

Study on Flow and Sediment Transport around Series of Spur Dikes with Different Head Shape

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Abstract

“Spur dikes” (“spur dykes”, “groynes”, or “groins”) are a kind of river training structures extending outward from the channel bank into the main stream. They are often constructed in series, not individual, in order to maximize their functions on the rivers. In the arrangement of a series of spur dikes, in addition to the local effects of an individual spur dike, the “fields” of spur dikes formed between two consecutive spur dikes have considerable consequences on the flow and sediment transport, not only inside the fields, but along the main stream. In general, the fields of spur dikes result in reduction of velocity field and accordingly deposition of (suspended) sediment between the spur dikes. Moreover, these regions of the streams are among the most habitable areas for the aquatic fauna and biota.

The current knowledge over the flow pattern and sediment transport around spur dikes is chiefly based on previous experimental works and numerical studies over the few past decades. Reviewing literature shows that despite the substantial amount of experimental researches and numerical works on spur dikes, there is still considerable interest and debate on how to optimize the spur dike shape, and spacing to increase their efficiency ((McCoy et al. 2008)). Moreover, the key elements of most previous studies on spur dikes were concentrated on erosion and sedimentation processes of the channel due to installation of spur dikes, and/or flood control. They were not concerned well with their effects on aquatic organisms or the biological aspects of installing spur dikes. Precisely speaking, whereas the biological communities of rivers have been well studied and the morphodynamic processes and hydrodynamics of stream channel in the presence of spur dikes have also received much attention over the past decades, in contrast, quality of linking these two aspects to address the eco-hydraulic effects of spur dikes is to a large extent unexplored.

To address the aforementioned issues, in current study, a detailed investigation about flow field and sediment transport of spur dike with different head shape (T-head) was

iii

accomplished under different geometrical conditions (opening ratio and spur dike's height). The outputs of this step were based on comparison between quality of performance T-head spur dikes and (conventional) straight spur dikes in terms of erosion and sedimentation processes near the bank and along the channel. Furthermore, apart from the performance of spur dikes on bank protection, current study examined the ecological implications of morphodynamic processes and hydrodynamics of channel in the presence of different type spur dikes. This study examined the different types of spur dikes as an eco-friendly approach that adapts conventional spur dikes built to protect the riverbank in the past into a measure to improve fish habitats in rivers. In addition, in current study, which the illustration of spatial heterogeneity of flow and bed changes over an area of channel is of main interest, a new approach to quantify the diversity of habitat in channel due to installation of different types of spur dikes was deployed. Despite the conventional methods for quantification of diversity, in current study the effect of “spatial complexity” will be considered and discussed.

In this research, both numerical analysis and laboratory experiments are conducted parallel to examine the performance of T-head and straight spur dikes under different hydraulics and geometric conditions. In experiment part, based on preliminary literature review and evaluation, an extensive study has been carried out to examine the bed deformation under the different opening ratios of spur dike fields as well as different submergence ratios. Utilizing a 3D numerical analysis, 3D flow analysis was also accomplished in order to shed lights on the flow pattern and the mechanism of sediment transport.

Experiments were done in two phases. In the first phase, several sets of experiments were carried out in fixed bed channel condition. The focus of this step was to examine the flow structure in two simple cases of series of T-head and straight spurs dikes.

In the second part of study, several series of experiments were done on the study of sediment transport in series of T-head spur dikes in emerged and submerged condition.

Results show that there is noticeable difference between performance of T-head spur dikes and straight type ones. It turned out that in T-head spur dikes, the magnitude of velocity vectors inside the spur dikes' fields are much smaller than the similar area in

straight spur dikes. While in all cases, one main recirculating zone is visible inside the spur dikes' fields, in T-head shape spur dikes, for opening ratio equal or less than 3, there is one counter-rotating cell near the second spur dike in series. The length and width of the recirculation zone (reattachment length) for the T-head spur dike is less than those amounts of straight spur dikes. The presence of the wing of the T-head spur dike has significant effects on the formation of horseshoe vortices around the spur dikes in the series. The existence of the wing can increase the stability of the body of the spur dike against the erosion because of the moving the high-stress (energetic) regions away from the body.

In all opening ratios the presence of the wing of the spur dikes, made a sort of uniform pattern alongside of the spur dikes' field and wing was able to prevent the extension of scour hole inside the spur dike's field. In terms of maximizing benefits to aquatic habitat's space availability, in all opening ratios, T-head spur dikes can give larger scoured area than straight spur dikes do, specifically for opening ratios of less than 3, that means they are potentially more beneficial in terms of space availability for fish habitat. For the same type of spur dike, opening ratio of 2 for T-head spur dikes has the best performance in proving largest pools in channel. For straight spur dikes, the greatest pools were observed in opening ratio of 5. In terms of effect of spur dike's type on flow suitability, T-head spur dikes showed the higher frequency for different range of Froude numbers ($Fr=0.0\sim0.15$; $0.15\sim0.30$; $0.30\sim0.45$; >0.6). Moreover, the wider distribution of water depth and velocity for T-head spur dikes obviously suggests the better performance of T-head spur dikes to improve the flow variation in these cases. The greater number of two fundamental habitat (pool and riffle) in case of T-head spur dikes also proves the better capability of them in enhancement of suitable physical habitats in streams after installation of the T-head spur dikes. It also turns out that T-head spur dikes could show better performance in increasing the frequency of pool-riffle units, specifically in the second half of channel, and as increasing the number of pool and riffle directly affects the chance of potential favorable physical habitat along the river, it is expected they can improve complexity and heterogeneity of habitat types required for biodiversity.

In terms of bed diversity, analysis of spatial diversity of bed levels in T-head spur dikes and straight spur dikes for different opening ratios turned out that the T-head spur dikes could lead to more diverse bed for all opening ratios. The greatest effect of head shape on diversity of bed levels was also observed in opening ratio of 3 in which it could induce 40% increase in diversity of bed in study area. For the same type of spur dike, opening ratio of 5 in both head shapes of spur dike was the best case in terms of providing spatially heterogeneous bed over the study area affected by presence of spur dikes.

Keyword: spur dike, T-head, straight type, I-head, bank erosion, habitat diversity, groynes, spur dyke, T-shape, embayment.

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Contents

1 INTRODUCTION.....	1
1.1 DEFINITION AND GENERAL CONCEPTS	1
1.2 TYPES OF SPUR DIKES	3
1.3 DESIGN PARAMETERS FOR SPUR DIKES.....	5
1.4 GENERAL FEATURES OF SPUR DIKES.....	9
1.5 PROBLEM DEFINITION	11
1.6 PURPOSE, AND OBJECTIVES OF THE STUDY	12
1.7 APPROACH OF THE STUDY.....	13
1.8 DISSERTATION OUTLINE	14
2 LITERATURE REVIEW	17
2.1 INTRODUCTION.....	17
2.2 RESEARCHES ON SINGLE STRAIGHT SPUR DIKES.....	18
2.3 RESEARCHES ON SINGLE SPUR DIKES WITH DIFFERENT HEAD SHAPES	20
2.4 PREVIOUS RESEARCHES ABOUT A SERIES OF STRAIGHT SPUR DIKES	23
2.5 PREVIOUS RESEARCHES ABOUT A SERIES OF SPUR DIKES WITH DIFFERENT HEAD SHAPES	30
2.6 WORKS ON THE IMPLICATIONS OF SPUR DIKES ON ECOLOGY	32
2.7 MOTIVATION OF CURRENT STUDY	36
2.8 ORIGINALITY AND NOVELTY OF CURRENT STUDY	37
3 FIXED BED CHANNEL CASE.....	38
3.1 INTRODUCTION.....	38
3.2 LABORATORY EXPERIMENTS	39

3.2.1	<i>Experimental Setup</i>	39
3.2.2	<i>Measurement Techniques</i>	41
3.2.3	<i>Experiment Conditions</i>	45
3.2.4	<i>Results</i>	45
3.2.5	<i>Analysis and Discussion</i>	49
3.2.5.1	Time Residence and Mass Exchange inside the Spur Dikes' Field	49
3.3	3D NUMERICAL MODELING OF FLOW STRUCTURE	54
3.3.1	<i>Introduction</i>	54
3.3.2	<i>Description of 3D RANS Model</i>	55
3.3.3	<i>Governing Equations</i>	56
3.3.4	<i>Boundary Conditions</i>	60
3.3.5	<i>Model Input</i>	60
3.3.6	<i>Verification</i>	62
3.3.7	<i>Analysis and Discussion</i>	63
3.3.7.1	Analysis of 3D Flow Structure	63
3.3.7.1.1	Effect on path of streamlines of the flow	63
3.3.7.1.2	Effects on Formation of Horseshoe Vortices	66
3.3.7.1.3	Impact on 3D structure of vortices around the series of spur dikes	67
3.3.7.1.4	Effects on Turbulence Characteristic	68
4	MOVABLE BED CHANNEL CASE	71
4.1	INTRODUCTION	71
4.2	LABORATORY EXPERIMENTS	72
4.2.1	<i>Experimental Setup</i>	72
4.2.2	<i>Experimental Conditions</i>	76
4.2.3	<i>Model Operation</i>	77
4.2.4	<i>Measurement Techniques</i>	79
4.2.5	<i>Experimental Results</i>	82

