/4	0.149	0.145	0.138
R13	b	b/10	0.15	0.146	0.14
R14	b	3b/20	0.146	0.141	0.136
R15	b	b/5	0.142	0.138	0.133
R16	b	b/4	0.148	0.143	0.138

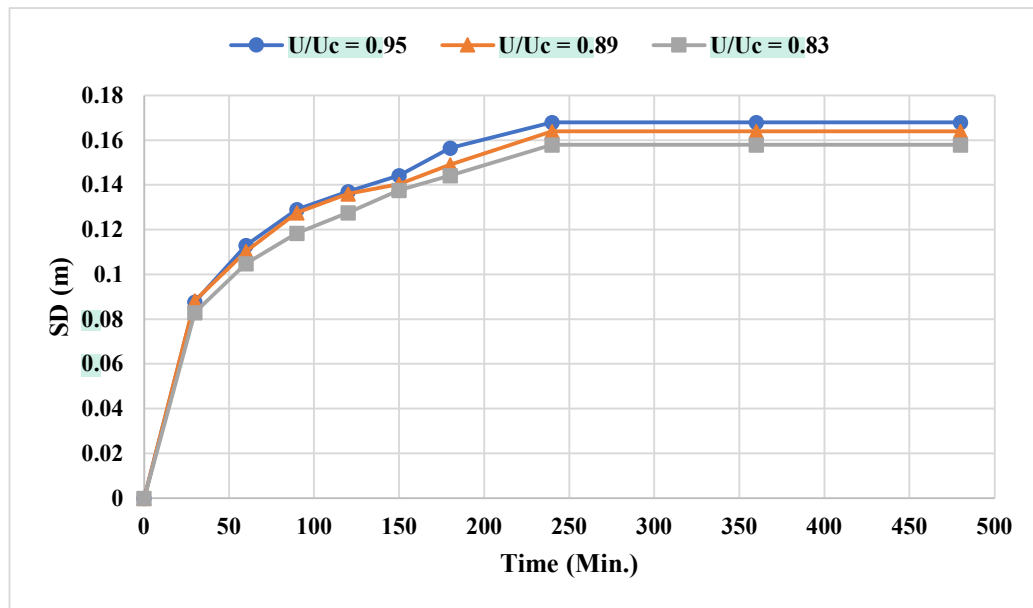


Figure 4.2: Temporal variation plot of R1 under the aforementioned flow conditions

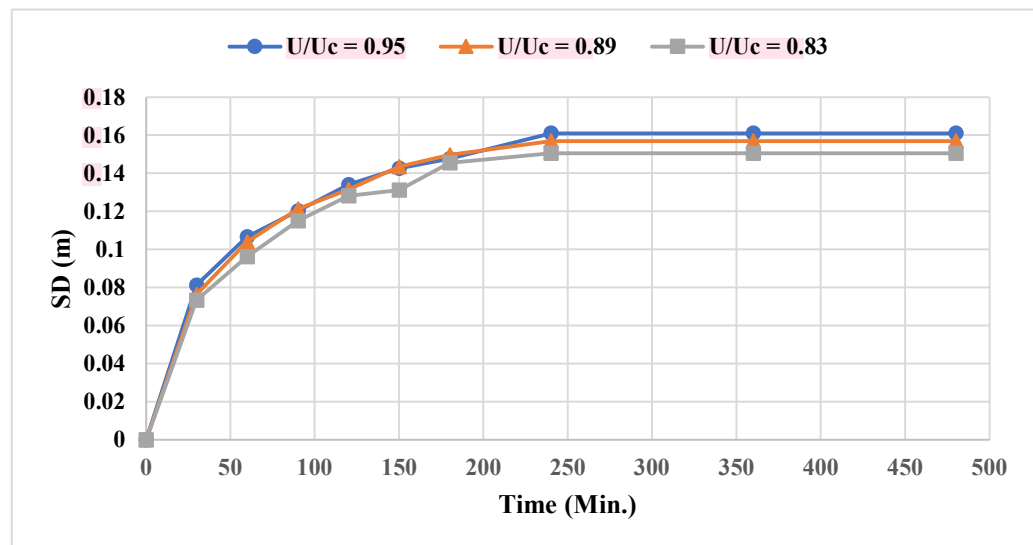


Figure 4.3: Temporal variation plot of R2 under the aforementioned flow conditions

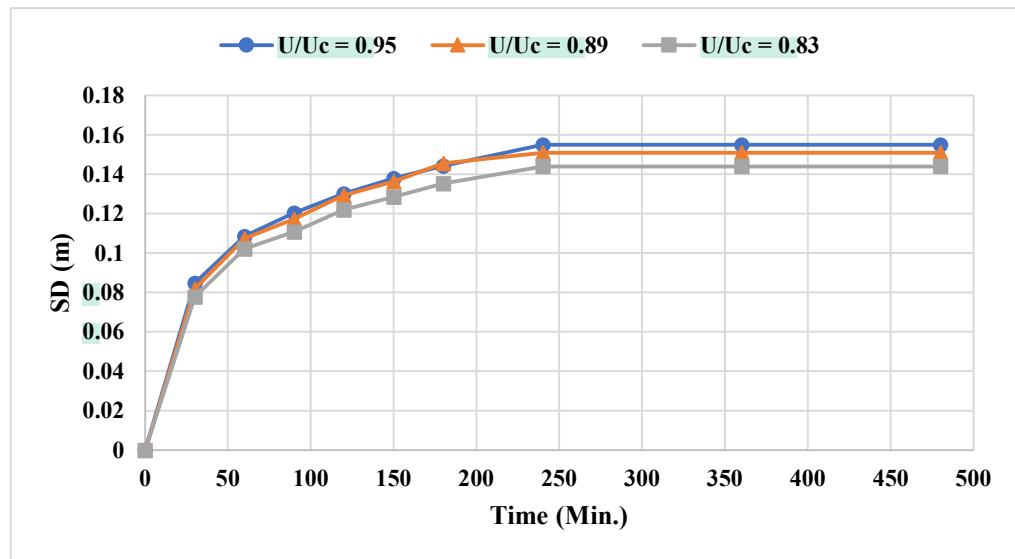


Figure 4.4: Temporal variation plot of R3 under the aforementioned flow conditions

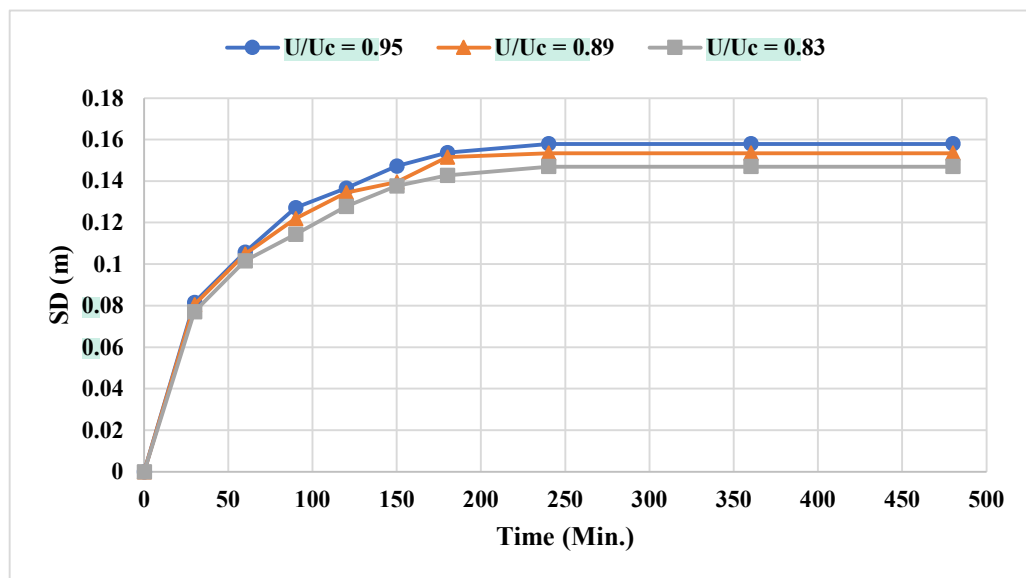


Figure 4.5: Temporal variation plot of R4 under the aforementioned flow conditions

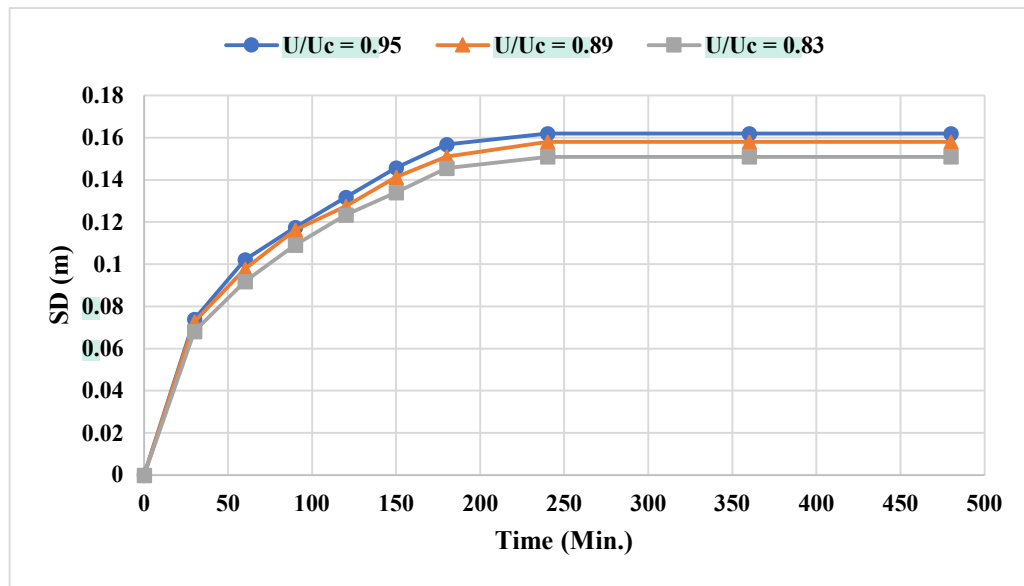


Figure 4.6: Temporal variation plot of R5 under the aforementioned flow conditions

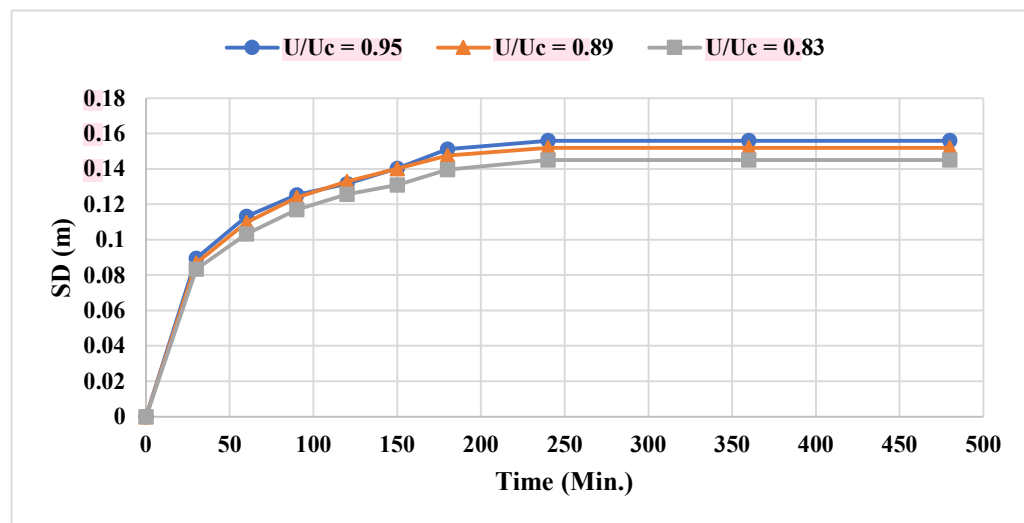


Figure 4.7: Temporal variation plot of R6 under the aforementioned flow conditions

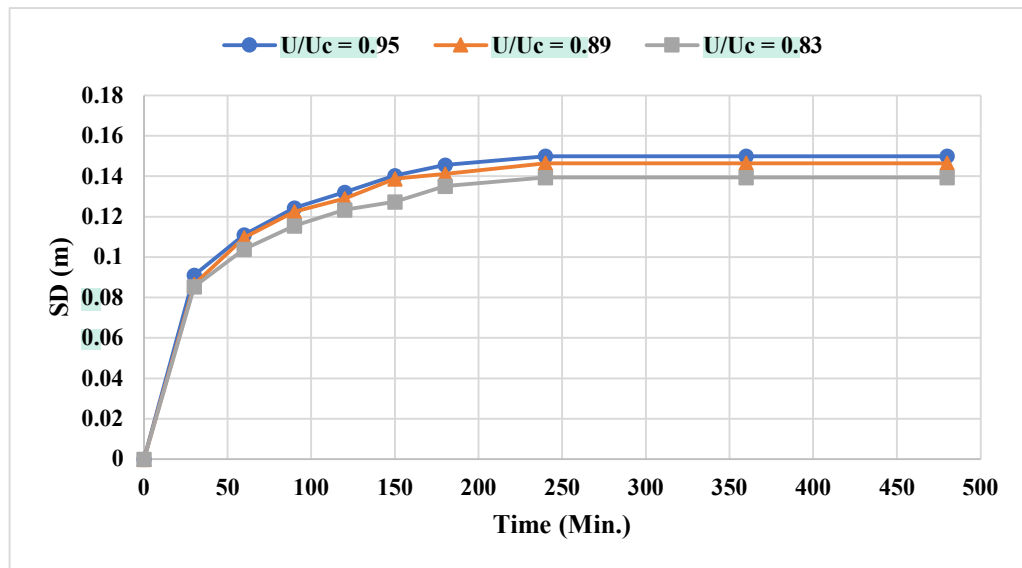


Figure 4.8: Temporal variation plot of R7 under the aforementioned flow conditions

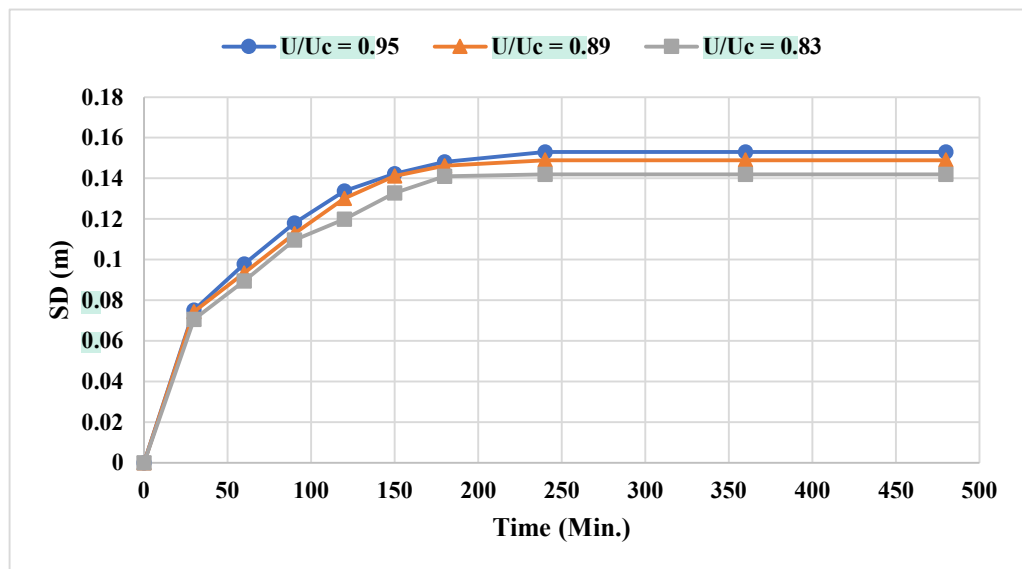


Figure 4.9: Temporal variation plot of R8 under the aforementioned flow conditions

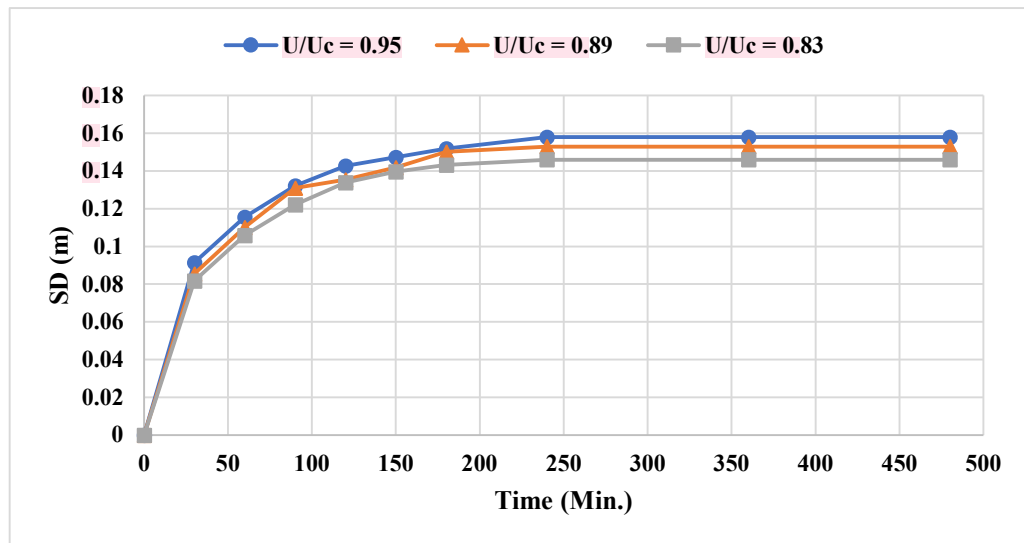


Figure 4.10: Temporal variation plot of R9 under the aforementioned flow conditions

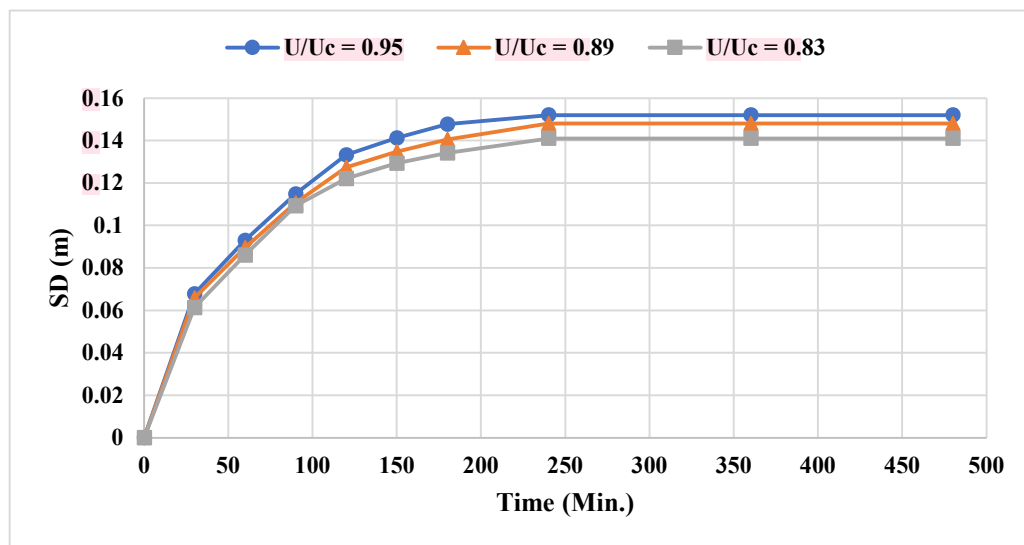


Figure 4.11: Temporal variation plot of R10 under the aforementioned flow conditions

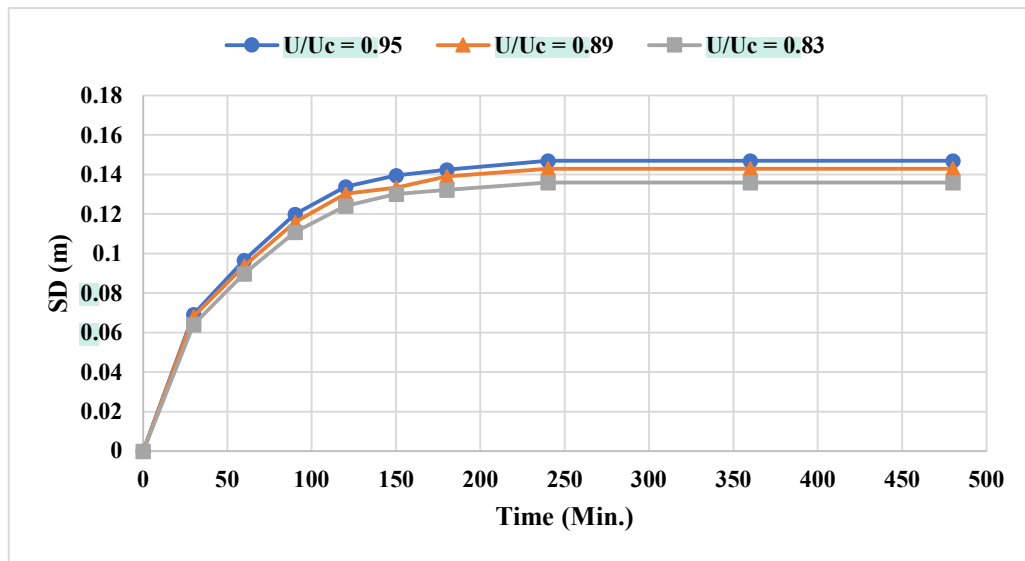


Figure 4.12: Temporal variation plot of R11 under the aforementioned flow conditions