4.2.5.1	Effect of Opening Ratio on Equilibrium Bed Variations Due to Series of Spur Dikes	82
4.2.5.2	Effect of Submergence on Equilibrium Bed Variations Due to Series of Spur Dikes	87
4.3	3D NUMERICAL MODELING OF SEDIMENT TRANSPORT	89
4.3.1	<i>Introduction</i>	89
4.3.2	<i>Governing Equation for Sediment Transport Modeling</i>	90
4.3.2.1	Bed Load Calculation	90
4.3.2.2	Moving Direction of Sediment Particles	91
4.3.2.3	Effect of Sloping Bed	92
4.3.3	<i>Model Input</i>	93
4.3.4	<i>Verification</i>	94
4.4	ANALYSIS AND DISCUSSION	101
4.4.1.1	The Potential for Bank Erosion	101
4.4.1.2	The Potential for Physical Habitat Improvement	105
4.4.1.2.1	Effect of Spur Dike's Type on Habitat's Space Availability	107
4.4.1.2.2	Effect of Spur Dike's Type on Flow Suitability	112
4.4.1.2.3	Pool-Riffle Sequence for Different Types of Spur Dikes	122
4.4.1.2.4	Effect of Spur Dike's Type on Spatial Diversity of Habitat	125
4.4.1.3	Temporal Development of Channel Morphology Due to Series of Spur Dikes	134
	5 CONCLUSION AND RECOMMENDATIONS	137
5.1	CONCLUSIONS	137
5.1.1	<i>Fixed Bed Channel Case</i>	138
5.1.2	<i>Movable Bed Channel Case</i>	138
5.2	RECOMMENDATIONS	143
	BIBLIOGRAPHY	145
	LIST OF FIGURES	158
	LIST OF TABLES	164

1

Introduction

1.1 Definition and General Concepts

“Spur dikes” (“spur dykes”, “groynes”, or “groins”) are a kind of river training structures extending outward from the channel bank into the main stream. On the contrary, biologists are, however, used “rock jetty”, “barb”, and “deflector” to discuss such structures. All these terms are used interchangeably in the literature, although “spur dikes” are frequently considered to be higher and and/or longer than “rock jetties”, “deflectors”, and “barbs”. To be exact, “spur dikes” may be “spurs” extending outward from continuous “dikes” or revetments along the bank. “Spur dikes” are partially exposed at most water levels (Klingeman, Kehe et al. 1984).

Having installed spur dikes, the flow structure and sediment transport in the rivers get significantly affected and the general pattern of erosion and deposition will dramatically change.

They are often constructed in series, not individual, in order to maximize their functions on the rivers. In the arrangement of a series of spur dikes, in addition to the local

effects of an individual spur dike, the “fields” (or “embayment” as it occurs in some literature) of spur dikes formed between two consecutive spur dikes have considerable consequences on the flow and sediment transport, not only inside the fields, but along the main stream. In general, the fields of spur dikes result in reduction of velocity field and accordingly deposition of (suspended) sediment between the spur dikes. Moreover, these regions of the streams are among the most habitable areas for the aquatic fauna and biota.

On the other hand, spur dikes are an indirect method of “bank protection”, with the help of deflection of currents’ direction away from the bank or by the reduction of the flow velocity. This function of spur dikes, to provide better protection against erosion along the banks of the rivers, had been chosen traditionally as the main purpose of construction of spur dikes over the years. However, throughout the past decades, specifically after mid-20th century and due to the escalation of environmental and ecological concerns to offer a diverse habitat for the aquatic ecosystems, a new aspect of the function for spur dikes has being grown.

In Japan, after introducing “Implementation of nature-oriented river works” by the “River Bureau of the Ministry of Land, Infrastructure, Transport and Tourism” in 1990, “nature-oriented river works” have been conducted in Japan on a substantial scale to conserve or create natural riverine habitats and landscapes. In 2006, “Nature-oriented River Works Development Basic Guidelines”, issued by the same governmental office, defined that “nature-oriented river management” is to conserve or create natural riverine habitats and diverse riverine landscapes, while taking harmony with people’s lives, the region’s history and culture into consideration (Naito and Imai 2006). Thereby, the potential of spur dikes to provide the diverse environment in stream has being further put in the center of attentions in all over Japan.

In Europe, since 2000 and after launching “the EU water framework directive”, this new function of spur dikes has been legally adopted. In fact, the WFD demands that the current ecological state of surface waters cannot be allowed to deteriorate and must be kept on a good level (Anlanger 2008). In that regard, this recent function of spur dikes would be an important measure to improve the physical diversity of habitat for stream ecosystems.

1.2 Types of Spur Dikes

Different types of spur dikes can be distinguished according to their construction material, angle of orientation and plan view shape.

According to the material of structure:

Spur dikes can be constructed from a wide range of materials, such as bamboo or timber piles, tree trunks, rock, soil, gravel, sandbags, riprap, prefabricated concrete elements, steel and wire, etc. As a result and based on the material, if the spur dike allows the water to flow through slowly, it is “permeable” and if it completely blocks and then deflects the current, it is called “impermeable”. Thus permeable spur dikes can easily make deposition of sediment in the lee of the dike near the bank. The accumulation of sediment behind a spur dike or between consecutive spur dikes and the retardation of flow both make the main channel to carry a bigger amount of discharge and sediment transport capacity and leads to a greater depth of the main channel. An example of a compound (partly permeable and partly impermeable) spur dike in Arkansas in US has been shown in Figure 1-1.

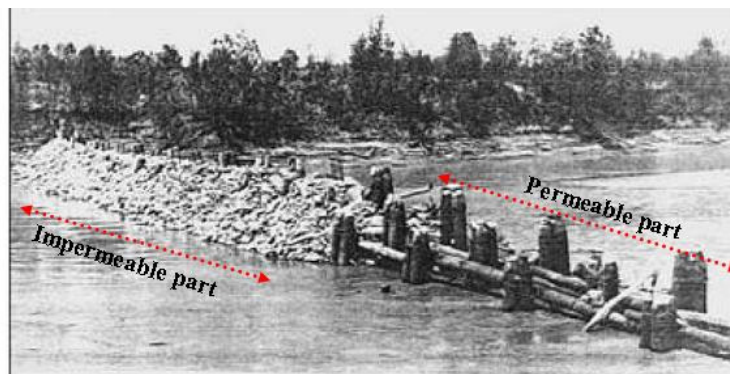


Figure 1-1. A compound (partly permeable and partly impermeable) spur dike in Arkansas in US (Yasi 2009)

According to submergence:

Upon the level of water in the stream, the spur dike might be observed as “submerged” or as “non-submerged”. Usually impermeable spur dikes are designed to be non-submerged

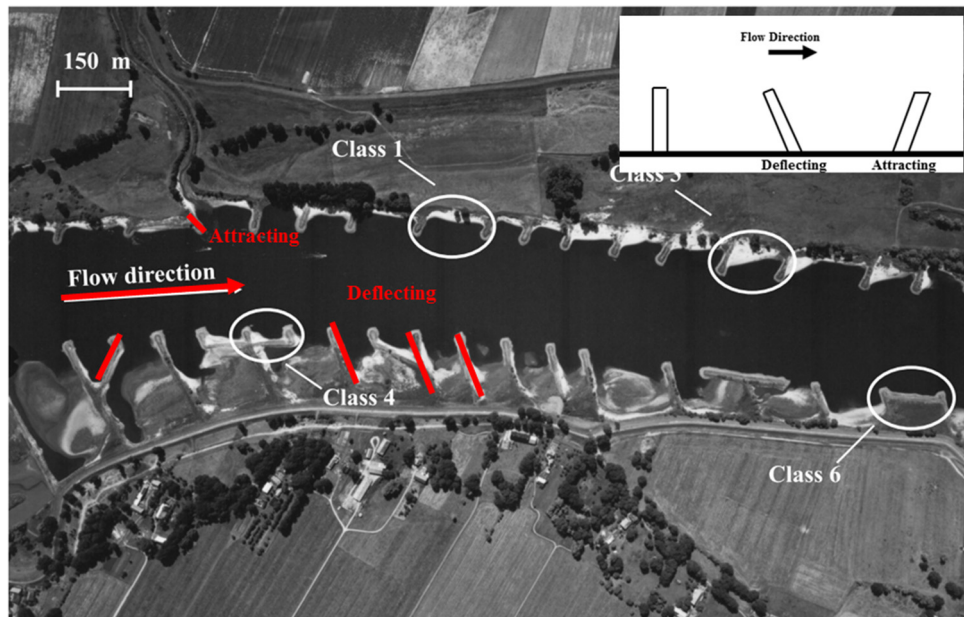


Figure 1-2. A series of spur dikes in River Elbe, Germany with different orientation
(Weitbrecht 2004)

since flow over the top of solid spur dikes may cause severe erosion along the banks. For submerged conditions, on the other hand, permeable spur dikes may be designed owing to the fact that they disturb the flow much less than solid spur dikes (Yossef and Klaassen 2002).

According to the angle of orientation:

Depend on angle of orientation, spur dikes might be “attracting”, “deflecting” or “repelling”. “Attracting” spur dikes are directed towards downstream and are seemed to “attract” the flow towards alongside near bank of river. In contrary, “deflecting” spur dikes are often used for changing the direction of flow without repelling it. “Repelling” spur dikes are directed towards upstream and are seemed to “repel” the flow toward the reverse bank of the river. A schematic view of different orientation for spur dike is illustrated in Figure 1-2.

According to their appearance in plan:

Spur dikes can be constructed with different plan view shapes, such as “straight” (as seen in a plan view), “L-head” in which outer tip is towards downstream flow (and conversely “J-head” in which outer tip is towards upstream flow), “T-head” in which outer tips are towards both upstream and downstream, “hockey shaped”, “inverted hockey shaped”, and etc (see Figure 1-3).

1.3 Design Parameters for Spur Dikes

Unlike the extensive application of spur dikes, there are no perfect hydraulic design criteria to follow. There are different important parameters affecting the design of spur dikes, among them are: river width, water depth, water velocity, channel sinuosity, bed material size, sediment transport rate, bank cohesiveness, length of spur dike, spaces between spur dikes (in a series), plan view shape of spur dike, longitudinal and transverse shape of spur dike, angle of orientation to the flow, crest elevation, and construction materials. Due to the different types of effective parameter in each engineering project, typically the design of spur dikes is being done based on experience and engineering judgment.

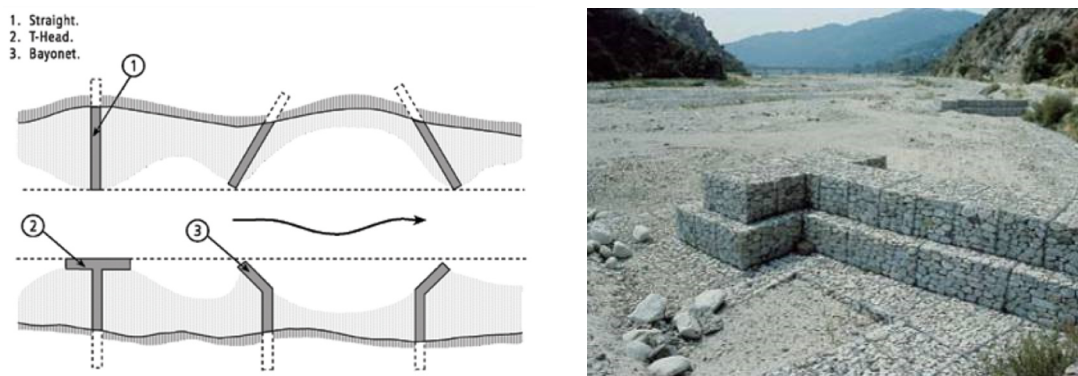


Figure 1-3. Left: Different kinds of spur dikes in plan view; Right: A T-head spur dike constructed in River Allaro, Italy (via maccaferri.com)

General Consideration

In general and regardless of the type of spur dike, it redirects the flow away from the downstream bank. This affects flow field and sediment transport in the channel. Permeable spur dikes cause sediment deposition which helps diversion of the flow. In impermeable spur dikes, by reduction of width of the river, the water slope and energy gradient become steeper and the velocity becomes greater, increasing the scour potential of the flow. The river may attempt to recover its original cross-sectional area by bank and bed erosion. But, in case the spur dike and the opposite bank are stable, the main flow may only be able to scour out the river bed in order to increase the cross-sectional area and reduce the velocity and scour potential. The size and stability of the bed material will determine the extent to which this can occur. The possible depth of main-channel scour caused by spur dikes and spur dike fields must be considered in spur dike design (Klingeman, Kehe et al. 1984).

Criteria for Plan View of Spur Dikes

L-head spur dikes have usually less scouring volume around the tip compared to the straight ones. On the other hand, they can provide more deposition of sediment inside the spur dikes' fields. They usually can provide better performance in wide stream, and in the outer bank of channel bends. They are also offered to be considered as the first and last of spur dikes in a series.

T-head spur dikes, generally are of use for direction of flow towards main channel of streams. The extension of scour hole around T-head spur dikes are relatively less than L-head or straight spur dikes. They are practically utilized to adjust the navigation routes in large rivers.

Criteria for Length of Spur Dikes (L_s)

From the view of bank protection against the erosion, the spur dikes with less than 30 meters are introduced as short and the ones with the effective length of greater than one-third of river width are long. In this context, the short spur dikes are not economical

compared to the direct countermeasures of erosion. Conversely, the long spur dikes put the opposed bank in risk. From the view of scouring, if L_{se}/h (in which “ L_{se} ” is effective length of the spur dike, and “ h ” is water depth) is less than 1, the spur dike is short, if L_{se}/h is more than 25, it is long and otherwise it is medium size. The short spur dikes cannot provide any deposition in downstream banks and just make some minor and local adjustments of the banks along the direction of main stream. They also can be utilized for the development of pools around the tip of the spur dike in order to restore the eco-environment of aquatic species and protect the bio-diversity.

Criteria for Spacing between Spur Dikes (S)

The flow (number and shape of recirculation gyres) and bed variation pattern inside a spur dike field is directly related to the geometrical dimensions of spur dike's field Sukhodolov, Uijttewaal et al. (2002), Sukhodolov, Engelhardt et al. (2004). In general, the minimum spaces between the spur dikes should be determined according to the stability of the geometry of the separation zone in different flow conditions. However, they are advised not to be less than the length of scour hole toward the main stream. It is also much related to river width, flow velocity, angle of orientation to the flow, bank curvature, and the purpose of construction of spur dike. For the purpose of well navigation channel, a spacing of 1.5 to 2 times the spur dike length is recommended, whereas for bank protection the spacing is advised to be increased to 2 to 6 times the spur dike length. If the spacing between spur dikes is too large, a meander loop may form between spur dikes. If the spur dikes are spaced too close together, construction costs will be higher and the system would work less efficiently, not making full use of each individual spur dikes (Yossef 2005).

Criteria for Longitudinal Shapes

In longitudinal direction, spur dikes can be designed as horizontal, sloped and stepped types. To protect the lateral banks, the sloped spur dikes are recommended in the literature. They have the advantages of reducing scour at the spur dike's tip, requiring less material for construction and faster deposition of sediment between them (Yasi 2009). The gabion type



Figure 1-4. An spur dike with trapezoidal shape cross section at Sarakhs river, Iran
(Yasi 2009)

of spur dikes are often built as stepped ones. For navigation channel control, level-crested spur dikes work best normal to the flow or angled downstream, whereas sloping-crested spur dikes work best normal or angled upstream (Richardson, Stevens et al. 1975). In sloped and stepped type spur dikes, the effective area for passing the flow in high water condition will be more.

Criteria for Cross-sectional Shapes of Spur Dikes

In cross sectional view, the spur dikes are plane type, box-stepped type and trapezoidal shape with lateral slope (Figure 1-4). To minimize the construction cost, facilitate the construction operations and to achieve to the natural stability of the body of spur dikes, they are often build as trapezoidal shape with lateral slope of 1:1.25 to 1:5.

Criteria for Angle of Orientation of Spur Dikes

The repelling spur dikes cause more deposition than a deflecting one. Therefore, the amount of deposition in spur dike fields is greater and can provide better countermeasure against bank erosion. The deflecting spur dikes however are often used in straight reach of streams to locally protect the banks against the erosion. The attracting spur dikes at angles greater than 45 degree acts as a weir and in submerged condition (high water level) forms a vertical jet just behind the spur dikes which results in formation of a vertical layer along the

longitudinal axis of the spur dike. This vertical layer tends to move to the downstream bank and leads to highly likelihood of collapse of bank in downstream as well body of spur dike itself. This kind of spur dike is usually recommended in the cases of meander bends given angle of orientation less than 10 degree (Yasi 2009).

1.4 General Features of Spur Dikes

Action of Spur Dikes

Having installed the spur dikes, they can act on the stream flow by “velocity reduction” and “flow diversion”.

Function of Spur Dikes

The main functions of spur dikes in river are as follows:

- Current direction control
- Scour protection
- Sediment deposition
- Backwater: Increase of water level just in front of spur dike by reducing the cross sectional mean velocity.

Purpose of Spur Dikes

- Bank Protection

The most common object of installation of spur dike in rivers is to prevent the erosion and collapsing of a bank especially during the floods. Bank protection by installation of spur dikes depends on main design parameters of spur dike such as hydraulic characteristics (the water level, velocity and etc), the length of spur dike, spacing between spur dikes and angle of orientation of spur dike. For instance, as the length of spur dike increases the level of bank protection extends. However, as the velocity of a main channel and the area around the head of spur dike change considerably at the same time, it might cause serious local scouring around the body of spur dike's structure. In addition, in case of installation of spur



Figure 1-5. Spur dikes for protecting banks in Zanjanoor river, Iran
(Image Courtesy of Google)

dikes in series recirculation gyres form between spur dikes. In this case it is very important to design the series of spur dikes with proper intervals to ensure the security of channel bank as the strong reverse flow may cause erosion of bank. **Figure 1-5** shows a series of T-head spur dike installed in Zanjanoor River in Iran to mainly protect the bank against erosion.

- Flood Control
- Improvement of Navigational Course
- Landscape Improvement and Ecosystem Restoration

Fish are likely to assemble in areas of a river where food, shelter, temperature range, oxygen content, and other factors are properly available in order to make a favorable habitat. A diverse stream, such as one with a sequence of riffles and pools, is usually more favorable to an abundance of fish than is a monotonous river, such as one limited to only runs or only wide plane water. Various structural measures can be utilized for improvement of fish habitat. Spur dikes positioned at proper positions along a channel bank are able to induce scour holes and pools or to deepen the local channel. They can also be used to reduce the water temperature, preserve existing pools, cause sediment deposition, and provide gravel beds suitable for fish spawning.



Figure 1-6. Spur dikes for landscape improvement and protecting banks in Tokachi river, Japan (Installation -left- and immediately after flood -right-) (Hong Koo 2007)

Spur dike fields in rivers show a high species diversity of benthos, periphyton, plankton and fish. This reflects the specific characteristic conditions of reduced flow, increased substrate stability, sediment accumulation, light and temperature conditions, high nutrient availability, etc (Wood, Hannah et al. 2007).

A case study in the River Severn, UK, reported concentrations of algal chlorophyll up to 40-times higher in retention zones than in the transit river flow (Wood, Hannah et al. 2007).

Figure 1-7 shows the spatial distribution of surface temperatures in Oder River, Germany in which the implication of a series of spur dike to provide a non-homogenous distribution of temperature along the banks (specifically inside the spur dike fields) are clearly distinct. Local temperature conditions are of importance for temperature dependent processes of species in the near bank area.