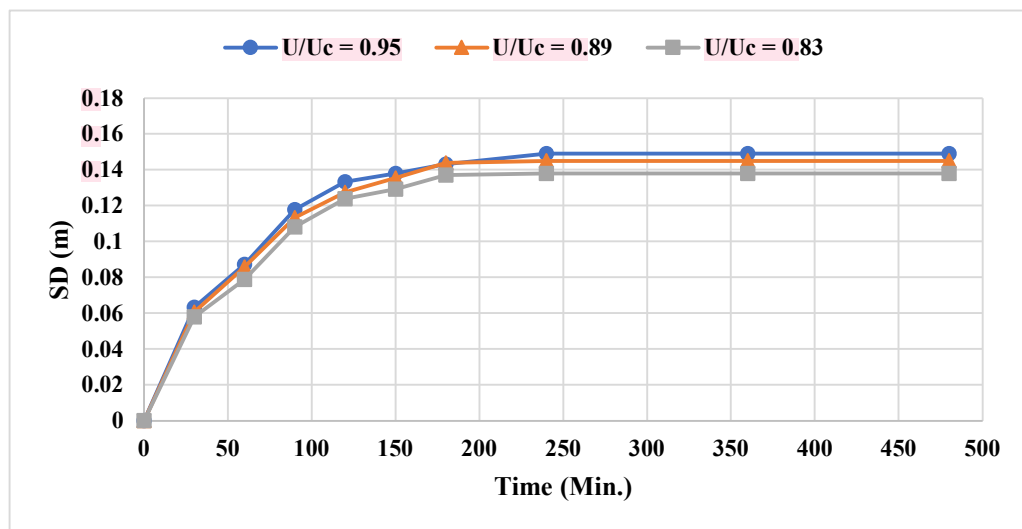


Figure 4.13: Temporal variation plot of R12 under the aforementioned flow conditions

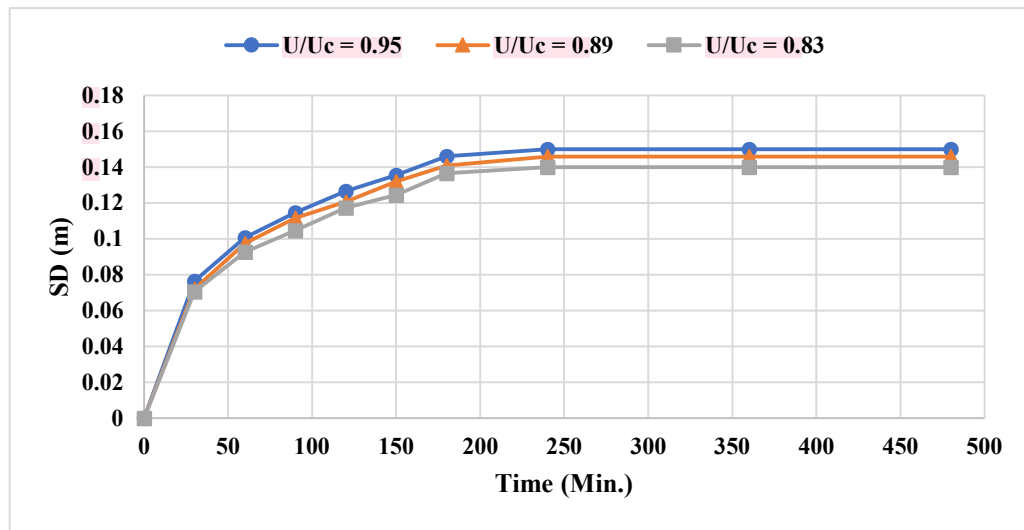


Figure 4.14: Temporal variation plot of R13 under the aforementioned flow conditions

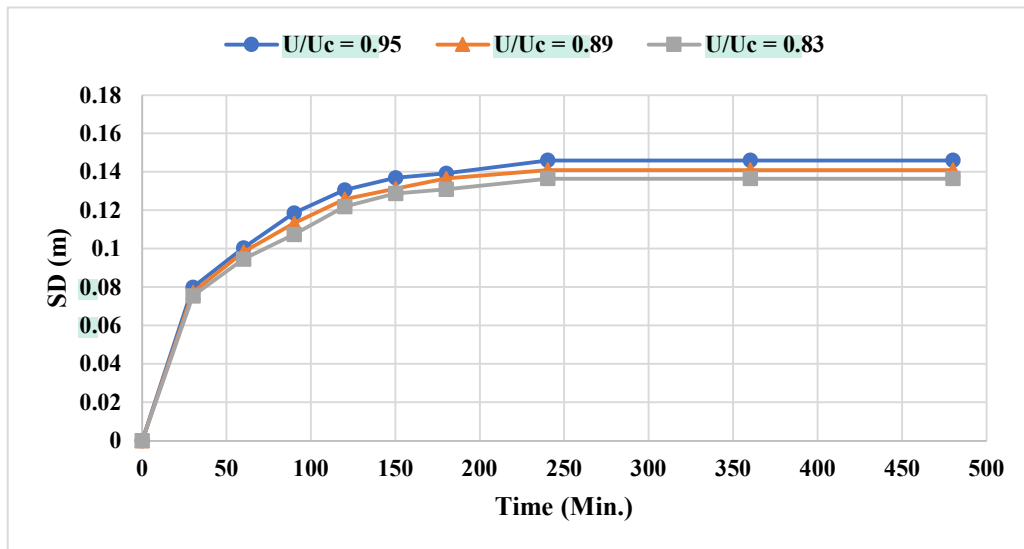


Figure 4.15: Temporal variation plot of R14 under the aforementioned flow conditions

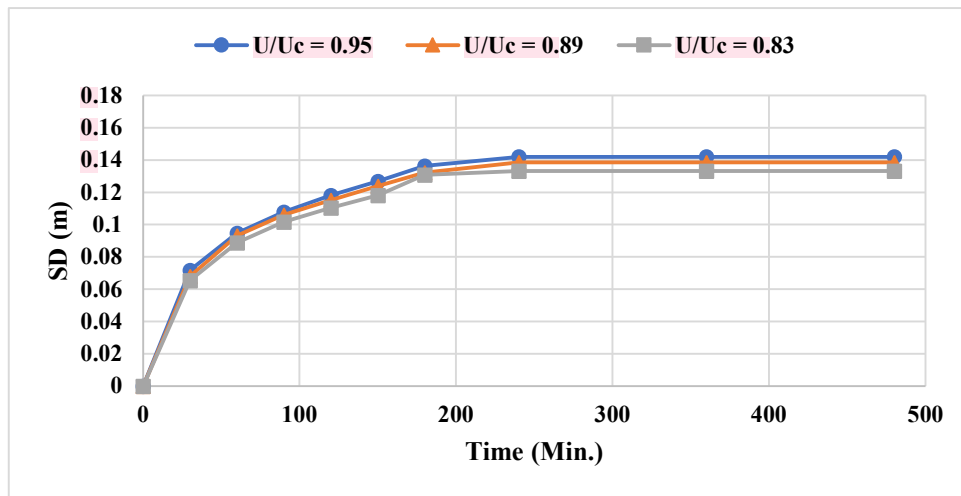


Figure 4.16: Temporal variation plot of R15 under the aforementioned flow conditions

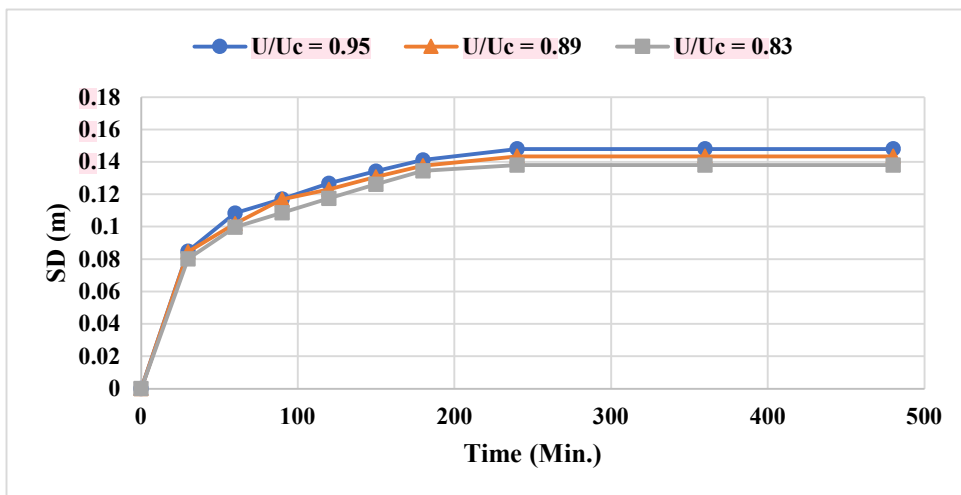


Figure 4.17: Temporal variation plot of R16 under the aforementioned flow conditions

Figures 4.2-4.17 present the temporal scour-depth variation, giving a clearer picture of the scour mechanism around the curved T-shape spur dikes under clear-water conditions. Across all sixteen configurations (R1-R16), scour was mainly governed by the hydraulic conditions, with SD rising as flow velocity increased from 0.2283 m/s ($U/U_c = 0.83$) to 0.2613 m/s ($U/U_c = 0.95$). Scour developed quickly at first before the rate of change tapered off, and by the end of each run the SD-time curve was essentially flat, with variation below 5% (Setia, 2008), confirming that equilibrium had been

reached. While every configuration followed this same pattern, the equilibrium SD itself varied with geometry, showing that both the rate and the magnitude of scour depend on the geometric configuration of the curved T-shape spur dike.

4.2.2.1 Influence of flange length (X) and crest width (Y) on scour depth

The influence of the geometric parameters flange length and crest width on scour depth under clear-water conditions is presented in Figures 4.18 and 4.19, with one parameter held constant and the other varying.

Figure 4.18(a) shows how SD varies with Y at a constant X of 0.110 m: SD fell as Y rose from 0.022 (b/10) to 0.044 (b/5), since the wider flange redistributed the flow around the spur dikes and lowered velocities, but rose again as Y increased from 0.044 to 0.055, reflecting localised flow contraction and secondary acceleration near the bed that raised shear stress slightly. Figures 4.18(b-d), for X held at 0.147, 0.183, and 0.22 m, respectively, show the same pattern, with the minimum SD in every case occurring at $Y = 0.044$ (b/5).

Figure 4.18 further shows that, for X between 0.110 and 0.183 m, SD fell steadily up to $Y = 0.044$ m and then levelled off, whereas for $X = 0.220$ m it fell up to the same point before rising again. This pattern suggests that raising Y from 0.022 to 0.044 m weakens the horseshoe vortex and lowers bed shear stress, slowing sediment removal, but beyond $Y = 0.044$ m the flow instead contracts and accelerates near the nose and wing of the spur dike, intensifying turbulence and bed shear stress and so eroding more sediment and giving a higher scour depth.

Figure 4.19 (a-d) presents the variation in SD with X while keeping Y constant at 0.022m, 0.033m, 0.044m, and 0.055m, respectively. The SD decreased with increasing values of X across all Y scenarios. The results indicated that X had a strong influence on SD. As X increases, it reduces the approach velocities near these structures and prevents the formation of horseshoe vortices, thereby reducing the SD. Further, it was observed that for Y, the SD decreased monotonically as X varied from 0.110m to 0.220m for Y varied from 0.022m to 0.044m. While for $Y = 0.055$ m, the SD decreased monotonically up to $X = 0.183$ m and then increased thereafter.

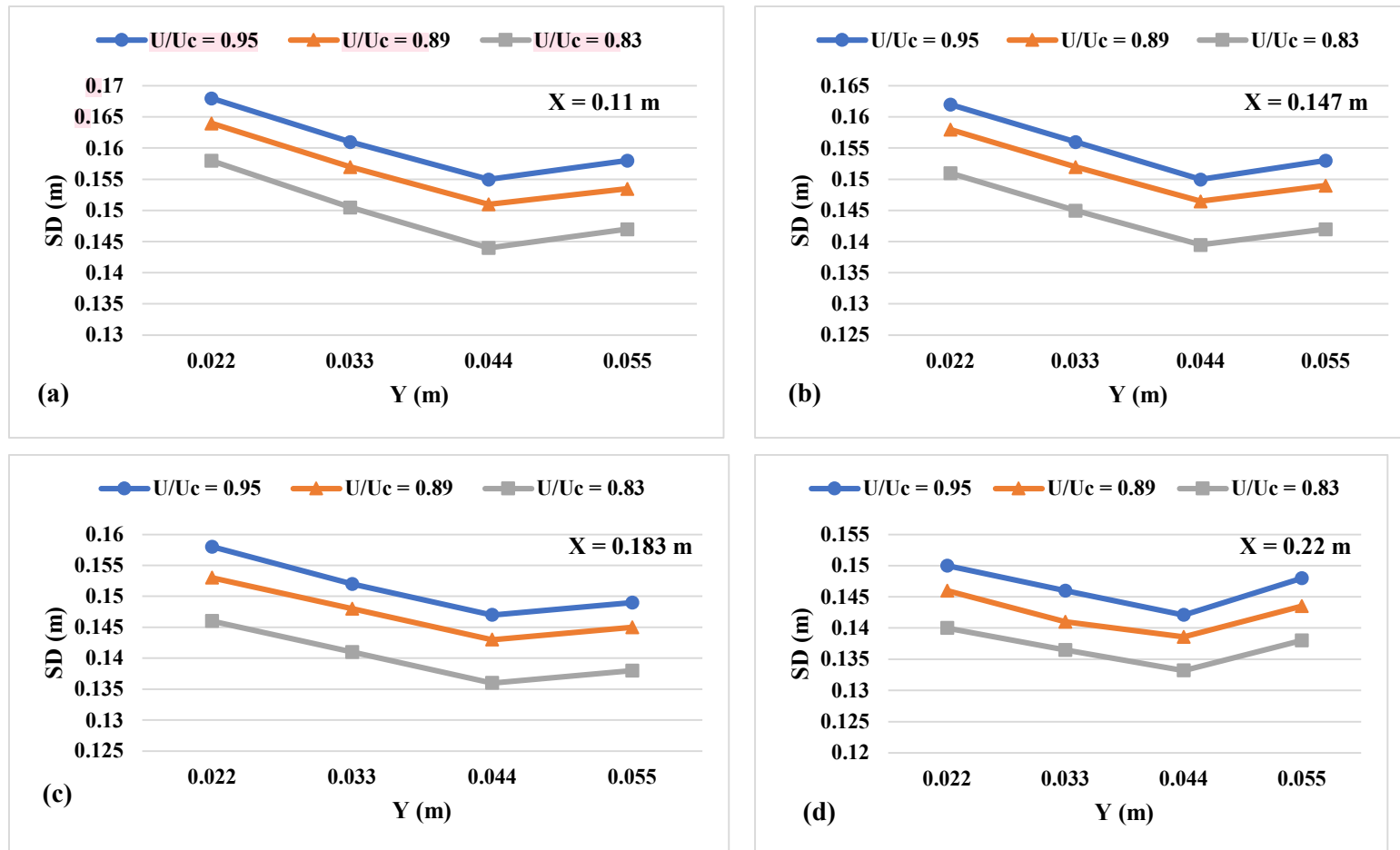


Figure 4.18: Effect of crest width (Y) on scour depth for different clear-water flow conditions with constant flange length (X)

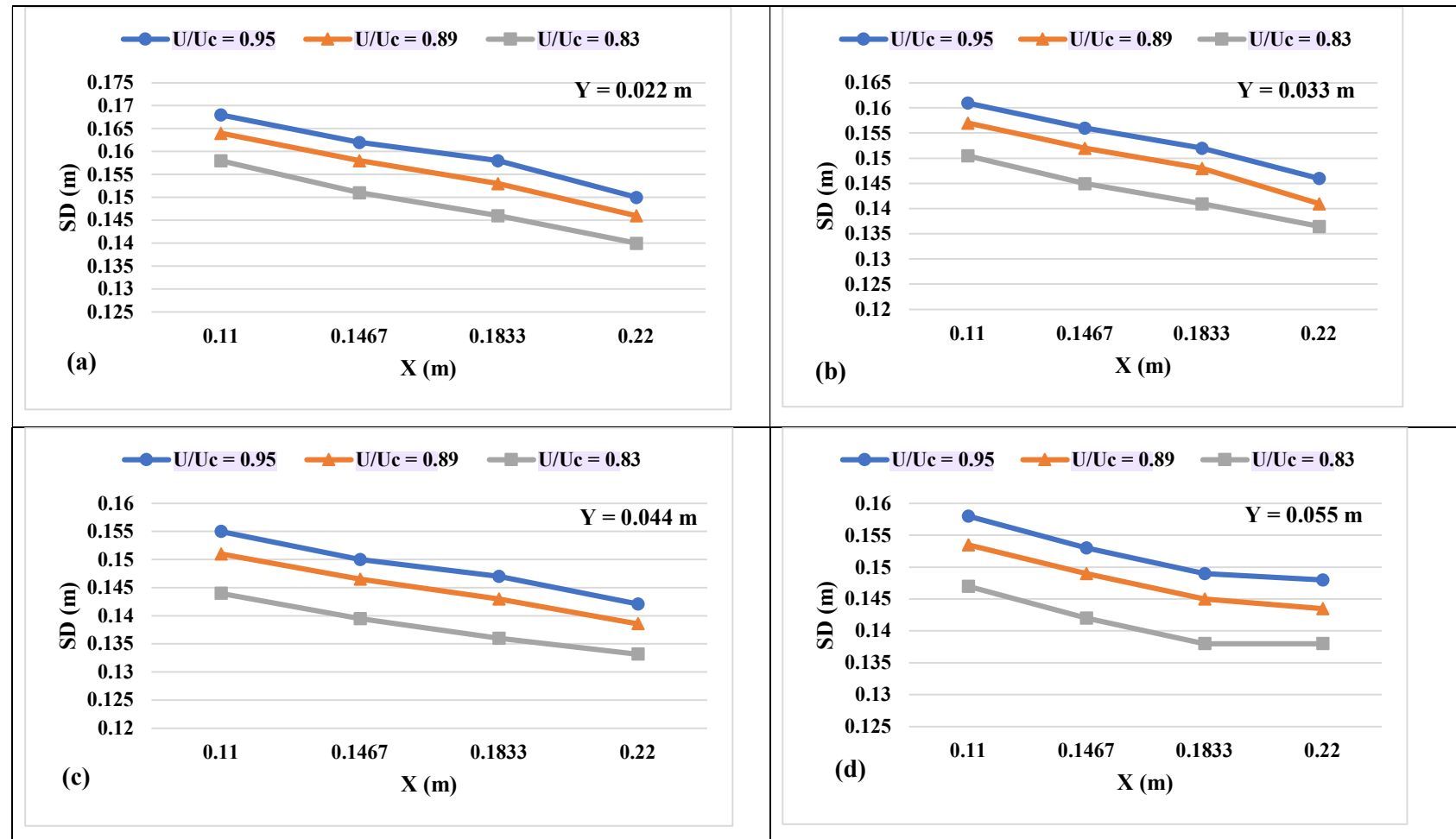


Figure 4.19: Effect of flange length (X) on scour depth for different clear-water flow conditions with constant crest width (Y)

4.2.2.2 Influence of U/U_c on scour depth

The variation of SD with flow conditions (U/U_c) for all geometric configurations of curved T-shape spur dikes under clear-water conditions is presented in Figure 4.20. The results suggested that SD increases with increasing flow condition. The highest SD was observed at $U/U_c = 0.95$, while the lowest was at $U/U_c = 0.83$, indicating the strong influence of flow conditions on scour development. An increase in flow condition results in stronger horseshoe vortices, which ultimately increase bed shear stress near the nose of the spur dikes and the sediment removal rate. The higher the sediment removal rate, the deeper the scour hole around the structure. Therefore, this evidence confirmed that the SD is highly sensitive to flow conditions and increases with increasing U/U_c .

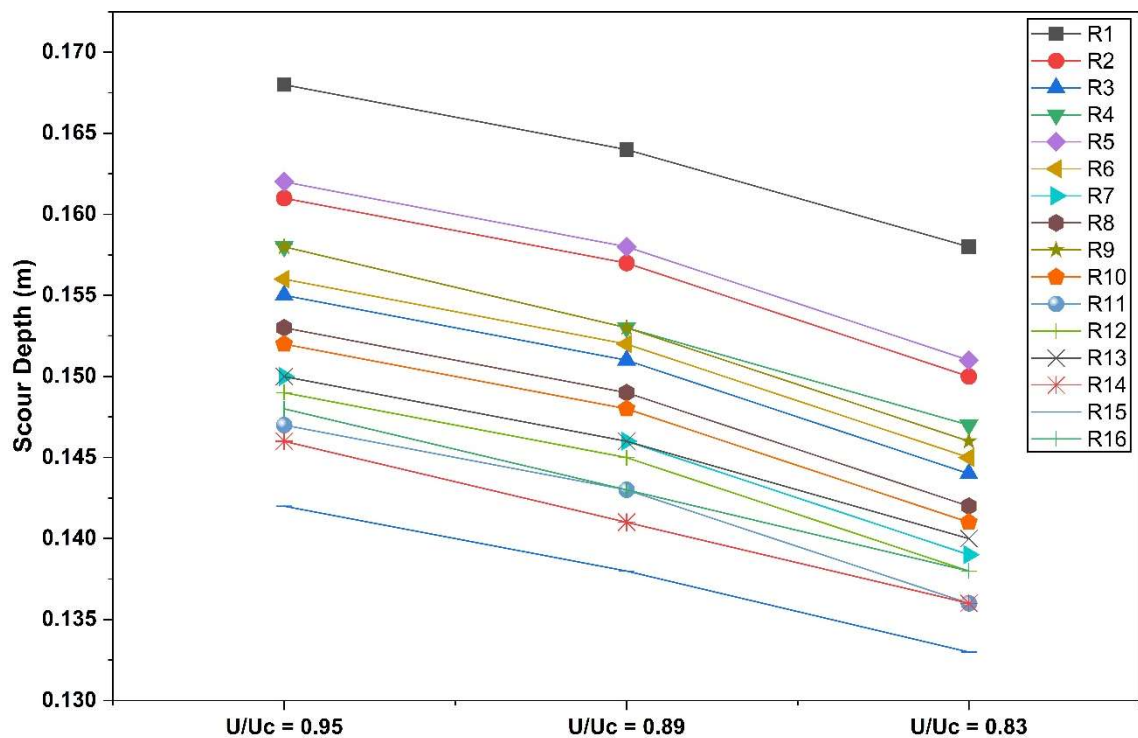


Figure 4.20: Effect of U/U_c on scour depth for different clear-water flow conditions

Overall, the results concluded that both geomatic parameters (X and Y) play a significant role in reducing the scour depth around curved T-shape spur dikes. An

increase in X consistently reduces scour depth, indicating its strong influence, whereas Y exhibits an optimum value of about 0.044 m, beyond which its effect on scour reduction decreases. The minimum SD was achieved at R15, in which $Y = 0.044$ m ($b/5$) and $X = 0.220$ m (b). It was also observed that the SD increased with increasing flow conditions from $U/U_c = 0.83$ to 0.95.

4.3 Spacing between two spur dikes

This section reports an experimental investigation of the optimum spacing between two curved T-shape spur dikes, installed in the flume's working section at spacings ranging from $2b$ through $2.5b$, $3b$, and $3.5b$ to $4b$.

4.3.1 Experimental plan and flow conditions for optimal spacing between two spur dikes

To determine the optimum spacing between two spur dikes, SD was measured around both for three flow conditions ($U/U_c = 0.95, 0.89, 0.83$) and two flow depths ($D = 0.11$ m and 0.19 m), with the experimental layout shown in Figure 4.21. SD around the first spur dike is denoted SD1 and around the second SD2, with the labels SD2 at $2b$, $2.5b$, $3b$, $3.5b$, and $4b$ indicating the spacing between the two dikes; the flow conditions are given in Table 4.3.

Table 4.3: Flow conditions for measuring scour depth around two curved T-shape spur dikes

Flow Velocity (U) (m/s)	Flow Depth (D) (m)	U_c (m/s)	U/U_c (--)	Discharge (Q) (m ³ /s)
0.261	0.19	0.275	0.95	0.0496
0.245	0.19	0.275	0.89	0.0465
0.228	0.19	0.275	0.83	0.0434
0.244	0.11	0.257	0.95	0.0269
0.229	0.11	0.257	0.89	0.0252
0.214	0.11	0.257	0.83	0.0235



Figure 4.21: Experimental placing of two curved T-shape spur dikes in the working section of the flume

4.3.2 Optimum spacing between two curved T-shape dikes

Figures 4.22-4.24 plot the equilibrium SD around the first (SD1) and second (SD2) curved T-shape spur dikes for flow conditions $U/U_c = 0.95, 0.89,$ and 0.83 at a flow depth of 0.11 m. Scour around the first dike behaves much as it does for a single spur dike, whereas scour around the second is governed by the spacing between them, with SD2 markedly lower than SD1 because the first dike shields the second, cutting the approach velocity and turbulence reaching it and so reducing scour there. Figures 4.25-4.27 present the corresponding SD1 and SD2 values at a flow depth of 0.19 m, showing

the same pattern as Figures 4.22-4.24. Across the tested spacings (2b, 2.5b, 3b, 3.5b, 4b), 3b consistently gave the minimum equilibrium SD and 4b the maximum, for every flow condition and flow depth.

Table 4.4: Percentage reduction of SD around second spur dikes

Flow conditions	Flow depths (m)	Percentage reduction in SD $\left[\frac{SD1 - SD2}{SD1} * 100 \right]$				
		2b	2.5b	3b	3.5b	4b
$U/U_c = 0.95$	0.11	40.39	46.01	51.06	37.78	23.31
$U/U_c = 0.89$	0.11	39.34	46.3	49.62	38.74	26.6
$U/U_c = 0.83$	0.11	42.47	43.99	50.45	36.89	25.41
$U/U_c = 0.95$	0.19	40.04	46.32	50.6	37.79	26.61
$U/U_c = 0.89$	0.19	42.93	40.69	50.72	38.37	21.94
$U/U_c = 0.83$	0.19	39.72	45.87	50.15	36.71	27.03

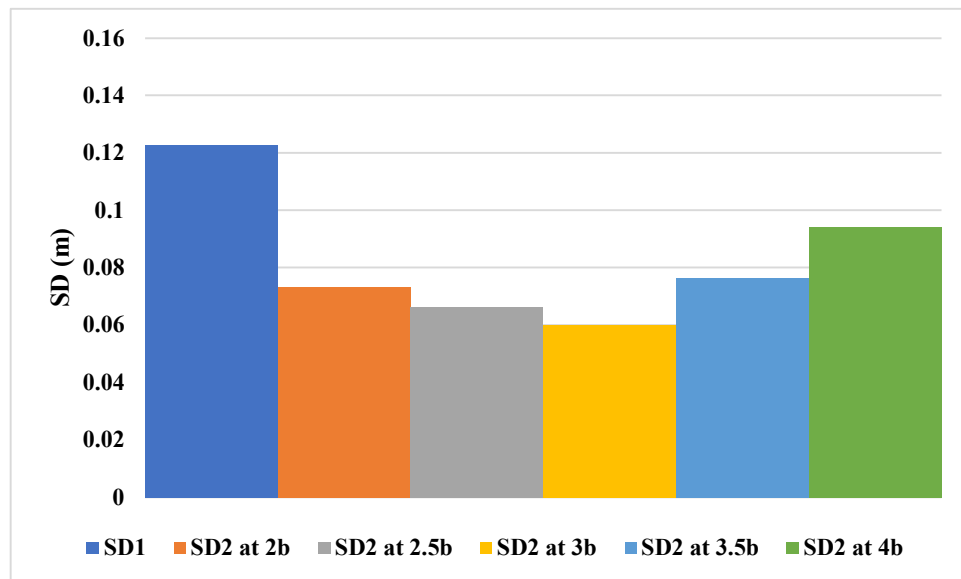


Figure 4.22: Equilibrium SD at first and second spur dikes for various spacing with $U/U_c = 0.95$ and flow depth = 0.11

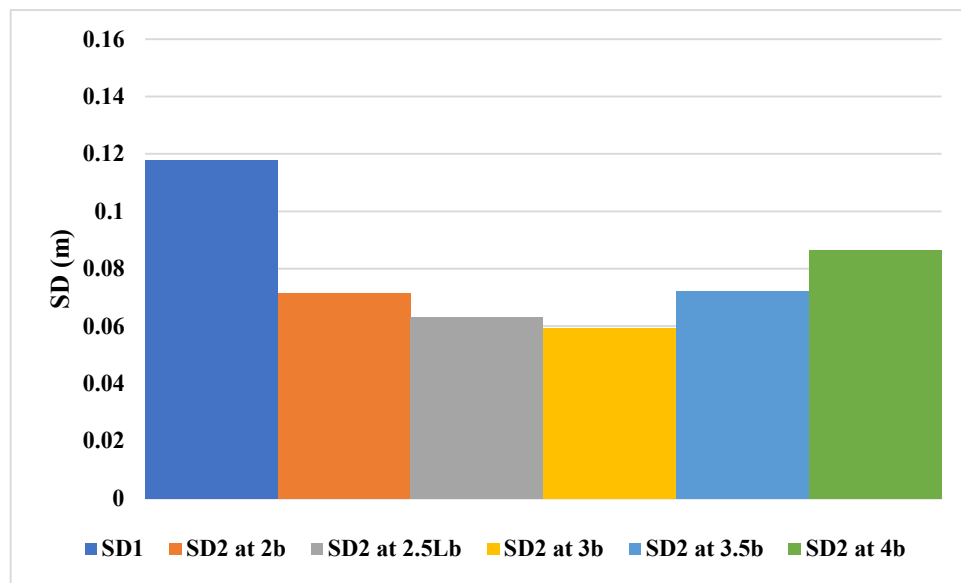


Figure 4.23: Equilibrium SD at first and second spur dikes for various spacing with $U/U_c = 0.89$ and flow depth = 0.11

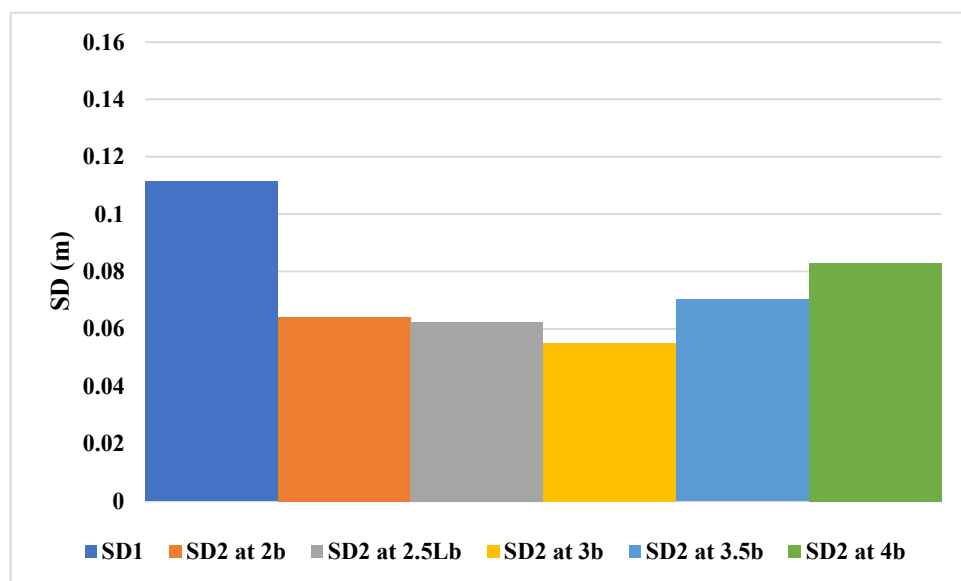


Figure 4.24: Equilibrium SD at first and second spur dikes for various spacing with $U/U_c = 0.83$ and flow depth = 0.11

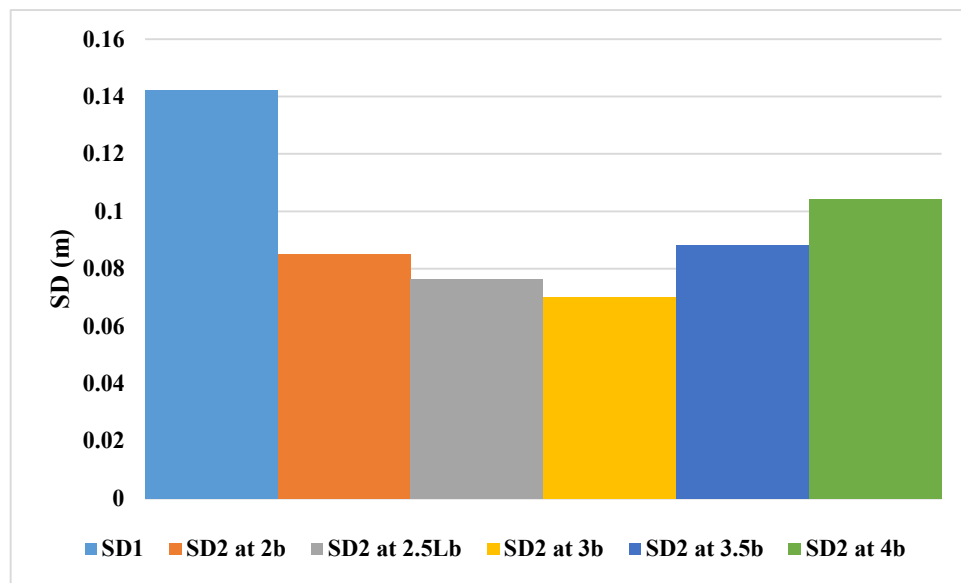


Figure 4.25: Equilibrium SD at first and second spur dikes for various spacing with $U/U_c = 0.95$ and flow depth = 0.19

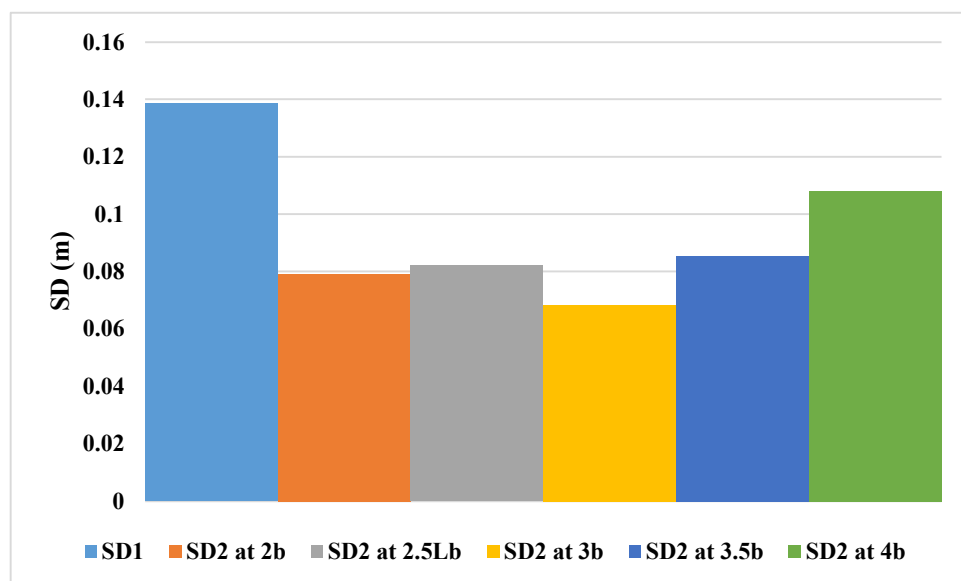


Figure 4.26: Equilibrium SD at first and second spur dikes for various spacing with $U/U_c = 0.89$ and flow depth = 0.19

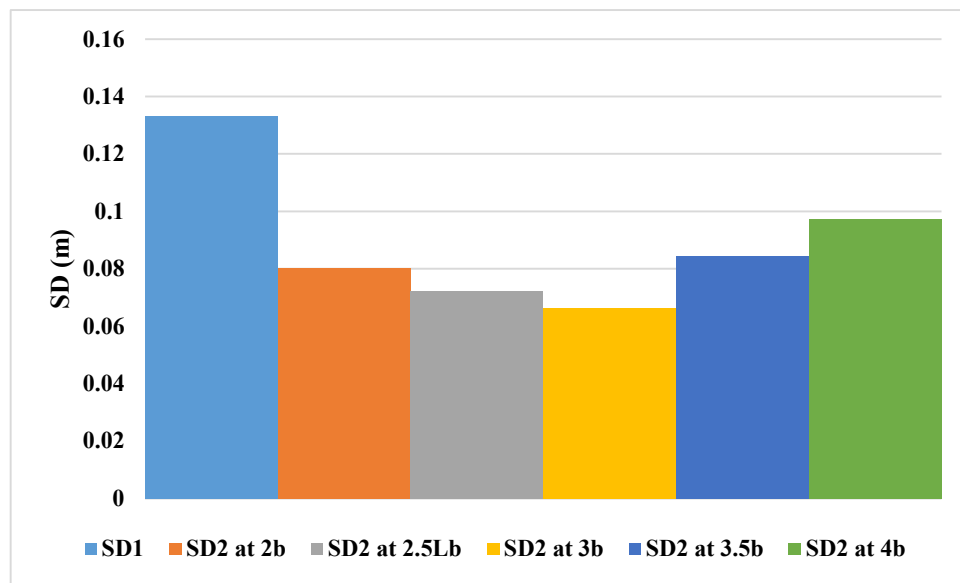


Figure 4.27: Equilibrium SD at first and second spur dikes for various spacing with $U/U_c = 0.83$ and flow depth = 0.19

Table 4.4 presents the percentage reduction in SD2 relative to SD1. The highest scour reduction occurs at a spacing of 3b, with percentage reductions ranging from 49.62% to 51.06%. The lowest reduction is observed at a spacing of 4b, with values ranging from 21.94% to 27.03%. The 2.5b spacing results in more scour reduction than 2b, 3.5b, and 4b, but less than 3b. In contrast, the 3.5b spacing produces less scour reduction than 2b, 2.5b, and 3b, but more than 4b. The sequence of spur dike spacings for reducing SD was $3b > 2.5b > 2b > 3.5b > 4b$, with the maximum reduction achieved at 3b. Therefore, the results from Figures 4.22-4.27 and Table 4.4 indicated that the spacing of the spur dike significantly reduced SD2. The 3b spacing provided the most protection to SD2 among the experimentally tested spacings.

4.4 Comparison of scour depth around the proposed curved T-shape spur dike with standard I-shape and T-shape spur dikes

In this section, the performance of newly developed curved T-shape spur dikes was compared with I- and T-shape spur dikes. The most economical and efficient shape of curved T-shape spur dikes was selected for the comparison with traditional spur dikes. The geometry of the most economical curved T-shape spur dikes was R15 with $X = b$ and $Y = b/5$. For a fair comparison, the T-spur dikes were modeled with $X = b$ and Y

= $b/5$, with a flat flange surface. The I-shape spur dike was the simplest, with the same length of b and crest width of $b/5$. The shapes of these spur dikes are shown in Figure 4.28.