1.5 Problem Definition

Stream bank erosion in rivers and streams causes annual losses of valuable land along thousands of kilometers of rivers. This problem occurs in all parts of the globe. In many instances, only low-cost techniques, rather than costly riprap protection, can be afforded by local authorities. On the other hand, scouring in channels is an effective natural means for

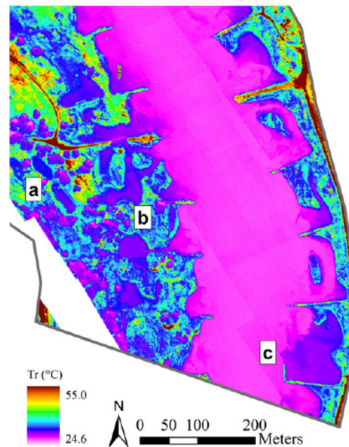


Figure 1-7. Spatial distribution of surface radiant temperatures using TIR imagery in Oder River, Germany (Tonolla, Wolter et al. 2012)

providing variable flow conditions and habitat for fish. Particularly in seasons of low stream flows, scoured zones provide resting and hiding opportunities for fish. Many simple scour-causing structures and gravel-trapping structures have been placed in streams by trial-and-error methods to enhance fishery habitat. Many more will be installed through ongoing programs by local and governmental authorities in the years ahead.

In both situations (bank erosion control and fish habitat Improvement), there is need for the hydraulic evaluation of a variety of low-cost and simple devices that can be used to control scour, protect stream banks, and provide fishery enhancement. In each situation, the hydraulics of local flow often is not well-understood nor adequately considered when such bank protection or stream enhancement is undertaken. Users of such channel structures need to know in advance the impact on bank protection and fishery enhancement and a better hydraulic basis is needed for activities that cumulatively cost many thousands of dollars each year.

1.6 Purpose, and Objectives of the Study

Purpose: The broad purpose of this research has been to determine the effects of spur dikes with different shapes of the head on local sediment scour and deposition and the

potential application of these structures for "simultaneous stream bank protection and fishery habitat enhancement". The structures investigated in this study, specifically will be included two types of spur dikes: "T-head" and "Straight".

Objectives: The specific objectives of the research have been:

1. To examine hydraulics and simulate flow field over a series (multiple) of T-head spur dikes using a combination of laboratory, and three-dimensional (3D) Computational Fluid Dynamics (CFD) approaches;
2. To investigate the sediment scour and deposition characteristics for a series (consequences) of T-head spur dikes and its distinction with a typical series of straight spur dikes;
3. To study the effect of submergence ratio on sediment transport and hydraulic characteristics of a series of T-head spur dikes in order to examine their performance in high water level and/or extreme weather condition.
4. To determine the desirable spacing of multiple spur dikes to provide stream bank protection and diverse environment for fish and aquatic biota and fauna;
5. To identify the opportunities for concurrent fishery habitat enhancement when spur dikes are used for bank protection;

In this research, all lateral boundaries are assumed as rigid. Among all effective parameters in the design of spur dikes, the length of spur dike and the length of the wing of T-head spur dikes is also considered as fixed. The main point of the study has been focused on the study of a sequence of spur dikes and therefore the study of local scour around the individual spur dike with same head-shape was out of the scope of the current study. The channel section was assumed as rectangular.

1.7 Approach of the Study

Both numerical analysis and laboratory experiments are conducted parallel to examine the performance of T-head and straight spur dikes under different hydraulics and geometric conditions. In experiment part, based on preliminary literature review and evaluation, an

extensive study has been carried out to examine the bed deformation under the different opening ratios of spur dike fields as well as different submergence ratios. Utilizing a 3D numerical analysis, 3D flow analysis was accomplished in order to shed light on the flow pattern and the mechanism of sediment transport. The final results and discussion were gained through integration and combination of the outcomes of these two respective phases.

1.8 Dissertation Outline

Figure 1-8 shows a schematic of workflow designed for current study. To obtain the workflow, first, the actions of spur dikes are considered and in the next level, the associated “functions” of spur dikes due to aforementioned “actions” are introduced. The relations of each “action” and “function” are also shown in this figure. The “purposes” of spur dikes and quality of affecting the “function” on them are also depicted. For instance, “bank protection” is affected by the pattern of “scouring” near the banks of channel, whereas “ecosystem restoration” is influenced by sediment deposition (i.e. bed substrate, pool-riffle consequences, etc.) as well as characteristics of backwaters (spur dikes’ fields) in river.

Among all conceivable purposes for installation of spur dikes, in current study more attention was particularly paid to two main purposes of “bank protection” and “ecosystem restoration” and the required parameters for study of each one were extracted (see Figure 1-8, fourth level in gray color). These parameters were chosen chiefly based on the effective “functions” of each “purpose”.

Finally, the general workflow of current research is also designed so that it covers the study of those required parameters effecting on “bank protection” and “ecosystem restoration”.

This dissertation is composed of 5 chapters, from introduction in Chapter 1 through conclusion in Chapter 5, as described below:

Chapter 1 briefly introduces the general concept of current research including the motivations for this study, purposes and objectives, and approaches to achieve the defined goal.

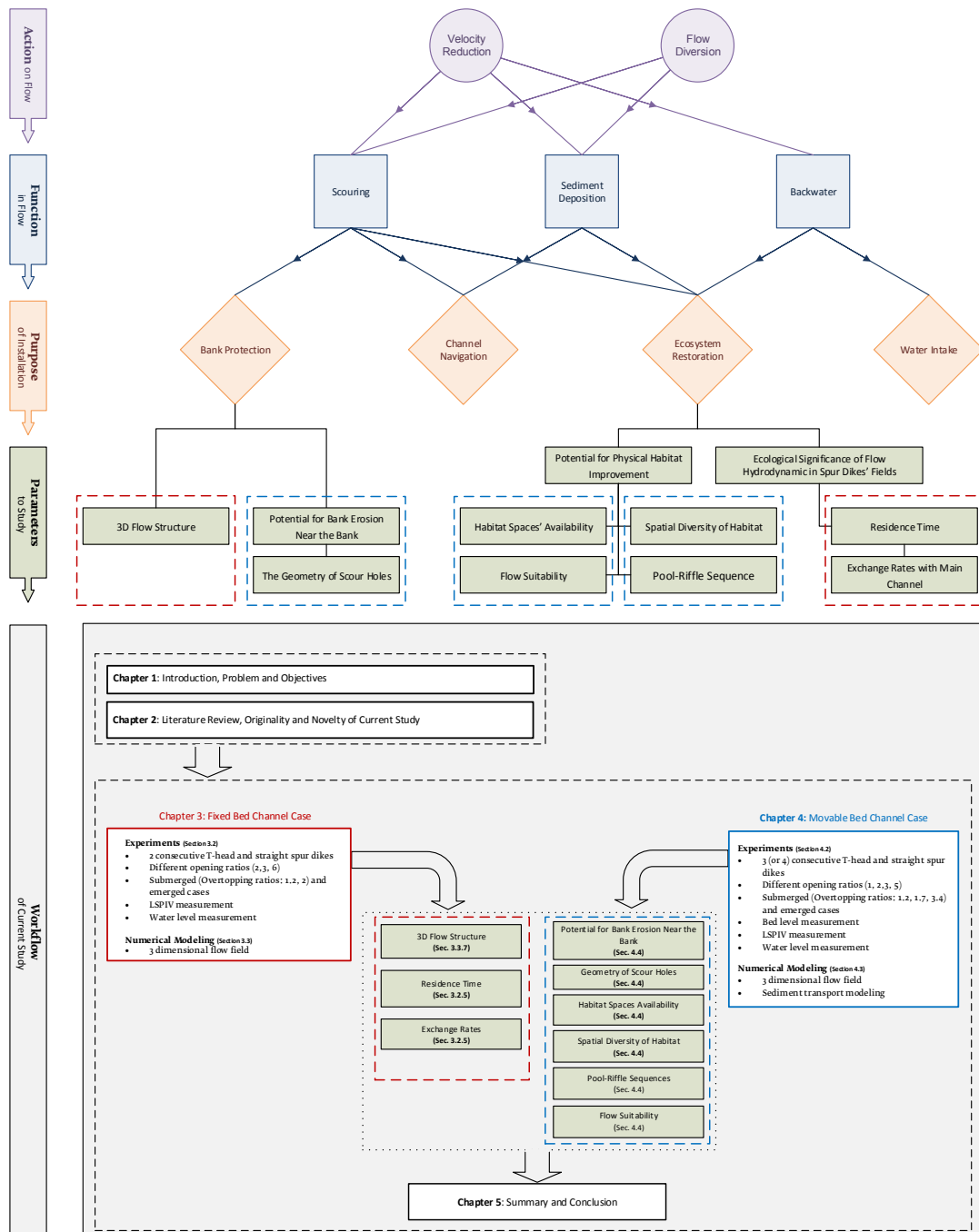


Figure 1-8. Schematic of workflow of current dissertation based on the required parameters for study on different aspects of installation of spur dikes

Chapter 2 presents some background information about previous researches over the topic of spur dikes. Comparing the accomplished researches in this field, it was tried to

Chapter 1. Introduction

highlight the gaps and points of lack of knowledge in this topic and accordingly the novelty and the originality of current research is introduced.

Chapter 3 represent the results of some series of experiments on the structure of flow in two simple cases of series of T-head and straight spur dikes in fixed bed channel. Moreover, using validation of 3D RANS numerical model, the 3D flow pattern around these types of spur dikes will be elaborated in detail.

Chapter 4 includes the results of several sets of experiments on the study of sediment transport in series of T-head spur dikes in emerged and submerged condition. In this chapter, the numerical models will be utilized as well to shed some light on the performance of this type of spur dikes and its distinctions with typical straight type of spur dikes.

Chapter 5 comprises the summary and conclusions of the whole research and several recommendations for following up this research topic in future.

The internal relations of each chapter of current study are depicted in Figure 1-8.

2

Literature Review

2.1 Introduction

The current knowledge about the flow pattern and sediment transport around spur dikes is chiefly based on previous experimental works, numerical studies, and field surveys over the few past decades.