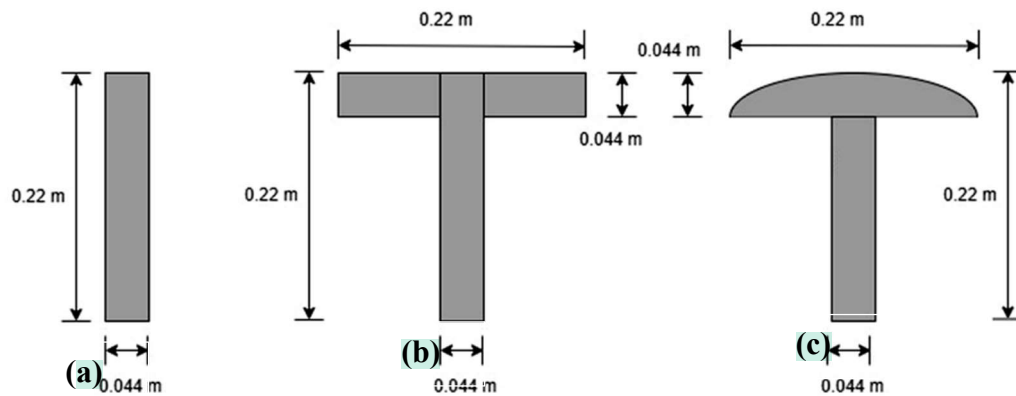


Figure 4.28: Shapes of (a) I-, (b) T-, and (c) Curved T-shape spur dikes

4.4.1 Experimental plan and flow conditions for different shapes of spur dikes

The experiments compared three spur-dike shapes - I-, T-, and curved T-shape - shown in Figure 4.29, all tested on the same Yamuna River sand, using wooden models in the same experimental setup within the flume's working section. Temporal SD was recorded for every shape under five flow conditions ($U/U_c = 0.95, 0.89, 0.83, 0.8, 0.76$) and two flow depths (0.11 m and 0.19 m), for which U_c was found to be 0.2573 m/s and 0.275 m/s, respectively; Table 4.5 summarises these flow conditions and depths.

Table 4.5: Flow conditions for comparing the performance of I-, T-, and curved T-shape spur dikes

Flow Velocity (U) (m/s)	Flow Depth (D) (m)	U/U_c (--)	Discharge (Q) (m ³ /s)
0.2444	0.11	0.95	0.0269
0.229	0.11	0.89	0.0252
0.2135	0.11	0.83	0.0235
0.2058	0.11	0.8	0.0226
0.1955	0.11	0.76	0.0215

4

Flow Velocity (U) (m/s)	Flow Depth (D) (m)	U/U _c (--)	Discharge (Q) (m ³ /s)
0.2613	0.19	0.95	0.0496
0.2448	0.19	0.89	0.0465
0.2283	0.19	0.83	0.0434
0.22	0.19	0.8	0.0418
0.209	0.19	0.76	0.0397



Figure 4.29: Placement of I-, T-, and curved T-shape spur dikes in the working section of the flume

4.4.2 Scour depth around various shapes of spur dikes

Experimental observations of SD with respect to time were measured around various spur dike shapes shown in Figure 4.30 under clear-water conditions. All the experiments were performed for 480 minutes with continuous flow. The temporal variation plots of SD around various spur dikes for different flow conditions are shown in Figures 4.30-4.34.

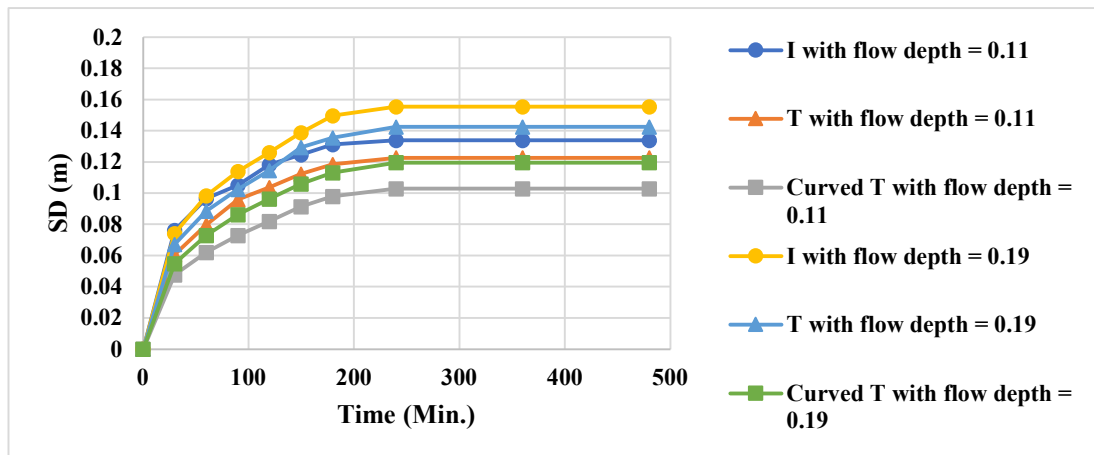


Figure 4.30: Temporal variation of SD for I-, T-, and curved T-shape spur dikes with different flow depths, with flow condition $U/U_c = 0.76$

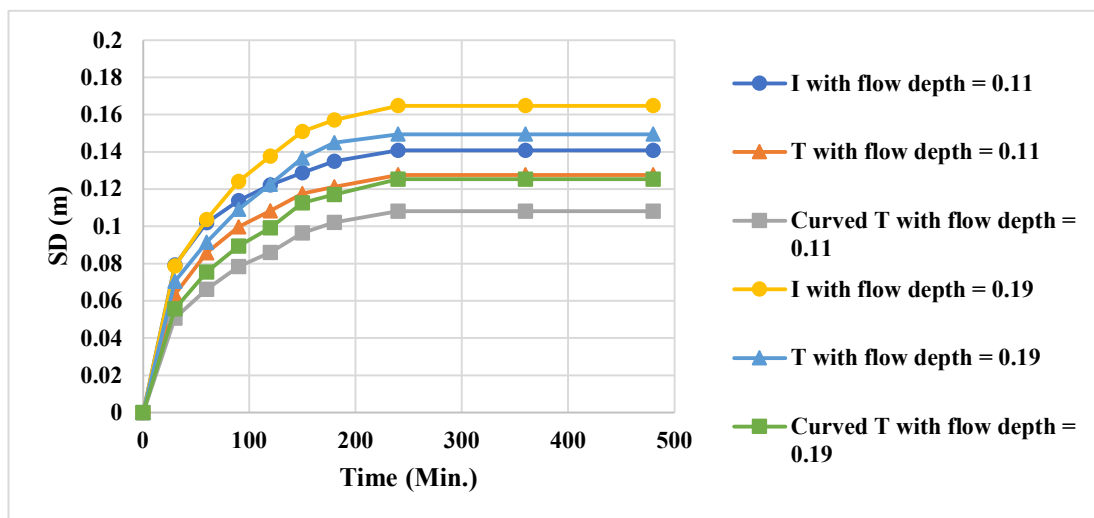


Figure 4.31: Temporal variation of SD for I-, T-, and curved T-shape spur dikes with different flow depths, with flow condition $U/U_c = 0.8$

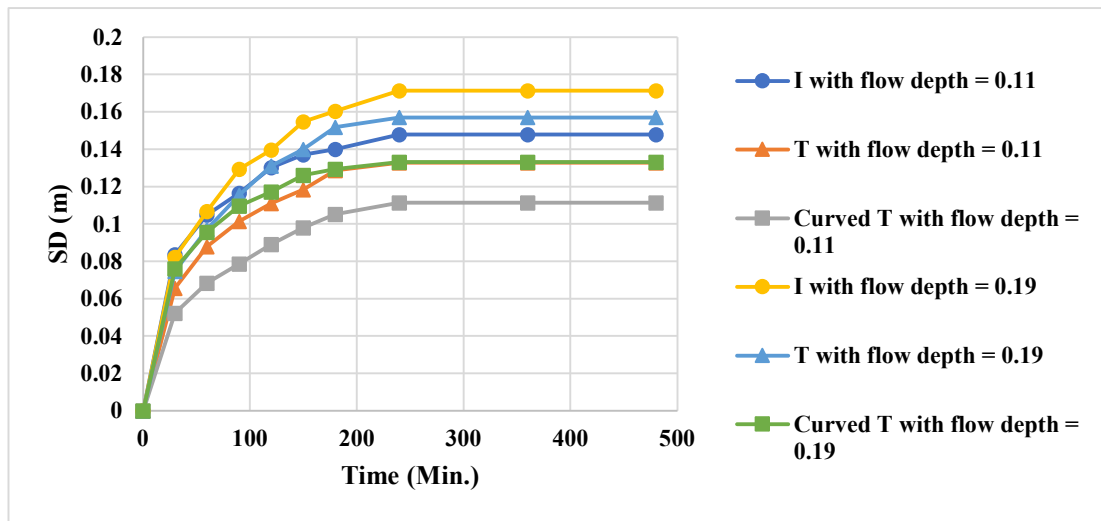


Figure 4.32: Temporal variation of SD for I-, T-, and curved T-shape spur dikes with different flow depths, with flow condition $U/U_c = 0.83$

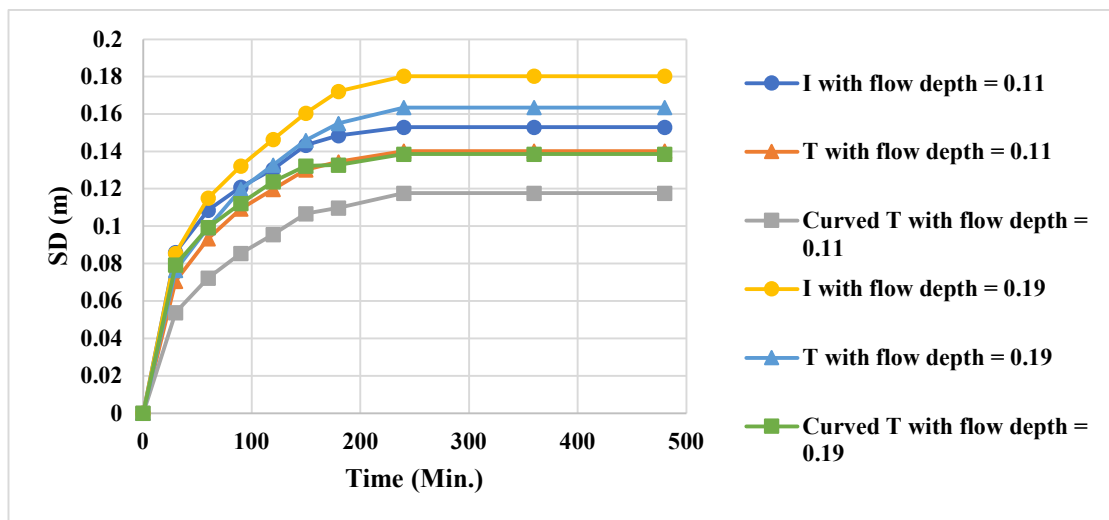


Figure 4.33: Temporal variation of SD for I-, T-, and curved T-shape spur dikes with different flow depths, with flow condition $U/U_c = 0.89$

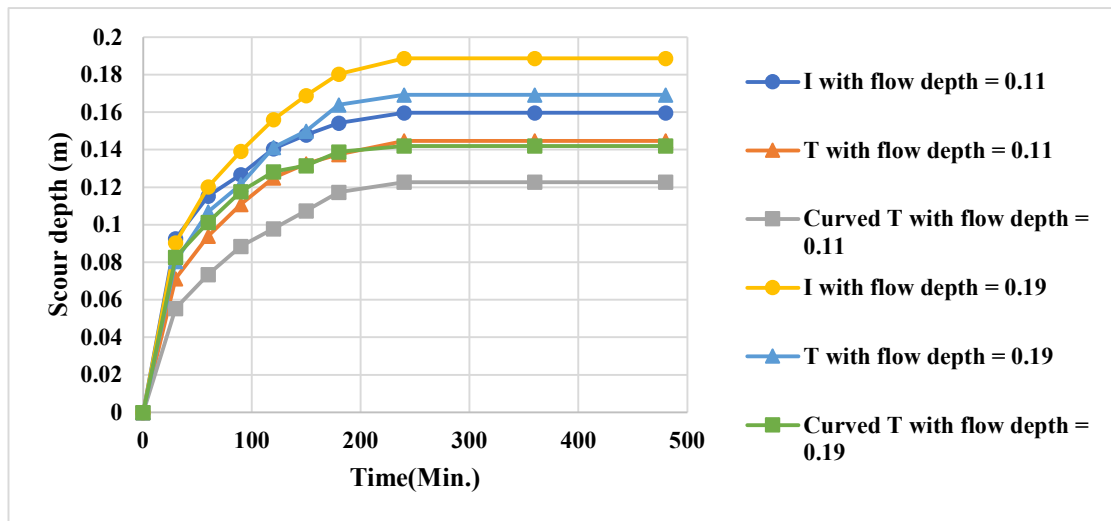


Figure 4.34: Temporal variation of SD for I-, T-, and curved T-shape spur dikes with different flow depths, with flow condition $U/U_c = 0.95$

Figures 4.30-4.34 show SD rising quickly at first and then levelling off. Of the three shapes, the I-spur dike at a flow depth of 0.19 m produced the most scour, owing to its greater obstruction of the flow; the T-shape spur dike scoured less, since its flange creates flow separation and turbulence near the nose; and the curved T-shape spur dike gave the least scour of all, its curved flange softening the impact of the approaching flow and redirecting it smoothly toward the centre of the channel. This pattern held consistently across every flow condition tested.

Therefore, the results showed that the shape of the spur dikes strongly influenced scour around them under clear-water conditions. The results showed that the curved T-shape spur dikes produced the least SD, redistributing flow towards the river center than the I-shape and T-shape spur dikes, thereby protecting the riverbank and improving navigation by increasing flow depth.

4.4.3 Analyzing the flow behavior around spur dikes using ANSYS Fluent

This section reports the numerical results for flow behaviour in and around the I-, T-, and curved T-shape spur dikes under clear-water conditions, modelled in Ansys Workbench 2025. Three aspects are considered: velocity contours (near-bed, mid-

depth, and near-surface), velocity vectors and streamlines, and the variation in bed shear stress, each discussed in the subsections that follow.

4.4.3.1 Velocity contours

In fluid dynamics, a velocity contour is a graphical representation, in the form of a color-coded map, used to visualize the speed and direction of fluid over a specific object or area. In this study, velocity contour plots are used to visualize velocity changes around spur dikes, with different colors indicating different velocity levels. The low velocity region is represented by the blue color, the moderate velocity region is visualized by green and yellow color, while the high velocity zone is represented by orange and red color. Velocity was visualized at three levels in this study: near the bed, mid-depth, and near the surface.

Figure 4.35 presents the near-bed velocity contours. The I-shape spur dike shows a large orange-red region near its nose, marking high near-bed velocity and, correspondingly, a strong horseshoe vortex and greater scour; the T-shape spur dike shows smaller orange-red and larger green-yellow regions, indicating lower near-bed velocities and hence less scour than the I-shape. The curved T-shape spur dike's contours are dominated by blue and green-yellow, showing the lowest near-bed velocities and the least scour of the three, since its curved arm smoothly directs the flow toward the channel centre and limits the formation of strong vortices near the bed.

Figure 4.36 presents the mid-depth velocity contours. Behind the I-shape spur dike, a large blue recirculation zone formed as the flow separated from the structure and rolled into wake vortices downstream, with extensive blue regions bordered by yellow and red indicating strong separation and elevated turbulence. For the T-shape spur dike this blue wake region was smaller, since the transverse arm spread the flow over a wider area before it reached the head, weakening the downstream wake vortices and giving a more uniform spread of green and yellow, indicative of greater flow stability. The curved T-shape spur dike produced the smallest recirculation zone of the three, its curved arm redirecting the flow gradually toward the channel centre and limiting both

abrupt separation and downstream vortex strength, leaving a more uniform, smoother distribution of green and yellow in the contours.

Figure 4.37 presents the velocity contours near the water surface. For the I-shape spur dike, prominent orange and red regions near the spur head and along the main flow path show the surface flow being strongly deflected toward the channel centre, reflecting sharp flow acceleration, steep velocity gradients, and heightened turbulence near the structure. For the T-shape spur dike, these orange-red regions are smaller and the deflection less pronounced, with more green and yellow visible, indicating a more even velocity distribution as the transverse arm spreads the approaching flow over a wider area. The curved T-shape spur dike gives the most stable surface velocity distribution of the three, dominated by green and light yellow with only a few localised high-velocity spots, since its curved arm guides the flow gradually toward the main channel and limits disturbance and turbulence near the spur head.

4.4.3.2 Flow velocity vectors

Figure 4.38 presents the velocity vector plots, showing the magnitude and direction of flow around the spur dikes. For the I-shape spur dike, the vectors show large recirculation zones downstream, with rapid changes in direction and extensive circulating patterns pointing to strong flow separation at the head and intense wake vortices. These recirculation zones were smaller and the vectors more organised for the T-shape spur dike, whose transverse arm altered the flow path and weakened the downstream wake vortices. The curved T-shape spur dike gave the most efficient pattern of the three, with the vectors showing the flow smoothly guided toward the channel centre and little recirculation behind the structure, indicating reduced separation and a more stable field than either the I- or T-shape spur dike.

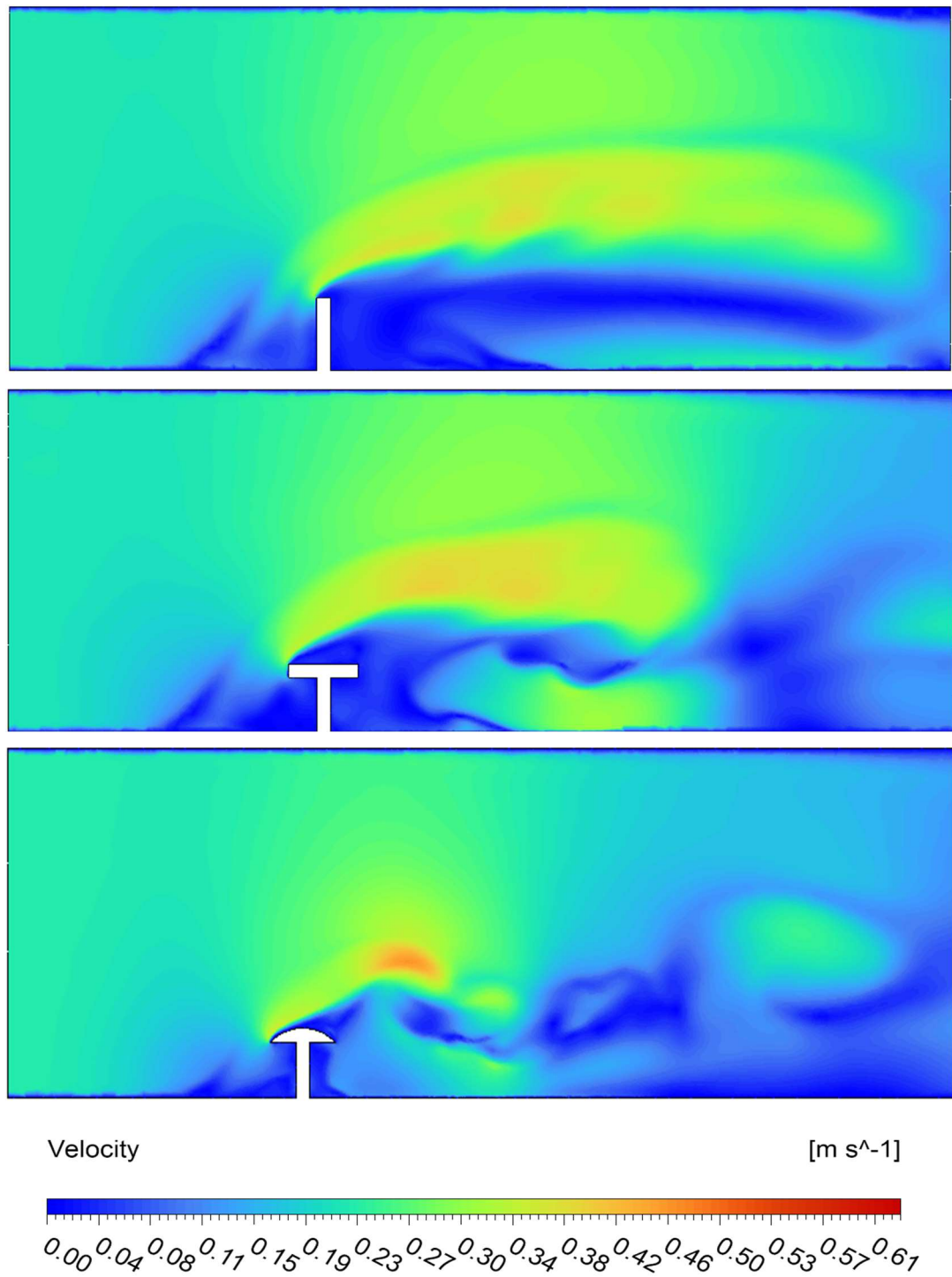


Figure 4.35: Near-bed velocity contours around different spur dike configurations: (a) I-shape spur dike, (b) T-shape spur dike, and (c) curved T-shape spur dike

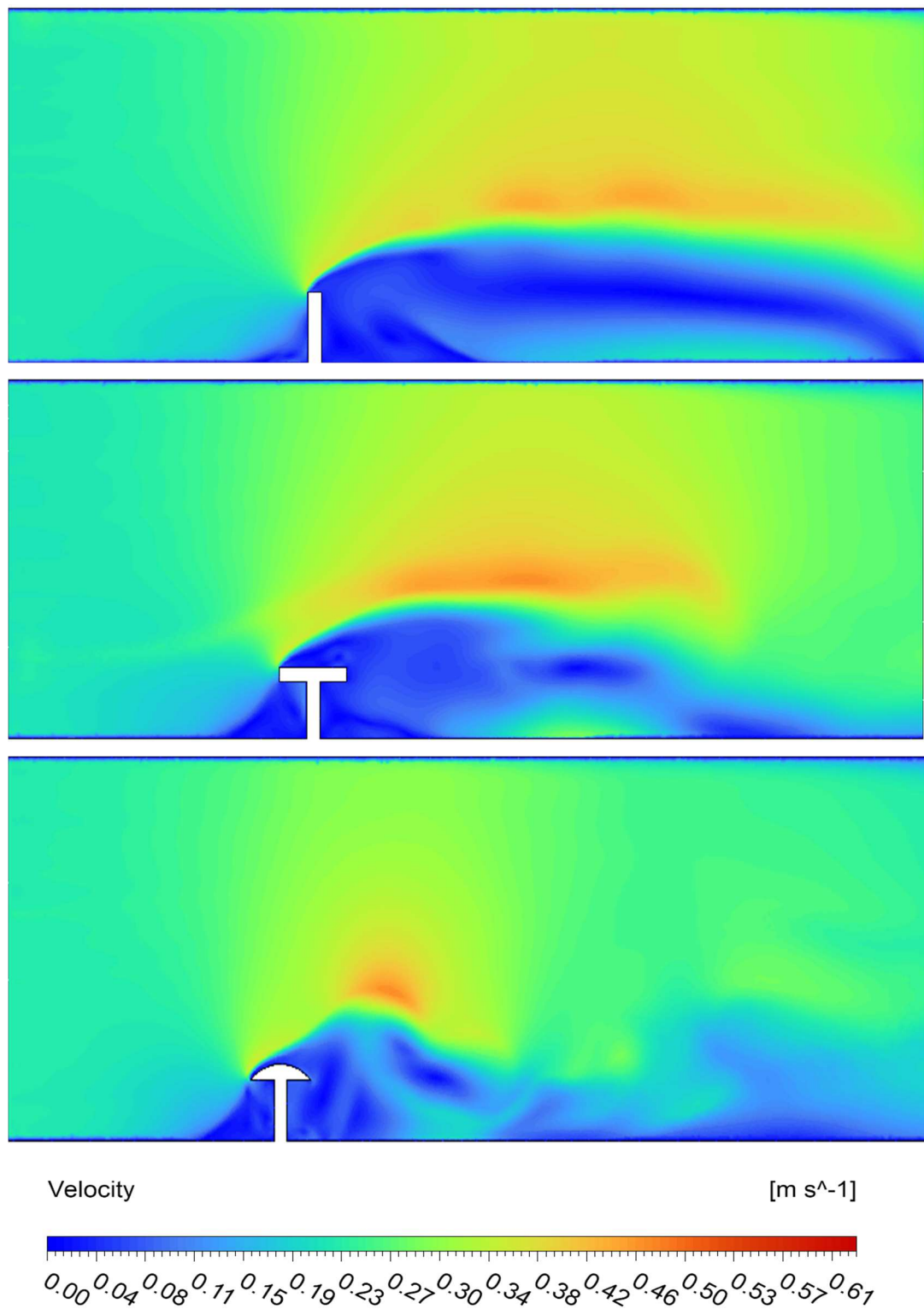


Figure 4.36: Mid-depth velocity contours around different spur dike configurations: (a) I-shape spur dike, (b) T-shape spur dike, and (c) curved T-shape spur dike

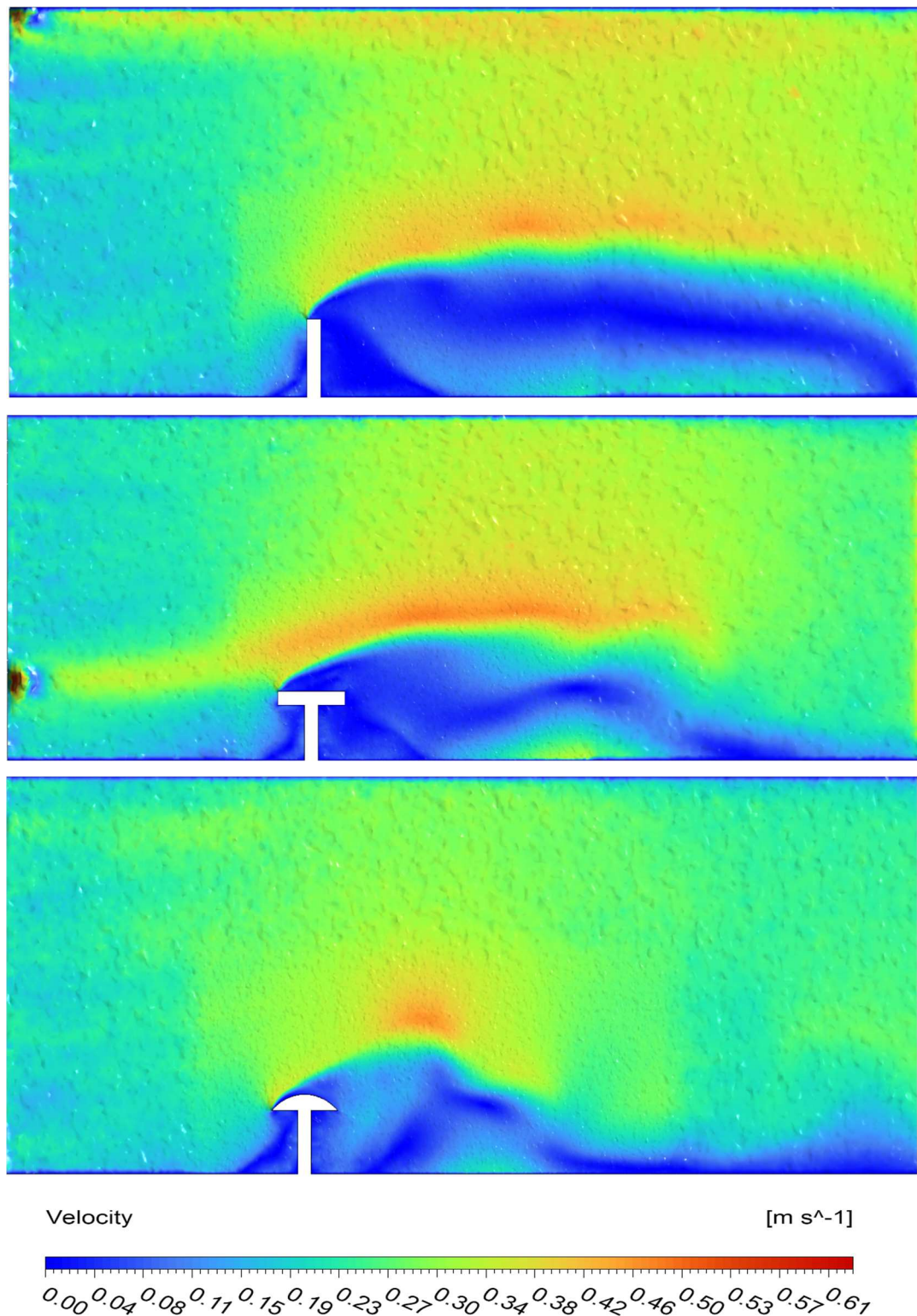


Figure 4.37: Near-surface velocity contours around different spur dike configurations: (a) I-shape spur dike, (b) T-shape spur dike, and (c) curved T-shape spur dike

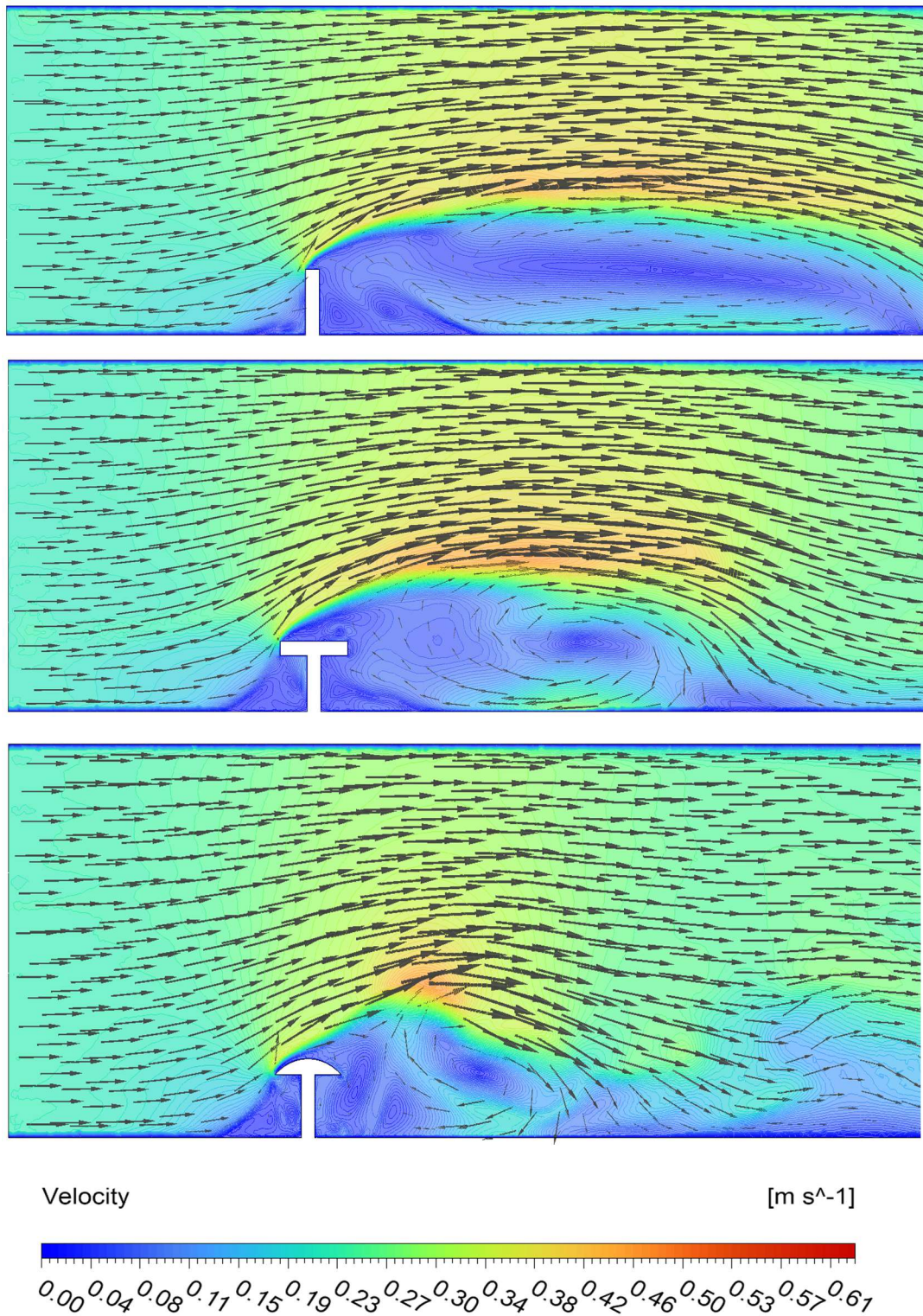


Figure 4.38: Flow velocity vectors around different spur dike configurations: (a) I-shape spur dike, (b) T-shape spur dike, and (c) curved T-shape spur dike

4.4.3.3 Streamlines pattern

The streamline plots are shown in Figure 4.39 provide additional information about the movement of water around the spur dikes. For the I-shape spur dike, the streamlines exhibited clear flow separation at the spur head and formed large circular patterns downstream of the structure. These large vortex structures indicate strong recirculation and unstable flow conditions in the wake region. In the T-shape spur dike, the streamlines showed smaller vortices and fewer recirculation zones. The transverse arm distributed the approaching flow more effectively, reducing the intensity of flow separation and improving overall flow stability. Among the three configurations, the curved T-shape spur dike exhibited the smoothest streamline pattern. The streamlines gradually followed the curvature of the arm and were directed toward the channel center with minimal flow separation. Only small recirculation zones were observed downstream of the structure, indicating a more stable flow field and lower turbulence levels than in the I- and T-shape spur dikes.

4.4.3.4 Bed shear stress variation

Figure 4.40 shows the distribution of bed shear stress around the spur dikes; since bed shear stress governs the flow's ability to erode the bed, blue regions in the contour plots mark low shear stress and green, yellow, orange, and red mark progressively higher values.

Of the three configurations, the I-shape spur dike showed the highest bed shear stress, marked by a pronounced red-orange region near its head, driven mainly by a strong downflow and a horseshoe vortex at the structure's base that intensified the erosive forces on the bed and produced greater scour. The red-orange region was smaller for the T-shape spur dike, with more pronounced green-yellow regions around the head, as its transverse arm lessened the direct impact of the approaching flow and so lowered bed shear stress and the erosive action near the structure.

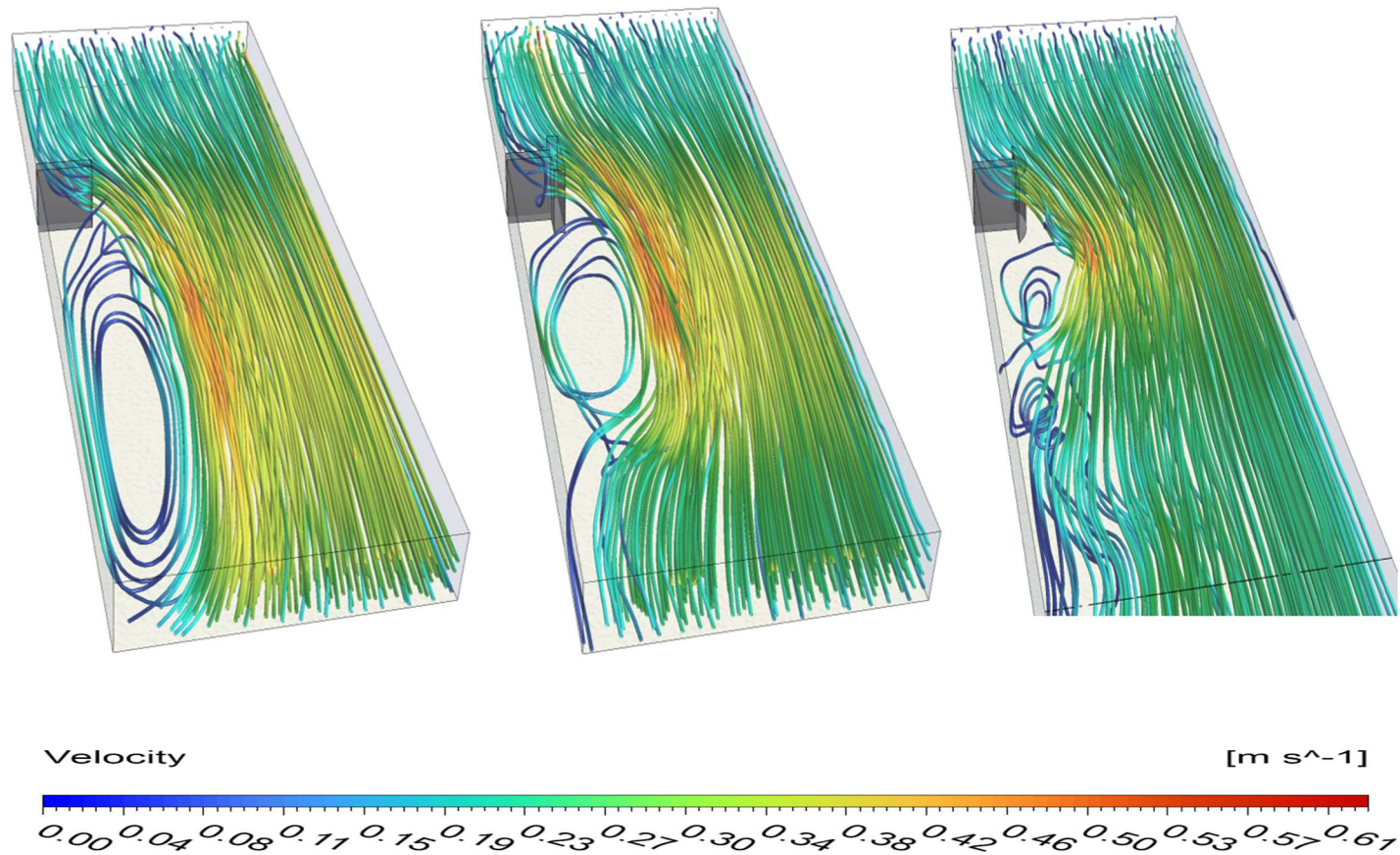


Figure 4.39: Streamlines pattern around different spur dike configurations: (a) I-shape spur dike, (b) T-shape spur dike, and (c) curved T-shape spur dike

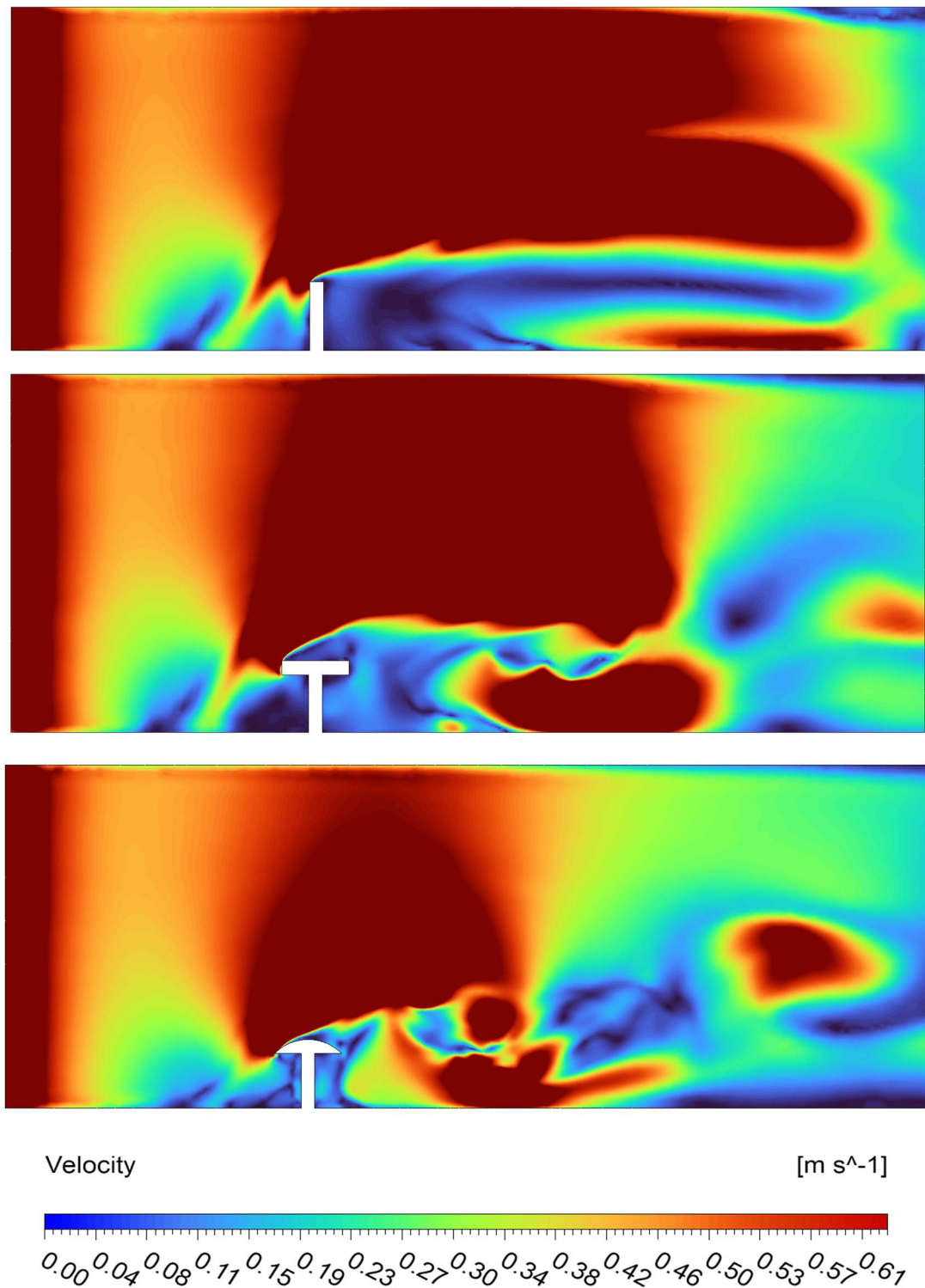


Figure 4.40: Bed shear-stress variation around different spur dike configurations: (a) I-shape spur dike, (b) T-shape spur dike, and (c) curved T-shape spur dike

The curved T-shape spur dike showed the lowest bed shear stress of all, its contour dominated by blue-green with only a small area of high shear near the head, its curved arm guiding the flow more gradually toward the channel centre, limiting the formation of strong near-bed vortices and so reducing the potential for sediment erosion and scour.