Reviewing the past researches shows that researches about spur dikes include an extensive range of studies that can mostly be classified into three main categories:

1. Investigations of “physics of flow” and “hydrodynamics” around this kind of structures;
2. Studies pertaining to characteristics of “local scour hole”, and with fewer frequencies in literature, general pattern of bed deformation in channel and/or the effect of spur dikes on morphology of stream;
3. Study of “bank erosion” control through the installation of spur dikes in the streams.

In terms of the number and arrangement of spur dikes, the previous studies can also be classified to two main groups:

1. Researches about (an individual) “single spur dike”; in which the main objectives of the research had been focused on the “local scour” and the characteristics of the scour hole around the tip of the spur dike
2. Researches about a “series of spur dikes”; upon which the main points of the study had been about mechanism of sediment transport in spur dike fields and the hydrodynamic and morphological interaction of the spur dike fields and the main channel.

Accordingly, in this chapter; first a concise review of researches about the simplest case of spur dike (single straight spur dike) is discussed. After then, respectively, the works devoted to the single spur dikes with different head shapes; series of spur dike with typical (straight) head shape; and finally a few works about a series of spur dikes with different head shapes (L, T) are introduced. For numerical studies, those ones in which the purpose of study was not merely concentrated to the development of numerical methods and the code was chiefly utilized to investigate the governing phenomena around the spur dikes was cited as well.

At the end of the chapter, the originality and novelty of this research is also highlighted.

2.2 Researches on Single Straight Spur Dikes

The oldest research about spur dike can be referred to Ahmad (1953) in which he studied the scour caused by spur dike in channel filled with sand and found some valuable conclusions with regard to the effect of various parameters on the maximum scour depth. After that, over the years and by improving the experimental and computational techniques, a good number of researches have been dedicated to the study of flow field and sediment transport around single straight spur dikes and/or similar hydraulic structures such as abutments. A review of such studies can be found in (Barbhuiya and Dey 2004) and (Zhang and Nakagawa 2008). Table 2-1 also shows summarized review of the latest works on this type of spur dikes. In this table, for each research experimental condition, measuring techniques and the main focus of study has been introduced separately.

Table 2-1. The researches on “single straight” spur dike

Single Straight Spur Dike							
Year	Researcher(s)	Type of Spur Dike		Channel Type	Condition of Bed	Studied Parameters	Focus of study
1983	(Rajaratnam and Nwachukwu)	• Single (1) • impermeable • Impermeable	• Straight head • Submerged (1.2, 1.8, 3.7) • Emerged	Straight	Rigid flat bed	• Velocity (Prandtl-type pitot-static tube, Yaw probe) • Bed shear stress (Prandtl tube) • Water surface profile (Water level detector)	• Study of flow and bed shear stress around a spur dike
1992	(Muneta, Shimizu et al.)	• Single (1)	• Straight head	Straight	Rigid flat bed	• Velocity (LDA)	• Study of flow around spur dikes
2002	(Kuhnle, Alonso et al.)	• Single (1) • Impermeable • Oriented: 40°,90°,135°	• Straight • Submerged	Straight	Movable bed (D50=0.3 mm) (U*/U*c=0.67~0.95)	• Velocity (total head tube) • Stagnation pressure (pressure transducer) • Water surface (Acoustic distance measurement device)	• Volume and dimensions of scour hole
2008	(Azinfar and Kells)	• Single (1) • Impermeable • Oriented: 40,90,112.5,135°	• Straight head • Submerged • Emerged	Straight	Rigid flat bed	• Drag force	• Quantification of flow resistance (drag force) due to spur dike
2008 (a, b)	(Koken and Constantinescu 2008, Koken and Constantinescu 2008)	• Single (1) • Impermeable • (+) Numerical investigation (LES)	• Straight • Emerged	Straight	Rigid flat bed (+) Rigid scoured bed	• Velocity (LSPIV) • Dye visualization	• Study of coherent structures in a rigid flat bed and fixed scoured bed channel with a series of spur dikes
2008	(Kuhnle, Jia et al.)	• Single (1) • Impermeable • (+) Numerical simulation CCHE3D, k-ε model)	• Straight head • Submerged	Straight	Rigid scoured bed	• Velocity (ADV)	• Bed profile (SedBed Monitor)Flow structure around scour hole
2009	(Biron, Carré et al.)	• Single (1) Paired • Impermeable • Oriented:135°	• Straight head • Submerged • Emerged	Straight	Movable bed (D50=1.1 mm)	• Velocity (ADV,PIV)	• Study of bed shear stress based on measured velocity field
2009	(Duan)	• Single (1) • Impermeable	• Straight head • Emerged	Straight	Rigid flat bed	• Velocity (ADV)	• Study of flow and turbulent around a spur dike
2009	(Koken and Constantinescu)	• Single (1) • Impermeable • Numerical investigation (DES)	• Straight head • Emerged	Straight	Rigid flat bed	-	• Study of coherent structures in a rigid flat bed
2010	(Baba, Camenen et al.)	• Single (1) • Impermeable Permeable:	• Straight head • Emerged	Straight Compound Channel	Rigid flat bed	• Velocity (EVM, LSPIV)	• Study of flow around spur dike in “compound” channel
2011	(Mizutani, Nakagawa et al.)	• Single (1) • Impermeable	• Straight head • Submerged / Emerged	Straight	Movable bed (Mixed and non-uniform sediment)	• Velocity (ECM) • Bed level (LBP)	• Study of flow around scour hole and dimensions of scour hole

Biron, Carré et al. (2009) examine hydraulics around complex flow deflectors using a combination of laboratory, field and Computational Fluid Dynamics (CFD) approaches. The differences between low flow conditions, where deflectors were emergent and high flow conditions where structures were submerged, were examined in terms of their impact on bed shear stress and flow velocity.

Baba, Camenen et al. (2010) examined the flow field in the case of a compound channel with a single spur dike on the floodplain.

Mizutani, Nakagawa et al. (2011) carried out experimental study on the impact of both spur dike height and grain size distribution on the bed topography and bed surface composition around an impermeable spur dike. They found that the maximum scour depth decreased with the increase of sediment particles' standard deviation.

Since in this type of works the local scour and the hydrodynamic analysis of flow was of main interest, the ecological effect of spur dike was not paid much attention.

2.3 Researches on Single Spur Dikes with Different Head Shapes

To highlight the studies on spur dikes with head shapes other than straight type, a summary of the researches on a single spur dikes with different head shapes under different conditions has been separately shown in Table 2-2.

The number of research in this case is very few. Similar to studies about single straight spur dike, the main focus of the studies in this kind of spur dikes had been mainly concentrated on the local scour and features of scour hole (its dimensions, extensions and so on) around the T-head spur dike.

Hashemi Najafi, Ayyoubzadeh et al. (2008) compared the maximum depth of scour around straight and L-head spur dike. The results showed that the maximum depth of scour around L-head spur dike with upstream wing is less than straight spur dike. They also examined the effect of angle of wing on scouring. They showed that optimal angle (minimum scour depth) of wing is $\alpha=110$ degree in downstream direction and $\alpha=60$ degree in upstream direction.

Table 2-2. The previous researches about “single” T-head and L-head spur dike

Single T-head or L-head Spur Dike							
Year	Researcher(s)	Type of Spur Dike		Channel Type	Condition of Bed	Studied Parameters	Focus of study
2008	(Hashemi Najafi, Ayyoubzadeh et al.)	- Single (1) - Impermeable	- L-head - Emerged	Straight	Movable bed (D ₅₀ =1.5mm)	Bed level (Digital point gauge)	Study of “scour hole” around a L-head spur dike
2009	(Ghodsian and Vaghefi)	- Single (1) - Impermeable	- T-head - Emerged	90° bend channel	Movable bed (D ₅₀ =1.28 mm)	- Bed level (Digital point gauge) - Velocity (ADV)	Study of local scour around T-head spur dike in 90° bend channel
2009	(Kadota, Kojima et al.)	- Single (1) - Impermeable	“T”, “L” head - Emerged	Straight	Movable bed (D ₅₀ =0.3 mm)	Bed level (LBP)	Dimensions of scour hole and location of maximum deposition
2009	(Kerman-Nejad, Fathi-Moghadam et al.)	- Single (1) - Permeable (31%, 40%, 45%, 49%)	- L-head - Emerged	Straight	Movable bed (D ₅₀ =1.5mm)	Bed level (Digital point gauge)	Study of “scour hole” around a permeable L-head spur dike
2010 and 2011	(Kadota and Suzuki 2010, Kadota, Suzuki et al. 2010, Kadota and Suzuki 2011)	- Single (1) - Impermeable	“T”, “L” head - Submerged - Emerged	Straight	Rigid flat bed	Velocity (PTV)	Study of large-scale vortex development and instantaneous coherent flow around spur dike
2010	(Suzuki, Kadota et al.)	- Single (1) - Impermeable	“T”, “L” head - Submerged - Emerged	Straight	Movable bed (d _m =0.03cm)	Bed level (LBP)	Study of local scour around T-head and L-head spur dike with different length of wing
2010	(Masjedi, Dehkordi et al.)	- Impermeable - Impermeable	- T-head - Emerged	180° bend channel	Movable bed (D ₅₀ =2 mm)	Bed level (Point gauge)	Study of local scour around T-head spur dike in 180° bend channel
2010	(Safarzadeh, Neyshabouri et al.)	- Single (1) - Impermeable	- Straight - T-head - Emerged	Straight	Rigid flat bed	- Velocity (ADV) - Shear stress (Yaw type Preston tube)	Study bed shear stress distribution around single straight and T-shape spur dikes
2012	(Mokhtari, Dehghani et al.)	- Single (1) - Impermeable	- T-head - L-head - Emerged	Straight	Movable bed (D ₅₀ =1.5 mm)	Bed level (LBP, Point gauge)	Study of local scour around T-head and L-head spur dike with different length of wing

Kadota, Kojima et al. (2009) studied the characteristics of bed morphology due to installation of T and L-type spur dike experimentally. They showed that scour depth becomes large in case of L-type (with its wing towards downstream) compared to the straight spur dike. However, in case of L-type spur dike (with its wing towards upstream) the local scour becomes smaller. Moreover, in these cases the sand wave length and height becomes larger and sand wave develops towards the opposite bank of the channel.