4.4.4 Discussion of CFD results and validation with experimental observations

The CFD simulations gave useful insight into the flow mechanisms behind scour around the spur dikes. The I-shape spur dike produced high-velocity concentrations, intense vortex formation, and elevated bed shear stress near its head, all of which increased the flow's ability to entrain and transport sediment and so produced deeper scour holes. The T-shape spur dike caused a less severe disturbance, its transverse arm redistributing the approaching flow and weakening the downflow near the head, which lowered vortex strength and bed shear stress relative to the I-shape and reduced scour potential accordingly. The curved T-shape spur dike showed the most favourable flow characteristics of the three: its curved arm gradually redirected the flow toward the channel centre, reducing separation, suppressing vortex formation, and lowering bed shear stress near the head, giving it the least potential for local scour.

These CFD results agreed well with the flume experiments, both showing the curved T-shape spur dike to give the least scour, followed by the T-shape, with the I-shape spur dike giving the most. The numerical analysis therefore confirms the experimental finding that the curved T-shape spur dike is the most effective of the three at reducing local scour.

4.5 Development of the hybrid machine learning models

This research has developed hybrid models to predict the scour depths around the spur dikes. The standalone machine learning model (RT) is hybridized using additive regression (AR), Bagging (B), and random subspace (RSS). By combining the standalone model (RT) with AR, B, and RSS, seven hybrid models were developed. These seven-hybrid machine learning models were AR_RT, B_RT, RSS_RT, RSS_AR_RT, RSS_B_RT, B_AR_RT, RSS_B_AR_RT. Finally, the performance of

the hybrid machine learning models was compared with that of the standalone model (RT) for predicting scour depths around spur dikes.

4.5.1 Performance of developed hybrid models

Performance evaluation is the process of assessing the performance of machine learning models. The performance evaluation outcomes for various machine learning models are shown in Table 4.6 for the training and testing subsets. Evidently, the B_AR_RT (R-Square = 0.9702, RMSE = 0.1305, NSE = 0.9692, and COC = 0.9845) and RSS_RT (R-Square = 0.9699, RMSE = 0.1321, NSE = 0.9685, and COC = 0.9841) models predicted greater efficiency in the testing phase, followed by B_RT; AR_RT; RSS_B_RT; RSS_B_AR_RT; and RT.

Table 4.6: Results of performance evaluation for different machine learning models

Machine Learning Models	R-Square	RMSE	NSE	COC	R-Square	RMSE	NSE	COC
	Training				Testing			
RT	0.9998	0.0106	0.9998	0.9999	0.9081	0.2308	0.8039	0.8966
AR_RT	1	0.0002	1	1	0.9502	0.1699	0.948	0.9736
B_RT	0.9866	0.0927	0.9855	0.9933	0.9609	0.1506	0.9591	0.9793
RSS_RT	0.9944	0.0605	0.9938	0.9972	0.9699	0.1321	0.9685	0.9841
RSS_AR_RT	0.9504	0.1887	0.94	0.9749	0.8967	0.2463	0.8905	0.9437
RSS_B_RT	0.937	0.2253	0.9143	0.9680	0.9192	0.2363	0.8993	0.9483
B_AR_RT	0.9873	0.0899	0.9864	0.9936	0.9702	0.1305	0.9692	0.9845
RSS_B_AR_RT	0.937	0.2253	0.9144	0.9680	0.9129	0.2383	0.8947	0.9459

Furthermore, the differences in COC, R-Square, RMSE, MAE, RRSE, RAE, SI, and NSE between the actual and predicted values in the training and testing subsets for B_AR_RT and RSS_RT are considerably smaller than those for other hybrid and standalone models. From Table 4.6, it is concluded that B_AR_RT and RSS_RT are the most efficient hybrid machine learning models for predicting scour depth. These conclusions also suggest that first-order hybridization increases the efficiency of the machine learning model. So, RSS_RT, B_RT, and AR_RT give better results than the

standalone model (RT). Second-order hybridization (B_AR_RT) also increases the efficiency of the machine learning models, except for RSS_AR_RT and RSS_B_RT, and achieves the highest accuracy among them. However, third-order hybridization decreases performance, though it is better than the standalone model. Thus, the B_AR_RT and RSS_RT hybrid machine learning model yields the best results for predicting scour depth and outperforms all competing models.

To demonstrate the performance of such machine learning models during training and testing, several plotting techniques, such as scatter plots, variation plots, box plots, and Taylor diagrams, have been used in the literature (Salmasi et al., 2023; Jaiswal et al., 2023; Malik et al., 2022). In this research, the authors have used these plotting techniques to validate the results of the performance indicators. The plots of this study for the prediction of scour depths around spur dikes are as follows:

- a. The scattered plots of scour depths with all machine learning models for training and testing subsets are plotted in Figures 4.41 (a) and 4.42 (b), respectively. It is plotted between the actual and predicted values of dimensional output variables (SD/b), and the diagonal line is the best fit. The model in which all the points lie on best-fit lines is the best. Figures 4.41 (a) and 4.41 (b) also suggested that B_AR_RT and RSS_RT are the best hybrid machine learning models, while RSS_B_AR_RT gives the worst result among all hybrid machine learning models in predicting scour depths. The results of the scattered plots also follow the same hierarchy, followed by the various performance indicators.

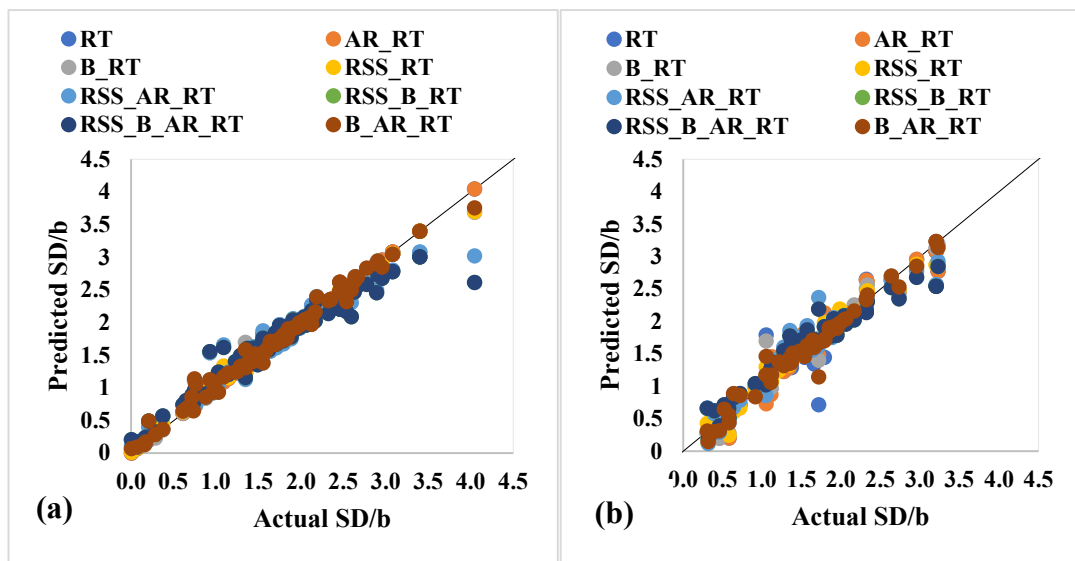


Figure 4.41: Scattered plot between the actual and predicted values of SD/b for (a) training subsets and (b) testing subsets

The variation plots for various machine learning models are shown in Figure 4.42 for the training and test subsets. As the name suggests, the variations plot shows a visual representation of the variation between the actual and predicted values of SD/b. Figure 4.42 shows the smallest difference between actual and predicted SD/b for the B_AR_RT and RSS_RT hybrid machine learning models, followed by B_RT, AR_RT, RSS_B_RT, RSS_B_AR_RT, RT, and RSS_AR_RT. The variation plot (Figure 4.42) suggests the same trend as in Table 4.6 and Figure 4.41 (a & b).

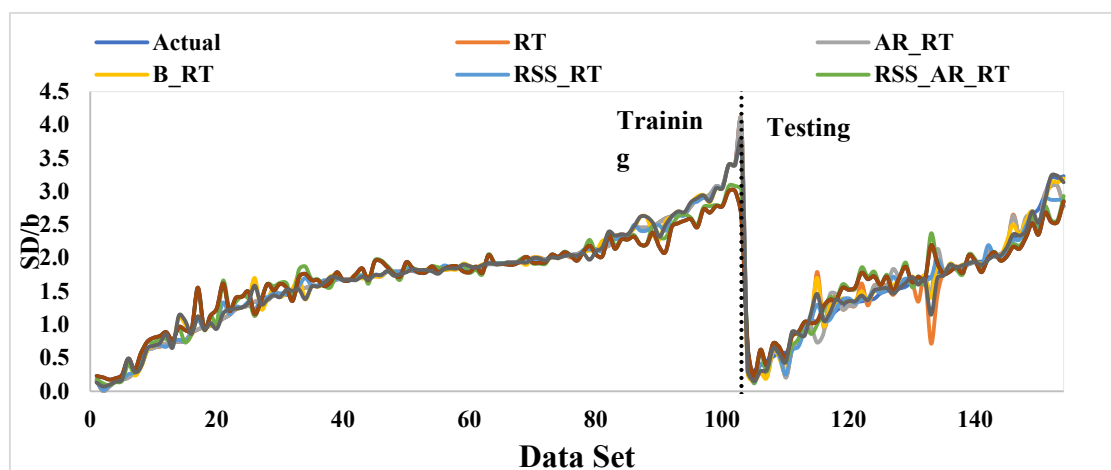


Figure 4.42: Variation plots of various machine learning models in the prediction of SD/b

- b. The distributions of the actual and predicted values of SD/b in the form of an open box plot for all models are plotted in Figure 4.43 (a & b) to illustrate the efficacy of the machine learning models. The box-and-whisker plots display the measures of central tendency, variability, skewness, and extreme values for the variables. These graphs visually represent the local discrepancies between predicted outputs and actual data based on four components: (1) Each box contains a central solid line, representing the median value, indicating the central tendency or location. (2) The box itself represents the variability around this central tendency, with the edges of the box representing the 25th and 75th percentiles. (3) Whiskers extend from the box to display the range of the data. (4) Values that fall outside the length of the whiskers are considered outliers and are represented by diamond symbol. These outliers are more than 1.5 times the interquartile range ($IQR = Q3 - Q1$) away from the top or bottom of the box. Upon examination of Figure 4.43, the descriptive statistics indicate that the minimum, maximum, 25th quartile ($Q1$), 75th quartile ($Q3$), and median ($Q2$) values for B_AR_RT and RSS_RT are quite similar to the actual values. When comparing the observed data with the results of the B_AR_RT and RSS_RT-based hybrid machine learning models, the widths of the top and bottom boxes are almost identical, as shown in Figures 4.43 (a) and (b). Also, the box plots suggest that the accuracy order of the different machine learning models is: B_AR_RT > RSS_RT > B_RT > AR_RT > RSS_B_RT > RSS_B_AR_RT > RT > RSS_AR_RT for the testing subsets.

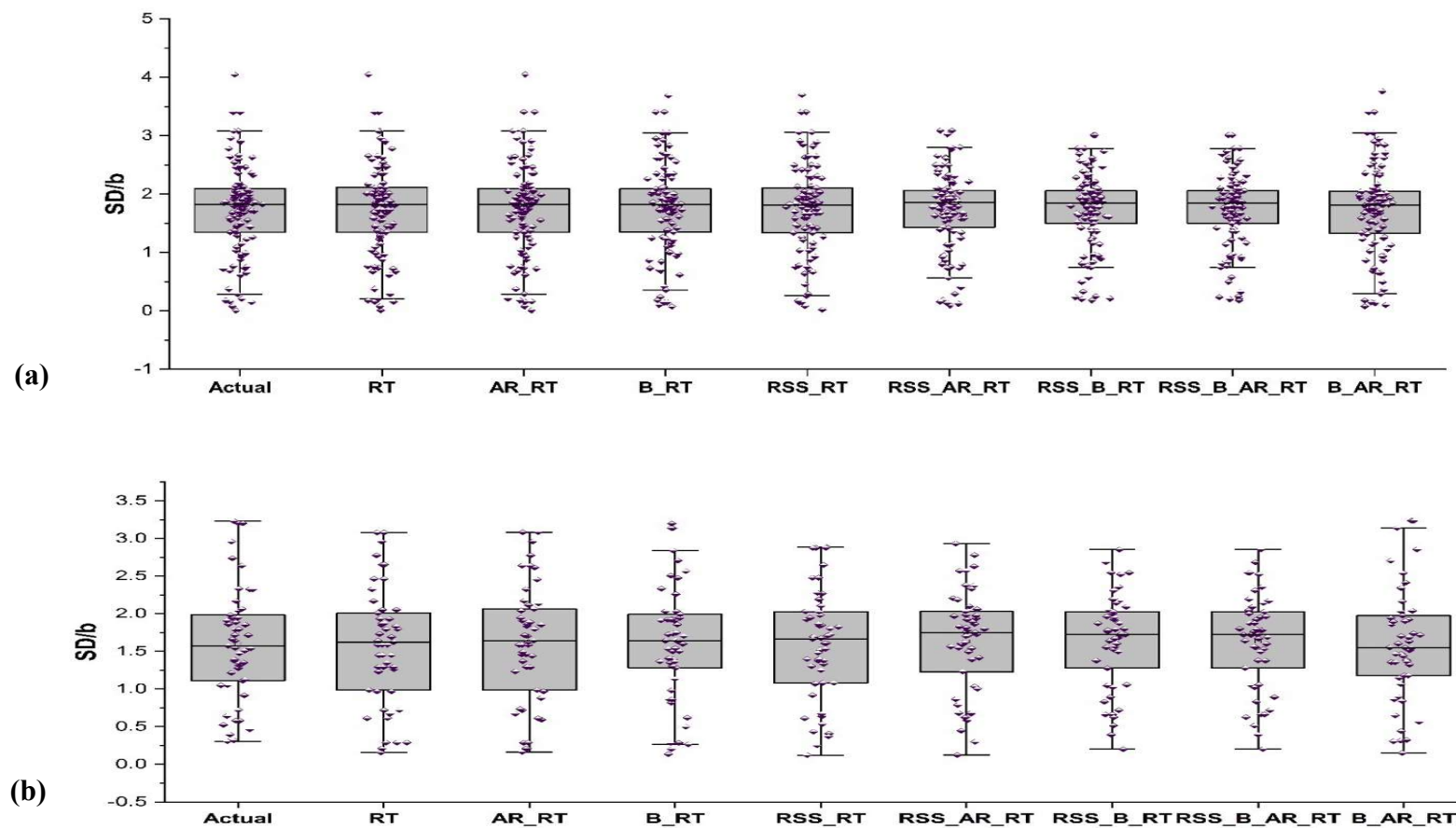


Figure 4.43: Box plot of different machine learning models predicting SD/b for (a). training, and (b). testing dataset

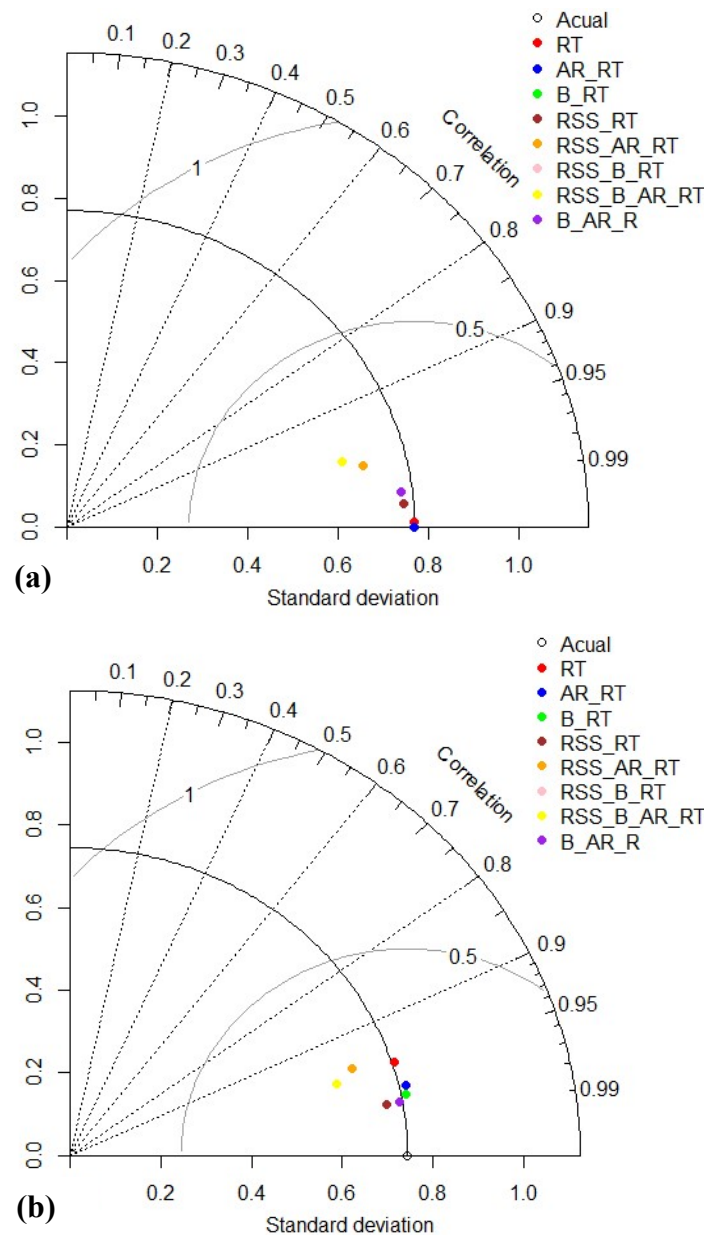


Figure 4.44: Taylor Diagram for the comparison of different machine learning models in the prediction of SD/b (a). training and (b). testing stage

- c. The Taylor diagrams for the machine learning model are displayed in Figure 4.44. The Taylor diagram is a widely used graphical tool for fairly comparing machine learning models. The Taylor diagram quantifies the agreement between observed and predicted values using three statistical measures: root-mean-square error (RMSE), standard deviation, and correlation coefficient (COC). Among the models depicted in this

mathematical diagram, the best-performing one is the one closest to the actual value point, represented by a hollow black circle. The Taylor diagram results showed that the B_RT_RT and RSS_RT-based models achieved superior accuracy compared to the other hybrid machine learning models for predicting scour depth around spur dikes.

4.5.2 Validation of machine learning models

The validation of the developed machine learning models, such as AR_RT, B_RT, RSS_RT, RSS_AR_RT, RSS_B_RT, B_AR_RT, RSS_B_AR_RT, has been performed using data obtained from experimental observations of I-shape spur dikes. The COC, RMSE, and R-Square were used to compare performance, and the results are shown in Table 4.7. The results suggested that the best-developed models (B_AR_RT) also performed superiorly in the validation phase. The B_AR_RT model achieved the highest COC (0.9491) and R-Square (0.9007) values, and the lowest RMSE (0.1801). The AR_RT model showed the worst result, with the lowest COC and R-Square values (0.7326 and 0.5368) and the highest RMSE values (0.5272). The performance sequence of machine learning models is as follows: B_AR_RT > RSS_B_AR_RT > RSS_B_RT > RSS_AR_RT > RSS_RT > B_RT > RT > AR_RT. The B_AR_RT not only performed well in the testing phase but also got the best results in the validation phase.