Ghodsian and Vaghefi (2009) studied characteristics of scour hole and flow field in a scour hole around a T-shape spur dike in a 90 degree channel bend. They found that by increasing Froude number the maximum scour depth and the volume of scour hole increases. Furthermore, the dimensions of the scour hole increase by increasing the length of the spur dike. The amount of scour at the upstream of spur dike was also much more as compare to that at the downstream of spur dike.

Masjedi, Bajestan et al. (2010) studied the temporal evolution of local scour at a T-head spur dike in a 180 degree bend. Tests were conducted using one (single) spur dike in the position of 60 degree under four different flow conditions (u^*/u^*_c). The time development of the scour hole around the model spur dike was compared with similar studies on straight head spur dikes. The results indicated that as u^*/u^*_c increases, the scour depth increases.

Kadota and Suzuki (2010) investigated the effects of spur dike head shapes on the instantaneous-coherent flow and mean flow structures around I-type (straight), T and L-type spur dikes. Experiments were conducted with those three types of spur dikes by means of flow visualization technique and Particle Tracking Velocimetry (PTV). The results showed that the distribution of large shear layer, coherent vortices changes dramatically and noticeably with the type of spur dike (head shape).

Safarzadeh, Neyshabouri et al. (2010) conducted experimental measurements to investigate the head shape effects on bed shear stress distribution around single straight and T-head spur dikes. He suggested that the extension of the high shear stress zone is smaller in T-head spur dike and its intensity decays much faster towards downstream. In the straight type, the region of shear stress amplification was adjacent to the upstream part of the separated shear layer, whereas in T-head case this region shifts toward the channel

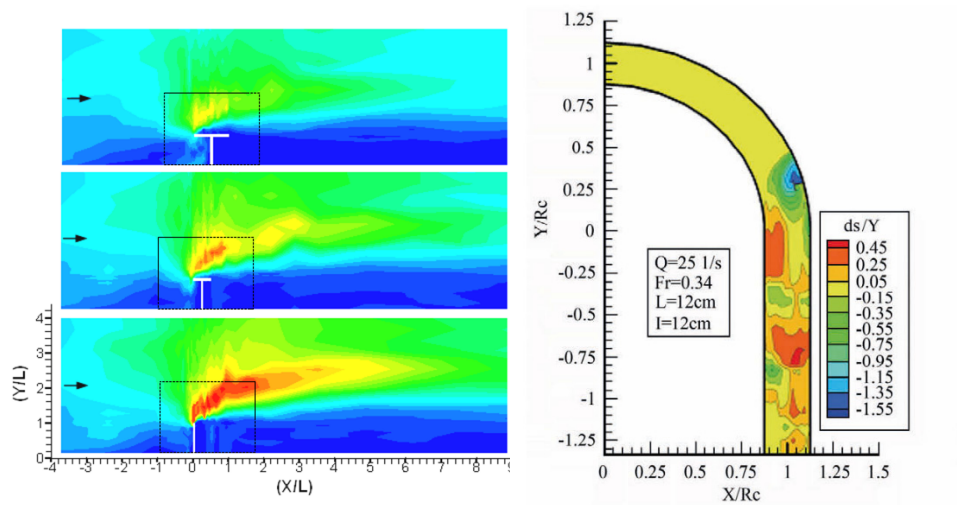


Figure 2-1. (right) Shear stress amplification contours for a single T-head spur dikes with different wing's length(Safarzadeh, Neyshabouri et al. 2010); (left) Bed changes due to presence of T-head spur dike in 90-degree channel bend(Ghodsian and Vaghefi 2009)

centerline. On the other hand, the maximum amplification of the bed shear stress (ratio of local bed shear stress to approaching flow shear stress) in T-head spur dike was about 35% smaller than for the straight one.

2.4 Previous Researches about a Series of Straight Spur Dikes

When it comes to the series of spur dikes, which is the focus of current study, the key purpose of research is being shifted from the problem of “local scouring” and characteristics of scour hole to the dynamics of flow and sediment transport in “spur dikes’ fields”. Similar to the single straight spur dike, thanks to the enhancing of the experimental instruments and computational capacities over the past decades, a well-documented of knowledge on such a case is available. Table 2-3 shows a review of most notable researches about a series of straight spur dikes in the chronological order of their publication. Having reviewed this table, it is clear that study of coherent structure and flow pattern inside the spur dike fields, exchange process between the spur dike fields and main channel, pattern of sediment and particulate deposition inside the spur dike field are amongst the most important outcomes

of these researches. However, it is noteworthy that even in this research cases, a three dimensional characterization of the exchange process and in particular its non-uniformity over the depth is still lacking (McCoy, Constantinescu et al. 2006). In addition, since in the most carried out researches of this topic (specifically in the cases of movable bed), the main purpose of the study had been around the function of bank protection and improvement of channel navigability due to installation of series of spur dikes, there is still lack of enough knowledge about the quality of performance of a series of spur dikes in improving landscape and biodiversity in streams.

Muto, Baba et al. (2002) applied large Scale particle image velocimetry (LSPIV) to examine the instantaneous and mean surface flow in a spur dike field located at the Yodo river in Japan. In addition to the field study, a laboratory study with down-scaled spur dike field geometry was carried out as well. The effects of the opening ratio and water depth on the velocity distributions were analyzed and turbulence characteristics at the spur dike field interface were elucidated. The PIV data collected in the field study showed the flow was highly unsteady inside the recirculation zone. The laboratory experiments did not exhibit these same unsteady characteristics. The authors concluded that difference between field and experimental studies are caused by the complex bathymetry of the natural river and by insufficiencies in the scaling, particularly due to the lower Reynolds numbers.

Sukhodolov, Uijttewaal et al. (2002) conducted flow velocity measurements in spur dike fields at the river Elbe and confirmed laboratory results from (Uijttewaal 1999) in which the opening ratio was identified to determine the number and location of gyres inside the spur dike field. For an opening ratio $0.5 < L_s/S_s < 2.0$, a single primary gyre develops. If the opening ratio is less than 0.5, a secondary, smaller gyre starts to develop. For opening ratios > 2.0 , two gyre create.

Appraisal of Table 2-3 also reveals that only a few studies were investigating “the effect of different submergence ratio”. One reason for this might be that submerged conditions were classically considered as insignificant, since the spur dikes were designed for emerged conditions in or below mean water levels. Another reason might be the complexity and three-dimensionality of the flow patterns around submerged spur dikes, which requires

Table 2-3. The previous researches about “series of” “straight” spur dike

Series of Straight Spur Dikes							
Year	Researcher (s)	Type of Spur Dike		Channel Type	Condition of Bed	Studied Parameters	Focus of study
1999	(Uijtewaal)	- Side cavity (5) - Impermeable - Opening ratios (1,5,3, 6)	- Straight - Emerged	Straight	Rigid flat bed	Velocity (PTV)	Study of flow pattern in spur dikes with different opening ratio
1999	(Wallast and Uijtewaal)	- Side cavity (10) - Impermeable	- Straight - Emerged	Straight	Rigid flat bed	Dye concentration measurement	Study of exchange process
2001	(Uijtewaal and Lehmann)	- Side cavity (5) - Impermeable - Opening ratios (1,5,3)	- Straight - Emerged	Straight	Rigid flat bed	- Dye concentration measurement - Velocity(PTV)	Study of exchange process between spur dike fields and main channel
2002	(Sukhodolov, Uijtewaal et al.)	- Side cavity (5) (+) Series (2) - Impermeable - Opening ratios (1,5, 3,5) (+) Field measurement	- Straight) Emerged	Straight (+) River reach	Rigid flat bed (+)River bathymetry	- Velocity (SPIV, ADV) - Suspended matter concentration (sampling) - River bathymetry(Echo sounder) - Thickness of fine sediment(Metal wading rod)	Patterns of velocity, scour and deposition and corresponding change of river bed morphology
2003	(Ohmoto and Hirakawa)	- Series (21), paired - Impermeable	- Straight - Emerged	Straight	Rigid flat bed	- Velocity (3D PIV, ECM) - Water surface oscillation (Inductive displacement sensors)	Study of water surface oscillation and momentum exchange in spur dike field
2004	(Biron, Robson et al.)	- Series (3), Paired - Impermeable - Oriented 45°, 90°, 135	- Straight - Submerged - Emerged	Straight	Movable bed (D50=1.1 mm)	- Velocity (ADV) - Bed level (Point gauge)	Study of orientation, height and length of spur dikes on scour hole dimension and potential for bed erosion
2004	(Matsuura and Townsend)	- Series (4) - Impermeable - Oriented: 20°, 30°, 40°	- Straight - Submerged (2, 26)	90° and 135° bend channel	Movable bed (D50=0.78 mm)	Bed level (Disto laser meter)	Effect of spur dikes on bank protection in bed
2004	(Sukhodolov, Engelhardt et al.)	- Series (2) - Impermeable - Field measurement	- Straight - Emerged	Straight	River bathymetry	- Velocity (ADV) - Suspended particulate matter - Thickness of fine sediment (wading rod)	Study of suspended particulate matter and flow structure in a series of spur dikes in a river reach

Table 2-3. The previous researches about “series of” “straight” spur dike

Series of Straight Spur Dikes							
Year	Researcher (s)	Type of Spur Dike		Channel Type	Condition of Bed	Studied Parameters	Focus of study
2005, 2006, 2007	(McCoy and Constantinescu 2005, McCoy, Constantinescu et al. 2005, McCoy, Constantinescu et al. 2006, McCoy, Constantinescu et al. 2006, McCoy 2007, McCoy, Constantinescu et al. 2007)	- Series (2, 6) - Impermeable - Numerical investigation (LES)	- Straight - non- Submerged - Submerged	Straight	Rigid flat bed	–	Study of coherent stricture and mass exchange
2005	(Zhang, Nakagawa et al.)	- Series (-4) - Impermeable - Field measurement	- Straight - Emerged	Straight (+) river reach	Rigid flat bed (+) River bathymetry	Velocity (LSPIV, ECM)	Study of behavior of large-scale circulation flow inside spur dike field
2005	(Uijtewaal)	- Series (6) - Impermeable - Permeable - Hybrid - Sloped head	- Straight - Submerged - Emerged	Straight	Rigid flat bed	Velocity (PTV)	Understanding the physical process like vortex formation, detachment near the spur dike head
2005	(Zhang)	- Series (8), Paired - Impermeable	- Straight - Emerged	Straight	Movable bed (D ₅₀ =0.12mm) Live bed (U*/U* _c =2.95)	- Bed level (LBP) - Suspended sediment concentration (Turbidity meter) - Velocity (ECM)	Study of flow and sediment transport around spur dikes in live bed condition
2006	(Le Coz, Brevis et al.)	- Side cavity - Emerged (+) Field measurement	rectangular (L/w=2)	Straight	Rigid flat bed	Velocity (in laboratory: 3D PTV; in field: ADCP, LSPIV)	
2006		- Series (4) - Impermeable - Field measurements	- Straight - Submerged - Emerged	Straight	River bathymetry	Velocity (ADCP)	Study of flow in a series of spur dikes by Field measurement
2007	(Fazli, Ghodsian et al.)	- Series(2) - Impermeable	- Straight - Emerged	90° bend channel	Movable bed (D ₅₀ =1.28 mm)	Bed level (Point gauge)	Study of the effected location of spur dike in 90° bend on the patter of scouring and deposition
2008	(Gissoni and Hager)	- Series(4) - Impermeable	- Straight - Submerged	Straight	Movable bed (D ₅₀ =1.1 mm)	Failure mod of riprap around spur dike	Study of failure of spur dike protected by riprap

Table 2-3. The previous researches about “series of” “straight” spur dike

Series of Straight Spur Dikes							
Year	Researcher (s)	Type of Spur Dike	Channel Type	Condition of Bed	Studied Parameters	Focus of study	
2008(a, b)	(Koken and Constantinescu 2008, Koken and Constantinescu 2008)	• Oriented 60°, 90°, 120°	Straight	Rigid flat bed Rigid scoured bed	• Velocity (LSPIV) • Dye visualization	• Study of “coherent structures” in a rigid flat bed and fixed scoured bed channel with a series of spur dykes	
		• Series(2) • Impermeable • (+) Numerical investigation (LES)					
2008	(Matsumoto, Tominaga et al.)	• Series (3) • Permeable (70%) • Oriented: 45°, 90°	• Straight • Submerged	Straight	Movable bed	• Velocity (3D PIV) • Bed level (LBP)	• Effect of permeability on bed variation and flow structure
2008	(Weitbrecht, Socolofsky et al.)	• Series (8) • Impermeable • Oriented: 64°, 90°, 116° • Opening ratio: 0.3-6	• Straight • Emerged	Straight	Rigid flat bed	• Velocity (LSPIV) • Dye concentration (PCA)	• Study of mass exchange
2009	(Brevis)	• Series (6) • Impermeable	• Straight • Emerged	Straight	Rigid flat bed	• Velocity (3D PTV)	• Discussion about 3D flow structure in spur dike field using 3D PTV method
2009	(Jong and Tominaga)	• Series (2) • Impermeable	• Straight • Submerged • Emerged	Straight compound channel	Rigid flat bed	• Velocity (3D PIV)	• Study of 3D flow structure in spur dikes located in flood plain of a compound channel
2009, 2010, 2011	(Nugroho and Tominaga 2009, Nugroho and Tominaga 2010, Nugroho and Tominaga 2011)	• Side cavity (1) • Emerged	• Rectangular	Straight	Rigid flat bed	• Velocity (3D PIV) • Temporal variation of dye concentration (Image analysis)	• Study of flow pattern in side cavity with different entrance configuration
2009	(Yaeger)	• Series (4) • Impermeable • Oriented: 90°, 150°	• Straight • Submerged • Emerged	Straight	Rigid flat bed	• Velocity (micro ADV)	• Examining the turbulence distribution and its effects on bed shear stress
2010	(Azinfar)	• Series (3) • Impermeable	• Straight • Submerged • Emerged	Straight	Rigid flat bed	• Drag force • Break water	• Study of flow resistance (drag force due to spur dikes)
2010	(Kinzli and Thornton)	• Series (>6) • Impermeable	• Straight • Emerged	S-curved channel (125° and 73°)	Rigid flat bed	• Flow depth (Point gauge) • Velocity (ADV)	• Predicting eddy velocities behind spur dikes

Table 2-3. The previous researches about “series of” “straight” spur dike

Series of Straight Spur Dikes							
Year	Researcher (s)	Type of Spur Dike		Channel Type	Condition of Bed	Studied Parameters	Focus of study
		- Oriented: 60°, 90° - Opening ratio: 3.4-7.62		Trapezoidal section		Bed shear stress (Preston tube)	
2010	(Muto and Taisuke)	- Series (~40) - Impermeable	- Straight (+) Box type - Submerged - Emerged	Compound meander	Rigid flat bed	- Velocity (PIV, ECM) - Sediment deposition	Study of flow in a series of spur dikes in meander channel
2010	(Tominaga and Jong)	- Side cavity (1) - Emerged	- Trapezoidal - Rectangular	Straight	Rigid flat bed	- Velocity (3D PIV) - Temporal variation of dye concentration (Image analysis)	Study of flow pattern in side cavity with different entrance configuration
2010	(Yossef and de Vriend)	- Series (8) - Impermeable	- Straight - Emerged - Submerged (1, 1.4, 1.7, 2)	Straight	Movable bed (D ₅₀ =0.164mm) Live bed	- Velocity (LSPIV, ECM) - Bed level (PROFO) - Suspended sediment concentration (TSS: Transverse Suction System) - Bed form propagation (LSPIV)	Study of sediment exchange between spur dike field and main channel
2011	(Alauddin)	- Series - Impermeable - Permeable - Combined - Bandal type	- Straight - Emerged	Straight	Movable bed ($U^*/U^*c=0.88-0.92$)	- Velocity (ECM) - Bed Level (LBP)	Finding the optimum orientation, alignment, configuration, and permeability of spur dikes for low land rivers comparison of scour and deposits in the embayment and main channel
2011	(Jong and Tominaga 2009) (Jong and Tominaga 2011)	- Side cavity (1) - Submerged	- Rectangular - Trapezoidal - Parallelogram	Straight compound channel	Rigid flat bed	- Velocity (3D PIV) - Deposition of sediment	Study of 3D flow structure and deposition of suspended sediment in lateral embayment with different geometry in a compound channel
2011	(Teraguchi)	- Series (2) - Impermeable - Permeable - Bandal type	- Straight - Submerged - Emerged	Straight	Movable bed (D ₅₀ =0.835mm)	- Velocity (SPIV, ECM) - Bed level (LBP)	Study of flow pattern and bed deformation affected by presence of Bandal like structure
2011	(Tominaga, Horibe et al.)	- Side cavity (1) - Emerged	Trapezoidal	Straight	Movable bed (Mix Sediment D ₅₀ =0.3mm, 0.13mm) Live-bed	- Bed level (LBP) - Velocity (ECM)	Study of sand deposition in a trapezoidal side cavity with different entrance configuration

advanced measurement techniques which resolve the vertical flow structures (Anlanger 2008).

Tominaga, Ijima et al. (2001) were among the first researchers who utilized particle image velocimetry (PIV) measurements within a spur dikes' fields under submerged and emerged conditions.

Uijtewaal (2005) conducted a series of experimental studies using surface PIV technique and found that in submerged condition the flow becomes quite complex and highly affected by three-dimensional effects. He pointed out that the conventional depth average numerical models or 3d numerical models with a coarse resolution are unable to reproduce the features of the flow around submerged spur dikes precisely. A fully 3D LES model was advised to be applied to represent the complex three-dimensionality of the large-scale flow structures.

In several sets of laboratory experiments, Yossef (2005) studies emerged and submerged spur dikes in a movable bed channel. He showed that the mechanism of sediment transport into the spur dike fields differed according to the flow stage. In the emerged situation, the sediment was mainly advected toward the spur dike's fields following the direction of the primary circulation cell. In the submerged situation, the sediment was transported to the spur dike fields across the whole length of the normal line, primarily by residual advective transport by large-scale coherent structures.

Zhang, Nakagawa et al. (2005) studied bed forms, bed deformation, flow field and suspended sediment distribution in channels with series of impermeable spur dikes installed on both sides of channel under liver-bed scour condition. They concluded that flow structure and bed deformation around the most upstream pair of spur dikes are subject to change easily according to approach flow conditions and a relatively stable area forms in the middle stretch of the grouped spur dikes.

Teraguchi, Nakagawa et al. (2008) investigated turbulent flow and bed deformation around two consecutive impermeable and non-impermeable spur dikes with experimental and numerical methods. They concluded that in the case with impermeable spur dikes, the

local scour hole around the upstream spur dike resulted deeper than that of the case with permeable ones.

2.5 Previous Researches about a Series of Spur Dikes with Different Head Shapes

Unlike the researches about a sequence of straight spur dikes, to the best of Author's knowledge, the previous researches about a series of spur dikes with different head shapes are very scarce and limited. In Table 2-4 a summary of those few works has been pointed out.