Table 4.7: Validation results of machine learning models using experimental results

Models	COC	R ²	RMSE
RT	0.7949	0.6318	0.4821
AR_RT	0.7326	0.5368	0.5272
B_RT	0.9221	0.8503	0.2642
RSS_RT	0.9373	0.8786	0.3934
RSS_AR_RT	0.9384	0.8805	0.3788
RSS_B_RT	0.9418	0.8869	0.3602
RSS_B_AR_RT	0.942	0.8874	0.3602
B_AR_RT	0.9491	0.9007	0.1801

4.5.3 Comparison of results with previous studies

Machine-learning models for predicting scour depth around spur dikes have also been developed by Tripathi & Pandey (2023), Pandey et al. (2021a), and Karami et al. (2012), against which the best model of this study (B_AR_RT) was compared using R-Square, RMSE, and COC (Table 4.8). B_AR_RT ranked first overall, ahead of the stacked (BRT) model of Pandey et al. (2021a) in second place and its MGGP model last, while the ANN_FFBP and ANN_RBF models of Karami et al. (2012) ranked sixth and seventh, respectively. The proposed hybrid ensemble model is thus more accurate and robust than both the competing hybrid and standalone models developed here and the models reported by Tripathi & Pandey (2023), Pandey et al. (2021a), and Karami et al. (2012).

Table 4.8: Comparison of results with previous studies

Studies	Models	Performance evaluation			Rank
		R-Square	RMSE	COC	
This study	B_AR_RT	0.9702	0.1305	0.9850	1
Tripathi & Pandey, (2023)	GEP	0.9400	--	0.9695	4
Pandey et al., (2021a)	MARS	0.9332	0.2116	0.9660	6
	MGGP	0.9116	0.2385	0.9548	9
	KELM	0.9384	0.1958	0.9687	5
	Stacked (BGT)	0.9490	0.1831	0.9742	3
	Stacked (BRT)	0.9577	0.1654	0.9786	2
Karami et al., (2012)	ANN_FFBP	0.93	0.014	0.9644	7
	ANN_RBF	0.92	0.015	0.9592	8

This study introduced seven hybrid machine learning models for predicting spur dikes and compared their performance with that of the standalone model (RT). The results

showed that all models except RSS_AR_RT, RSS_B_AR_RT, and RSS_B_RT satisfactorily predicted scour depth. However, based on several performance evaluation indicators and plots, B_AR_RT is the most efficient hybrid machine learning model for predicting scour depth, followed by RSS_RT, B_RT, AR_RT, RSS_B_RT, RSS_B_AR_RT, RT, and RSS_AR_RT in the validation phase. It is also found that hybridizing hybrid machine learning models improves prediction efficiency. The efficiency increases in the second-order hybridization when the RT hybridization is performed with AR, followed by B. However, it decreases in the case of AR, followed by RSS, and B, followed by RSS. Third-order hybridization also decreases the efficiency of the hybrid machine learning models. Also, the developed best hybrid model (B_AR_RT) outperforms the previous studies. Thus, the B_AR_RT hybrid machine learning model, the second-order hybridization model, best predicts scour depth in testing subsets and has supremacy among all hybrid machine learning models.

4.5.4 Sensitivity analysis

The sensitivity of the input variable to the output was analyzed using the best-performing model (B_AR_RT). Various training data sets were generated by eliminating one input variable at a time, and results were reported using the evaluation metrics COC and RMSE. Findings from Table 4.9 suggest that (b/d_{50}) plays a crucial role in predicting scour depth around spur dikes with respect to other input variables.

Table 4.9: Sensitivity analysis study utilizing the B_AR_RT model

Input Combinations	Parameter to be removed	Training		Testing	
		COC	RMSE	COC	RMSE
U/U _c , D/b, b/d ₅₀ , Fd ₅₀		0.9872	0.0899	0.9694	0.1305
D/b, b/d ₅₀ , Fd ₅₀	U/U _c	0.9845	0.1004	0.9686	0.1326
U/U _c , b/d ₅₀ , Fd ₅₀	D/b	0.9902	0.0824	0.9649	0.1472
U/U _c , D/b, Fd ₅₀	b/d ₅₀	0.9730	0.1343	0.8917	0.2465
U/U _c , D/b, b/d ₅₀	Fd ₅₀	0.9892	0.0856	0.9779	0.1132

4.6 Statistical prediction of scour depth around spur dikes

To predict scour depth around spur dikes, a regression technique was used to develop the equations. Several types of equations were initially selected, including linear, non-linear, polynomial, power, logarithmic, and exponential, but based on performance, three were finally selected. These equations are linear, non-linear, and second-order polynomials. These three equations were developed for I- and T-shape spur dikes.

4.6.1 I-shape spur dikes

Data from the literature and experimental results were used to develop regression-based equations to predict the SD around I-shape spur dikes. The dataset consists of 164 observations and includes four-dimensional input variables (U/U_c , D/b , b/d_{50} , and Fd_{50}) and one output variable, SD/b . The correlation between the input and output variables was calculated and plotted using a scatter matrix (Figure 4.45). The distribution of each input dimensional variable is shown in the diagonal histogram. FD_{50} and U/U_c are well distributed around their means, while b/d_{50} shows some skewness due to a few extreme values. Similarly, some important information was displayed by the pairwise scatter plots. The variables U/U_c and SD/b exhibited a positive relationship, indicating that higher flow conditions are associated with greater SD. The relationship between D/b and SD/b also shows a solid positive correlation, highlighting the influence of relation flow depth on SD. Similarly, Fd_{50} shows a positive correlation with SD/b , indicating that higher densimetric Froude numbers are associated with greater scour depth, whereas SD/b and b/d_{50} show a negative correlation.

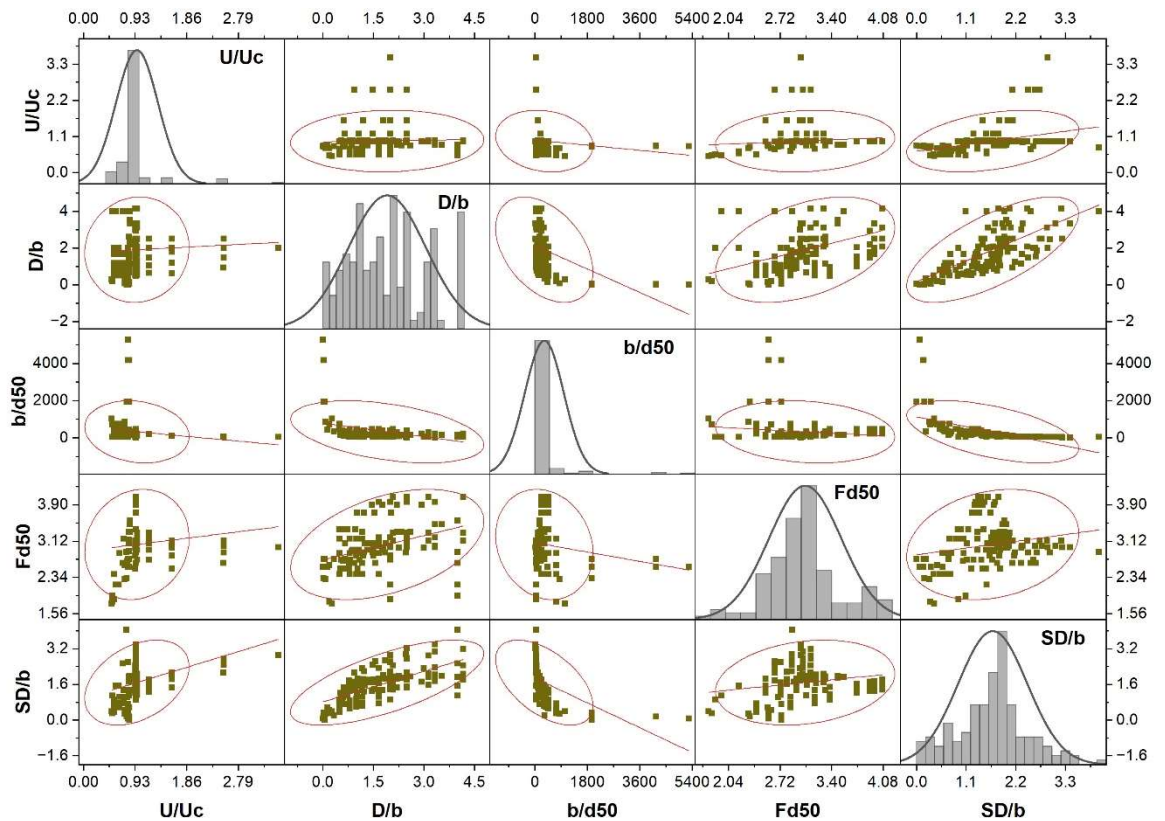


Figure 4.45: Scatter matrix plot showing correlation between the dimensional input and output variables for I-shape spur dikes

Scour depth around I-shape spur dikes was fitted with three statistical predictors - linear, non-linear, and second-order polynomial regression - using the least-squares method, which selects coefficients that minimise the sum of squared differences between predicted and observed values. The resulting equations are given below:

Linear regression equation

$$\frac{SD}{b} = 1.002 + 0.6441 * \frac{U}{U_c} + 0.4117 * \frac{D}{b} - 0.003 * \frac{b}{d_{50}} - 0.2050 * Fd_{50} \quad (4.1)$$

Non-linear regression equation

$$\frac{SD}{b} = 3.7442 * \left(\frac{U}{U_c}\right)^{0.2299} * \left(\frac{D}{b}\right)^{0.2457} * \left(\frac{b}{d_{50}}\right)^{-0.4129} * (Fd_{50})^{0.9622} \quad (4.2)$$

Second-order polynomial regression equation

$$\begin{aligned} \frac{SD}{b} = & -0.8692 + 3.1485 * \frac{U}{U_c} + 0.7121 * \frac{D}{b} + 0.0017 * \frac{b}{d_{50}} - 0.4006 * Fd_{50} - \\ & 0.2657 * \left(\frac{U}{U_c}\right)^2 - 0.1411 * \left(\frac{D}{b}\right)^2 + 0.2331 * Fd_{50}^2 - 0.0599 * \frac{U}{U_c} * \frac{D}{b} - 0.0051 * \\ & \frac{U}{U_c} * \frac{b}{d_{50}} - 0.6509 * \frac{U}{U_c} * Fd_{50} - 0.0033 * \frac{D}{b} * \frac{b}{d_{50}} + 0.1595 * \frac{D}{b} * Fd_{50} + 0.0008 * \\ & \frac{b}{d_{50}} * Fd_{50} \end{aligned} \quad (4.3)$$

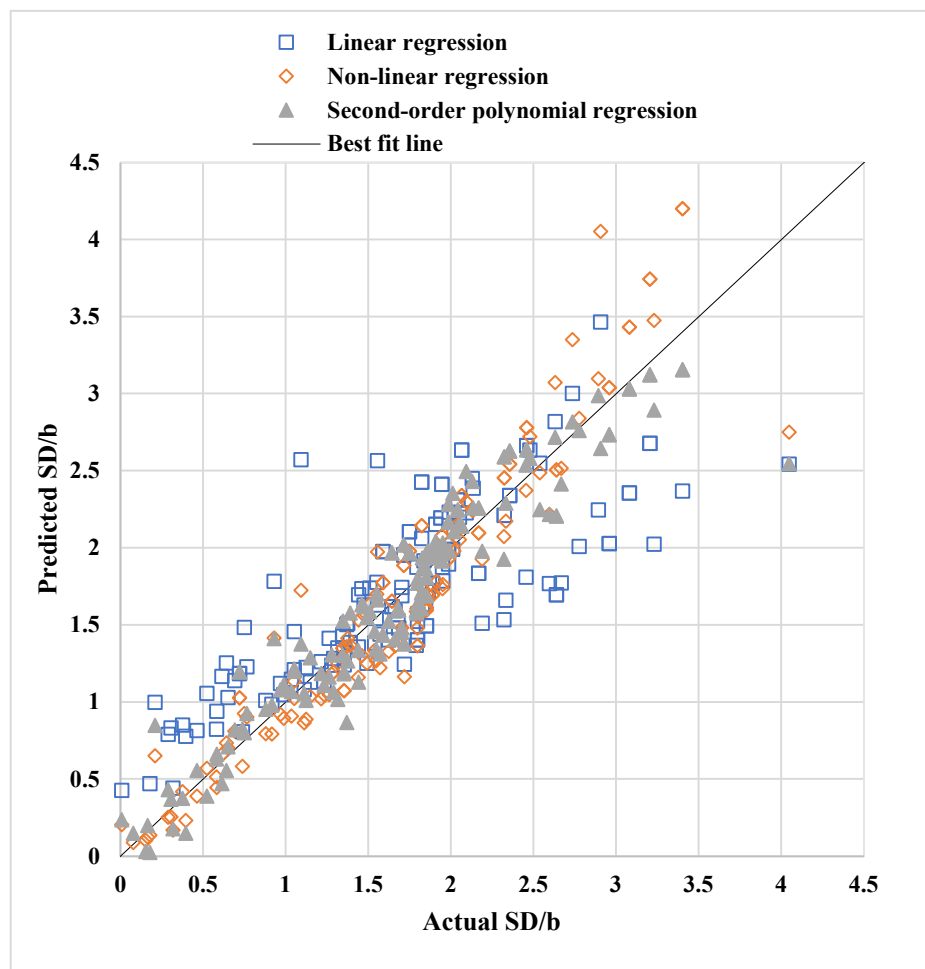


Figure 4.46: Scatter plots of regression equations for I-shape spur dikes

The performance of the developed (linear, non-linear, and second-order polynomial) equations for predicting SD/b around I-shape spur dikes is given in Table 4.10. The performance of equations was checked using COC, R-Square, RMSE, and NSE. The linear regression equations gave the worst results with a COC of 0.8102, an R-Square

of 0.6564, an RMSE of 0.4480, and an NSE of 0.6564. The non-linear equation yielded better results than the linear regression equation, with higher COC (0.9471), R-Square (0.8970), and NSE (0.8700), and a lower RMSE (0.2756). Whereas, the best performance was provided by the second-order polynomial equation, which exhibited the highest COC (0.9525), R-Square (0.9073), and NSE (0.9073), and the lowest RMSE (0.2327).

Table 4.10: Performance of regression equations using statistical parameters for I-shape spur dikes

Equations	COC	R-Square	RMSE	NSE
Linear regression	0.8102	0.6564	0.4480	0.6564
Non-linear regression	0.9471	0.8970	0.2756	0.8700
Second-order polynomial regression	0.9525	0.9073	0.2327	0.9073

Figure 4.46 presents a scatter plot of three regression-based equations for predicting SD/b. The ideal condition is represented by the best-fit line (black line), where the predicted SD/b values match the actual values. The blue squares display the values from linear regression, the orange star those from non-linear regression, and the grey triangle those from the second-order polynomial regression equation. The blue squares (points of the linear regression) are widely scattered in the plot, indicating the low accuracy of the equation. The cluster of orange circles (points of non-linear regression) is relatively present closer to the best-fit line, whereas most of the cluster points of the second-order regression (grey triangle) are concentrated near the best-fit line. These results show the superiority of the second-order polynomial regression equation for predicting SD/b around I-shape spur dikes. This equation can be used to predict SD/b around I-shape spur dikes when no experimentally observed values are available.

4.6.2 Curved T-shape spur dikes

The data collected during the experimentations were used to develop regression-based equations to predict the SD around curved T-shape spur dikes. The dataset consists of 55 observations and has three input variables: U/U_c , X , Y , & D , and one output variable, SD. The correlation between the input and output variables was calculated and plotted using a scatter matrix shown in Figure 4.47. The diagonal elements of the

plot displayed the histograms of variables, along with their corresponding probability density functions. The scatter matrix showed that U/U_c and D were negatively correlated with SD , suggesting that SD increases with increasing U/U_c and D . SD also showed negative correlations with X and Y . The trend suggested that SD increases as X and Y decrease.

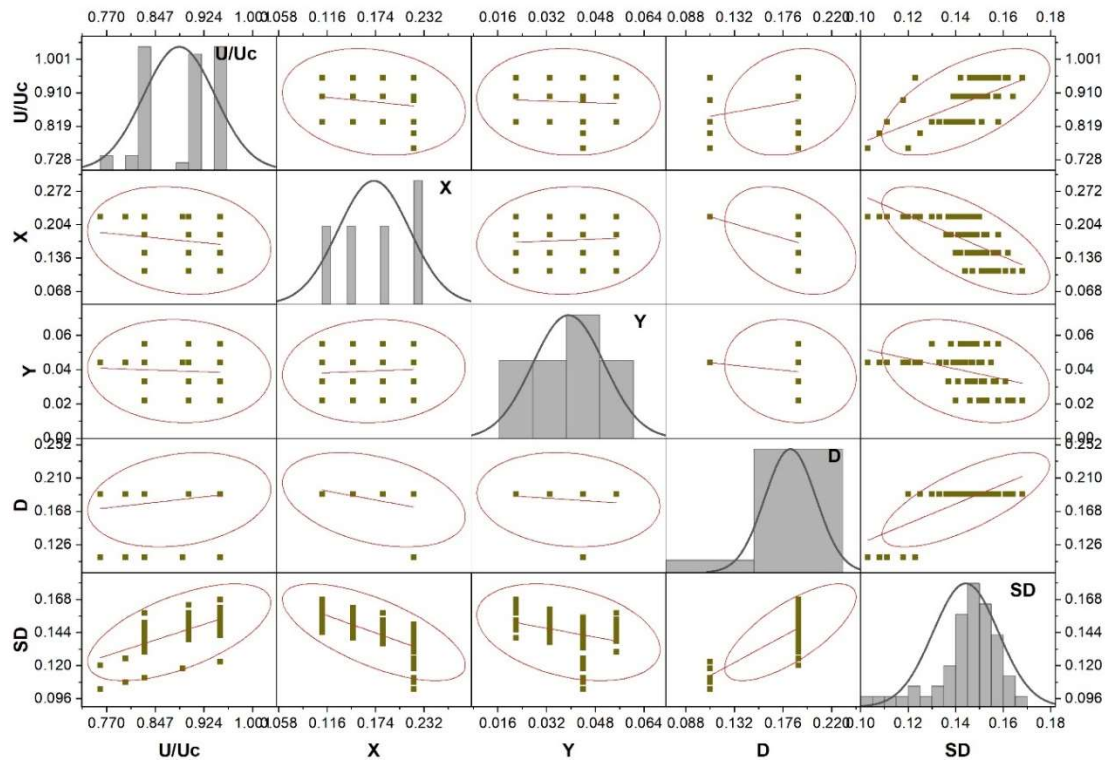


Figure 4.47: Scatter matrix plot showing correlation between the input and output variables for curved T-shape spur dikes

Three different statistical predictors for scour depth around curved T-shape spur dikes, namely linear, non-linear, and second-order polynomial regression equations, were developed using the least squares method. The least-squares method determines the coefficients by minimizing the sum of squared differences between the actual and predicted values. These equations are applicable only when the d_{50} value is 0.22 mm. The developed equations are as follows:

Linear regression equation

$$SD = 0.0375 + 0.1028 * \left(\frac{U}{U_c}\right) - 0.1352 * X - 0.2751 * Y + 0.2723D \quad (4.4)$$

Non-linear regression equation

$$SD = 0.1664 * \left(\frac{U}{U_c}\right)^{0.66} * (X)^{-0.144} * (Y)^{-0.071} * D^{0.326} \quad (4.5)$$

Second-order polynomial regression equation

$$SD = -0.0345 + 0.42956 * \frac{U}{U_c} - 0.3249 * X - 2.2672 * Y + 0.0986 * D - 0.23646 * \left(\frac{U}{U_c}\right)^2 + 0.1585 * \frac{U}{U_c} * X + 0.5670 * \frac{U}{U_c} * Y + 0.1948 * \frac{U}{U_c} * D + 0.0065 * X^2 + 1.5272 * X * Y - 0.04 * X * D + 17.1453 * Y^2 - 0.4264 * Y * D + 0.03 * D^2 \quad (4.6)$$

Table 4.11: Performance of regression equations using statistical parameters for curved T-shape spur dikes

Equations	COC	R-Square	RMSE (m)	NSE
Linear regression	0.9809	0.9621	0.0026	0.9621
Non-linear regression	0.9827	0.9657	0.0025	0.9656
Second-order polynomial regression	0.9958	0.9915	0.0012	0.9915

The performance of the developed (linear, non-linear, and second-order polynomial) equations for predicting SD around curved T-shape spur dikes is given in Table 4.11. The performance of equations was also evaluated using COC, R-Square, RMSE, and NSE. All of the regression equations yielded good results, as indicated in Table 4.11, although the performance of the second-order polynomial regression (COC = 0.9958, R-Square = 0.9915, RMSE = 0.0012 m, and NSE = 0.9915) is slightly superior to non-linear regression (COC = 0.9827, R-Square = 0.9657, RMSE = 0.0025 m, and NSE = 0.9656) and linear regression (COC = 0.9809, R-Square = 0.9621, RMSE = 0.0026 m, and NSE = 0.9621).

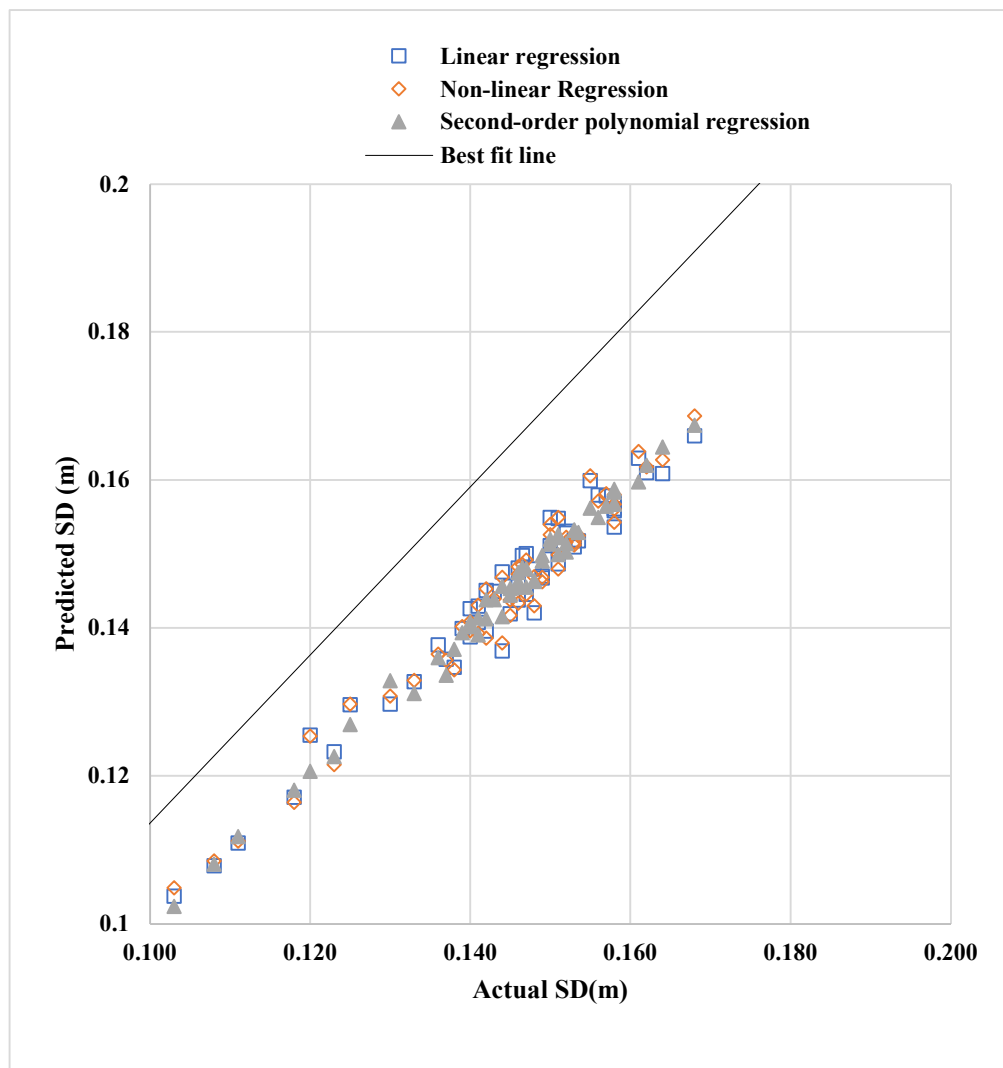


Figure 4.48: Scatter plots of regression equations for curved T-shape spur dikes

Figure 4.48 presents a scatter plot of three regression-based equations for predicting SD. The ideal condition is represented by the best-fit line (black line), where the predicted SD values match the actual values. The blue squares display the values from linear regression, the orange star those from non-linear regression, and the grey triangle those from the second-order polynomial regression equation. Figure 4.48 indicates that all the equations performed well in predicting SD around curved T-shape spur dikes, but the second-order regression equation performed slightly better than the others. Similarly, this equation can also be used to predict SD around curved T-shape spur dikes when no experimentally observed values are available.

4.7 Uncertainty in the results and its causes

Every experimental result is subject to some uncertainty, and the conclusions drawn from the measured SD are reliable only when this uncertainty is small compared with the differences being interpreted (Moffat, 1988). Three sources of uncertainty were identified in the results reported in this thesis, namely, the measurement of discharge, the measurement of SD, and the nature of the bed sediment. These are discussed below.

- a. The discharge for each experimental run was measured with the V-notch weir fixed at the end of the flume, using the coefficient of discharge ($C_d = 0.595$) obtained from its calibration. This reading was cross-checked against the approach velocity recorded by the ADV, and the two measurements were found to be in close agreement. Hence, the possibility of a significant error in the reported discharge is very low.
- b. The SD was measured with a vernier point gauge of 0.1 mm least count (Section 3.3.2). Six runs were repeated to check the repeatability of the measurements (Section 3.4.1), giving a maximum departure of the repeated values from their set mean of 1.27 to 1.59% - smaller than the spread in SD across the sixteen curved T-shape configurations (0.142 m to 0.168 m at $U/U_c = 0.95$) and smaller than the 2-3% margin by which the optimum configuration, R15, beat the next best across the three flow conditions. The identification of R15, and the trends of SD with X and Y, are therefore not materially affected by this uncertainty, though configurations differing by only about 0.001 m (e.g., R11, R16, and R12 at $U/U_c = 0.95$) cannot be reliably ranked from the measured values alone.
- c. The bed material used in all the experiments was a uniformly graded river sand, collected from the Yamuna River, with a median particle size (d_{50}) of 0.22 mm, so as to represent the bed material of a single prototype river reach (Section 3.2.2). The ratio d_{95}/d_{50} and the geometric standard deviation of the sand were 2.7 and 1.35, respectively, which are within the limits adopted for uniform sediment (Raudkivi, 1986). In a graded bed, the coarser grains left behind in the scour hole form an armour layer that reduces the equilibrium SD (Raudkivi & Ettema, 1983). Since the sand used here is uniform, armoring and grain sorting do not occur, and the

chance of an error arising from the sediment is minimal. At the same time, the results are valid for this sediment ($d_{50} = 0.22$ mm), and they should not be extended to non-uniform or cohesive beds without further experiments (Section 5.2).

The uncertainties discussed above relate to the laboratory measurements. The uncertainty that arises from the random nature of the flows in natural rivers, and the applicability of the results to real rivers, are discussed in Section 4.8.

4.8 Applicability of the results to real rivers

All the data used in this thesis, i.e., the observations of the present experiments and the datasets collected from the literature (Section 3.5), were obtained in laboratory flumes, and no field data were included. The transfer of laboratory results to prototype rivers is a long-standing problem in hydraulic modelling, because geometric, kinematic, and dynamic similarity cannot all be satisfied at the same time in a reduced-scale model, and scale effects are therefore unavoidable (Heller, 2011). In scour experiments, the scour depth scales linearly with the size of the structure only when the structure, the flow, and the bed particles are all scaled geometrically, a condition that is rarely met (Ettema et al., 1998). The SD measured in the flume, and the equations based on it, should therefore not be taken as the SD expected at a prototype spur dike without an appropriate check.

The extent of this limitation depends on the size of the river. For small streams and channels, in which the flow depth, channel width, and sediment size are not very different from those used in the flume, the results, particularly the relative performance of the I-, T-, and curved T-shape spur dikes and the optimum flange geometry, are expected to be transferred with relatively little distortion. Large alluvial rivers, on the other hand, generally carry sediment from upstream, develop bed features, and experience floods with discharges well beyond the clear-water range ($U/U_c = 0.76$ – 0.95) tested in this study. Under live-bed conditions, the sediment supplied from upstream influences the development of the scour hole, and the equilibrium SD can differ from that under clear-water conditions (Melville & Coleman, 2000). For such rivers, the SD equations of Section 4.6, which are also valid only for $d_{50} = 0.22$ mm,

should not be applied directly, and a site-specific study is recommended before the design of the spur dike is finalized.

Natural rivers are also subject to unsteady flow, and the extreme events that cause most scour occur randomly, their magnitude and frequency shaped by rainfall over the basin, land use and land cover, and basin characteristics generally. Because the present experiments used prescribed steady clear-water flows, they do not capture the effects of flood hydrographs, unsteady flow, or basin-scale factors, so the results describe the hydraulic and scour response of the spur dike only under the flow and sediment conditions tested. Applying them to the design of a spur dike on a particular river therefore requires combining them with site-specific hydrology - for example, the design flood and its return period, as in the procedure of Arneson et al. (2012) - and with a reliability-based assessment that accounts for the uncertainty in estimated scour depth when setting safety factors (Johnson, 1992).

Natural rivers shift course over time through bank erosion, bend migration, and bar movement, changing both the angle between the approach flow and a spur dike and the curvature of the channel near it over the structure's service life. The present study tested the curved T-shape spur dike only in a straight channel with the flow perpendicular to it (90°), leaving the effect of alignment angle uninvestigated, even though this angle is known to influence scour depth and the location of the scour hole (Kuhnle et al., 2002), and secondary currents are known to affect T-shape spur dikes in a bend (Akbari et al., 2021). The present results therefore cannot predict how an installed curved T-shape spur dike would perform under a shifting river course, and the study of curved T-shape spur dikes in meandering and compound channels - already identified as future scope in Section 5.3 - is recommended as a priority for further work.

Thus, the results of this thesis apply to the conditions under which they were obtained, namely, laboratory scale, clear-water flow, uniform sediment, and a single fixed orientation of the spur dike to the approach flow.

CHAPTER V

CONCLUSIONS, FUTURE SCOPE OF WORK, AND SOCIAL IMPACT

5.1 Conclusions

This thesis concerns SD around spur dikes, for which a new shape, called a curved T-shape spur dike, was designed by optimizing the flange curvature. So far, no attempt has been made to develop this shape of spur dike to reduce scour. A performance comparison of the curved T-shape spur dikes was done with the I- and T-shape spur dikes. Additionally, the optimum spacing between multiple spur dikes was determined for ideal stream bank protection. Furthermore, hybrid machine learning models were developed to predict scour depth around spur dikes. Additionally, statistical regression equations were formulated for predicting the SD around I-shape and curved T-shape spur dikes. So, based upon the above-mentioned objectives, the findings of the study were as follows:

1. A new curved T-shape spur dike was proposed, considering 16 geometric configurations obtained by varying the flange length (X) and crest depth (Y), and experimentally investigated under clear-water flow conditions to evaluate its effectiveness in reducing local scour. It was observed that scour depth increased significantly with increase in U/U_c and flow depth, confirming that hydraulic conditions strongly control scour formation. The optimum geometric configuration was identified as $X = b$ (0.22 m) and $Y = b/5$ (0.044 m) (R15), where b is the length of spur dikes, which produced the minimum equilibrium scour depth among all tested combinations.
2. The optimum spacing between two curved T-shape spur dikes was found to be $3b$, giving nearly a 50% reduction in scour depth at the downstream dike through the shielding effect of the upstream one.
3. Experimental analysis showed that I-shape spur dikes produced maximum scour, T-shape showed moderate scour, while curved T-shape spur dikes produced

minimum scour depth by avoiding direct flow impingement, smoothly redistributing flow toward the channel center, and reducing turbulence intensity. Further, CFD analysis confirmed that curved T-shape spur dikes produced smoother streamlines, smaller vortices, lower velocity concentration, and minimum bed shear stress compared to I- and T-shape spur dikes. Lower bed shear stress near the curved spur nose indicated reduced erosion potential and improved structural stability of the river training structure.

4. The hybrid machine-learning models clearly outperformed the standalone Random Tree model, confirming that hybridisation improves both the accuracy and robustness of scour prediction. B_AR_RT and RSS_RT emerged as the best performers, with the highest COC, R-Square, and NSE and the lowest RMSE at the testing stage; B_AR_RT in particular achieved the highest correlation coefficient (COC = 0.9491), the highest coefficient of determination (R-Square = 0.9007), and the lowest RMSE (0.1801) of all models developed, and also outperformed the models reported by Tripathi & Pandey (2023), Pandey et al. (2021a), and Karami et al. (2012), with R-Square = 0.9702 and RMSE = 0.1305 against their results. These results confirm that the proposed model gives more reliable scour-depth predictions than earlier models, and also show that first- and second-order hybridisation improved prediction accuracy, though further, higher-order hybridisation gave no additional benefit.
5. Sensitivity analysis using the best-performing hybrid model, B_AR_RT, showed the ratio of spur length to median sediment size (b/d_{50}) to have the greatest influence on scour depth.
6. Statistical regression equations were successfully developed for both I-shape and curved T-shape spur dikes. For I-shape spur dikes, the performance of the second-order polynomial regression model with COC = 0.9525, R-Square = 0.9073, RMSE = 0.4480 m, and NSE = 0.9073 was superior to linear and non-linear equations. For the curved T-shape spur dike, all equations performed well for predicting the scour depth around spur dikes.

5.2 Limitations of the study

The present study, though it offers valuable insight into the performance of curved T-shape spur dikes, is subject to the following limitations:

1. The experimental investigation was conducted at laboratory scale; therefore, the results may show some variations in the behaviour of curved T-shape spur dikes in natural rivers.
2. The experiments were carried out under clear-water conditions, with U/U_c ranging from 0.76 to 0.95; how the proposed spur dike performs under live-bed conditions could not be examined, since the available facilities could not introduce a controlled silt load.
3. The experiments were conducted using uniformly graded cohesionless sediment. The effects of non-uniform, cohesive, or stratified river-bed materials were not investigated.
4. The study considered a limited range of flow depths and flow intensities. Unsteady flow, extreme flood conditions, and rapidly varying discharge conditions were not investigated.
5. The experiments could be conducted in a straight channel due to the limitations of the experimental setup. The effects of channel curvature, meandering, and secondary currents on scour around the proposed spur dike were not examined.
6. The curved T-shaped spur dike was tested at a specific orientation relative (90°) to the approach flow. The influence of different alignment angles was not systematically investigated; instead, a series of spur dikes along the riverbank was investigated to determine the optimum spacing between the spur dikes as a possible space of alteration.

5.3 Future scope of work

Based on the outcomes of the present study, the following scope for future work was identified:

1. The experiments carried out in this study may be extended to live-bed flow conditions. Future studies may consider using non-uniform or cohesive sediments to simulate actual riverbed conditions.
2. The effect of permeable or partially permeable curved T-shape spur dikes may be investigated.
3. The performance of curved T-shape spur dikes may be studied in compound and meandering channels. Multiple spur dike arrangements and staggered configurations may also be examined in future research.
4. Further CFD simulations using other turbulence models - k-epsilon, the Reynolds Stress Model (RSM), Large Eddy Simulation (LES), and Detached Eddy Simulation (DES) - could be used to examine flow structure and turbulence characteristics in more detail.
5. High-frequency ADV measurements around the curved T-shape spur dike could be used to obtain the turbulent kinetic energy and Reynolds shear stresses, allowing the forces and energy dissipation responsible for scour to be linked directly to the measured scour depth.
6. The influence of the alignment angle of the curved T-shape spur dike, and of a change in the river course that alters the angle of the approach flow, may be investigated to assess the performance of installed spur dikes when the channel shifts its course.

5.4 Social impact

Alluvial riverbank erosion poses severe humanitarian risks by damaging infrastructure and displacing communities. This study introduces a novel curved T-shape spur dike to enhance the safety of riverside populations affected by climate-induced migration. By optimizing the spur dike geometry, flow is redirected to mitigate destructive vortices and improve bank stability. An optimal structural spacing arrangement is also proposed to significantly reduce scour depth and enhance riverbank stability. Using Computational Fluid Dynamics (CFD) for design refinement, the research provides solutions that extend the lifespan of infrastructure and shift governmental focus from emergency response toward proactive community development. These social impacts

map onto several United Nations Sustainable Development Goals (SDGs). Table 5.1 identifies the goals to which this research makes a substantive, evidence-based contribution.

Table 5.1: Mapping of relevant SDGs to the present study

S. No.	SDG (Number / Official Title / Logo)	Relevance to Thesis	Strength of Contribution
1	 SDG 6 Clean Water and Sanitation	The curved T-shape spur dike developed in this study reduces local scour and strengthens riverbank protection, directly supporting Target 6.6 (protect and restore water-related ecosystems). Sixteen geometric configurations were experimentally evaluated to identify the arrangement that minimises scour, and the optimum spacing between spur dikes in series was established to guide their use in sustainable river-channel management.	Strong
2	 SDG 9 Industry, Innovation and Infrastructure	The curved T-shape spur dike is an innovation in river-training infrastructure, developed by introducing curvature into the flange of the conventional T-shape design, thereby directly supporting Target 9.1 (resilient infrastructure). The CFD simulations and the seven hybrid machine-learning models built on Random Tree, additive regression, bagging, and random subspace techniques support Target 9.5 (upgraded technological capabilities); the best of these, B_AR_RT (R-Square = 0.9007), provides engineers with a validated alternative to extensive laboratory testing at the preliminary design stage.	Strong
3	 SDG 11 Sustainable Cities and Communities	Excessive local scour can undermine river-training structures and expose riverside communities, farmland, and infrastructure to erosion and flood damage. Since the curved T-shape spur dike yielded a lower scour depth than the	Moderate

S. No.	SDG (Number / Official Title / Logo)	Relevance to Thesis	Strength of Contribution
	SDG 11 Sustainable Cities and Communities	I- and T-shape spur dikes under all tested hydraulic conditions, it strengthens the resilience of the structures that protect such communities, supporting Target 11.5 (reducing deaths and economic losses from disasters, including water-related disasters).	

Table 5.1 shows that this study contributes strongly to SDG 6 and SDG 9, through the design and validation of the curved T-shape spur dike and the machine-learning models that support it, and moderately to SDG 11 through the resulting reduction in erosion risk to riverside communities.

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Annexure

LIST OF PUBLICATIONS

Journals

- Singh, B., & Minocha, V. K. (2025). Hybrid ensemble models for scour depth prediction around spur dikes. *Measurement*, 256, 118277. (SCIE, IF-5.6).
- Singh, B., & Minocha, V. K. (2025). An optimized boosting-based machine learning model for predicting maximum scour depth around spur dikes. *Marine Georesources & Geotechnology*, 1-21. (SCIE, IF-2.2).
- Singh, B., & Minocha, V. K. (2024). Approximation in scour depth around spur dikes using novel hybrid ensemble data-driven model. *Water Science & Technology*, 89(4), 962-975. (SCIE, IF-2.6).
- Minocha, V. K., & Singh, B. (2023). Discussion of “Prediction of maximum scour depth near spur dikes in uniform bed sediment using stacked generalization ensemble tree-based frameworks” by Manish Pandey, Mehdi Jamei, Masoud Karbasi, Iman Ahmadianfar, and Xuefeng Chu. *Journal of Irrigation and Drainage Engineering*, 149(1), 07022018. (SCIE, IF-2.1).
- Minocha, V. K., & Singh, B. Experimental Development and Geometric Optimization of a Novel Curved T-Shaped Spur Dike for Reducing Scour Depth under Clear-Water Conditions. *Journal of Irrigation and Drainage Engineering* (Under Review). (SCIE, IF-2.1).
- Singh, B., & Minocha, V. K. Scour Around River Spur Dikes: A Review of Head-Shape Classification, Governing Factors, and Predictive Modelling Approaches. *Water* (Under Review). (SCIE, IF-3.5)

Conferences Attended

- Singh, B., & Minocha, V. K. “Scour Prediction around Spur Dikes using Multi-Kernel Gaussian Process and Support Vector Regression Machine Models”,

held on 12-13 September 2025, organised by Department of Civil Engineering, Graphic Era (Deemed to be University), Dehradun.

- Singh, B., & Minocha, V. K. “Comparative Study of Machine Learning Techniques for Prediction of Scour Depth around Spur Dikes”, held on 19-23 May 2024, organised by Environmental & Water Resources Institute of the American Society of Civil Engineers, at Baird Center, 400 W. Wisconsin Ave., Wisconsin, Milwaukee, Wisconsin 53203. (**Scopus indexed**).
- Singh, B., & Minocha, V. K. “Clear Water Scour Depth Prediction using Gradient Boosting Machine and Deep Learning”, held on 10-11 August 2023, organised by the School of Civil Engineering, Lovely Professional University (LPU) in Phagwara, India. (**Scopus indexed**)
- Singh, B., & Minocha, V. K. “Estimation of Maximum Scour Depth Around Spur Dikes.” 27th International Conference on Hydraulics, Water Resources, Environmental and Coastal Engineering (HYDRO 2022 INTERNATIONAL), held on 22-24 December 2022, organised by the Department of Civil Engineering, Punjab Engineering College, Chandigarh.