Linder (1964) conducted a set of experiments to find the optimum combination of a series of L-shape spur dikes in a left bank of a reach of Missouri River in the U.S. He finally found that using such kind of spur dike can form the bigger sand bars in the main channel and this can result in restricting navigation path along the river. According to these findings he suggested the optimum opening between two consequent spur dikes should be around 42 percent of the distance between the bodies of those spur dikes

Dehghani, Barzali et al. (2009) studied the temporal evolution of scouring profile caused by three consecutive L-head spur dikes experimentally. The results showed that sediments deposit inside the spur dike fields until 30 minutes after starting the experiments, and after 80 minutes scouring was observed between first and second spur dikes and sedimentation was observed between second and third spur dikes respectively. After 200 minutes, the scouring was extending to the space between second and third spur dikes, and the process continued 23 hours. In an equilibrium condition, the maximum scour depth between first and second spur dikes was greater than the scour depth between second and third spur dikes.

Cai and Tominaga (2012) studied the flow field inside a box spur dike (two consecutive spur dikes) with L-head shapes using PIV. They showed that the arrangement of box obviously influences the number and scale of circulating flow inside the spur dikes' field.

Table 2-4. The previous researches about “series of” “T-head and L-head” spur dike

Series of T-head or L-head Spur Dike							
Year	Researcher (s)	Type of Spur Dike		Channel Type	Condition of Bed	Studied Parameters	Focus of study
1984	(Klingeman, Kehe et al.)	- Series (1, 2, 3) - Semi-impermeable (Rock fill, Gabion) - Oriented: 30°, 60°,90°, 120°, 150° - Field measurement (series, 8, L- head)	- Straight (1, 2, 3) - L-head (1, 2) - T-head (1) - Emerged - submerged	Straight (+) bend channel)	Movable bed (D50=1.5 mm)	- Bed level (point gauge) - Velocity (Price current meter) - Water depth (Echo Sounder)	Study of the effect of length, spacing, and orientation on bed variation
2009	(Dehghani, Barzali et al.)	- Series (3) - Impermeable	- L-head - Emerged	Straight	Movable bed (D50=1.05mm)	- Bed level (Digital point gauge) - Evolution of bed (Video camera)	Study of evolution of bed scour holes over the time in a series of L-head spur dikes
2012, 2013	(Cai and Tominaga 2012, Cai and Tominaga 2013)	- Series (3) - Impermeable	- L- head - Emerged - Submerged	Straight	Rigid flat bed	Velocity (3D PIV)	Study of flow pattern and mass exchange in a series of combined L-head and Straight spur dikes
2013	(Sumi, Takebayashi et al.)	- Series (1) - Impermeable - Numerical simulation	- T- head - Emerged	River reach (Straight)	River bathymetry		Discussion about effect of installation of T-type and L-type spur dike in a river reach
2014	(Hayashida, Tazoe et al.)	- Series (10) - Impermeable	- T- head, L-head - Emerged	Straight	Movable bed (D50=1.0 mm)	Bed level (LBP)	Study of the effect of opening and head shape on bed variation

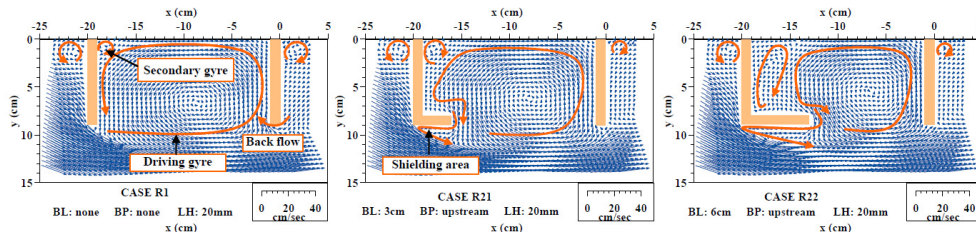


Figure 2-2. Time-averaged velocity vectors on horizontal plane near the middle of water depth in a box with L-head and straight type spur dikes (Cai and Tominaga 2012)

However the few works on spur dikes with different head shape have taken the first steps towards understanding the performance of them in river restoration projects, it is also revealed the need for more knowledge on flow and sediment transport for in these types of spur dikes. Further studies in pursuit of more quantitative and realistic information is still required in order to assess the ability of these types of spur dikes as an alternative measures against bank protection, flood control and improving stream ecology.

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2.6 Works on the Implications of Spur Dikes on Ecology

Over the past decades, due to increasing urbanization many rivers are regulated or canalized for navigational purposes, flood control, erosion control and so on with considerable negative impact on the biological function, water quality, ecosystem diversity and quality of aquatic habitats. Consequently, there are several evidences on decreasing the abundance and richness of aquatic and terrestrial biota and fauna.

Spur dikes are among the measures which are able to diversify the flow and morphology and potentially and theoretically can enhance the environment for the ecology. For example,

the areas between consecutive spur dikes are favorable habitats and reproductive environments for fish, whereas the shallowness and low flow velocity in this area gives rise to sedimentation and the development of vegetation (Schwartz and Kozerski 2003).

So far, several attempts to examine the ecological aspects of installation of spur dikes were done through field surveys of natural rivers in which they studied the abundance of specific species in river due to installation of spur dikes (Li, Schreck et al. (1984), Bischoff and Wolter (2001), Eggers, Kleinwächter et al. (2003), Garcia, Brauns et al. (2005), Shih, Lee et al. (2008), and Hartman and Titus (2010)).

Bischoff and Wolter (2001) caught fish on spur dikes' heads in the River Oder, Germany using point abundance sampling by electrofishing and compared with specimens collected by the same method in seven additional mesohabitats (navigable side-canal, sandy river bank, riprap, deep spur dike, sandy spur dike, connected backwater, polder waterbody) and concluded that that spur dikes' heads constitute an important habitat for both 0+ and 1+ juvenile rheophilic fish during summertime. In another study, Eggers, Kleinwächter et al. (2003) assessed ecological effects of modified spur dikes for several target indigenous and non-indigenous species in a spur dikes' field in Elbe river in Germany using sampling by Van Veen-Grab or stone brushing technique (Figure 2-3). Garcia, Brauns et al. (2005) assessed comparatively the ecological effects of the three shore protection types, namely standard spur dikes, broken spur dikes and parallel work in a reach of Elbe river on species composition, diversity and productivity of benthic macroinvertebrates by sampling benthic macroinvertebrates in different months of year using mesohabitat specific sampling protocol including seven substrate-types (stones, gravel, sand, mud, roots, macrophytes, dead wood) and three categories of current velocity (0-0.2, 0.2-0.6, > 0.6 m/s).

They suggested that the ecological conditions for invertebrates in the shore habitats of the River Elbe could be considerably improved by alternative ways of shore protection, without significant obstruction of navigation.

In another type of researches, habitat suitability approaches are widely used to describe relations between the physical habitat and probability of fish use and accordingly assess the ecological aspect of spur dikes. The key factor here is estimating habitat indices regarding

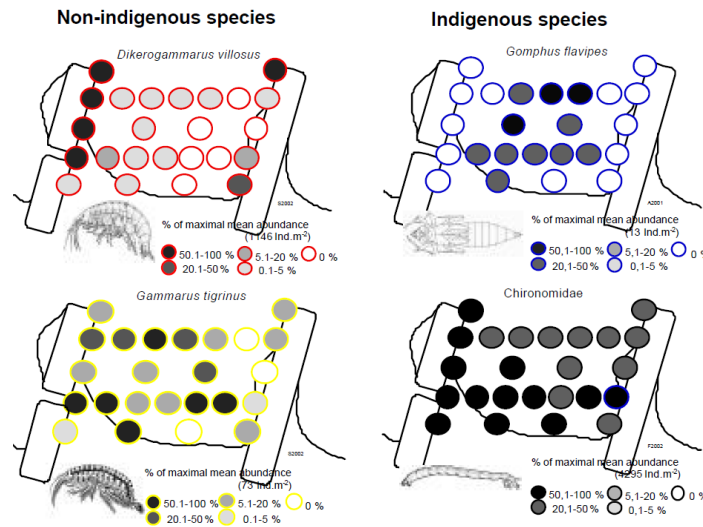


Figure 2-3. Distribution pattern of two non-indigenous aquatic macroinvertebrates and two indigenous aquatic macroinvertebrate taxa within a spur dike's field in Elbe river, Germany (Eggers, Kleinwächter et al. 2003).

an optimum range of abiotic conditions for indicator species (Leclerc, Saint-Hilaire et al. 2003).

Shih, Lee et al. (2008) calculated the weighted usable area (WUA) and percentage usable area (PUA) (both of which are employed to evaluate the fish habitat area) of two endemic species of fish In Taiwan. They assessed the fish habitat area (WUA and PUA) using the results of two numerical models which were employed to simulate the hydraulic characteristics in the presence as well as absence of constructed spur dikes in a river and concluded that the habitat area WUA of two specific species increased after installing spur dikes.

In lack of biotic attributes of habitats in river, another bunch of researchers tried to assess the ecological aspects of spur dikes by describing and quantifying the physical characteristic of habitat, such as flow variations, sediment supply, transport of sediments, particle size distribution and etc.. (Shields, Cooper et al. 1995) showed that a variable bathymetry composed of scour and deposition zones adjacent to spur dikes provided cover and shelter for fish from high velocities. They reported that extension of a spur dike in a

case study managed to improve aquatic habitats by accelerating natural processes, promoting the recovery of channel equilibrium, vegetation and stream-flood plain interaction. The channel cross-section and geometry remained fairly unchanged, but the pool habitats increased by five times due to increased scour and deposition. The biological response included an order of magnitude increase in fish biomass, doubling the number of fish species found in the reach, and an increase in average fish length.

In a few studies in laboratory experiment to investigate the influence of spur dikes on the stream ecology, the researchers mostly tried to examine the ecologically-relevant physical features of habitat in channel in order to provide better habitat for different species in real streams.

Zhang, Nakagawa et al. (2013) studied influence of installation of series of straight type spur dikes in a 90 degree bend channel and examined the influence of spur dikes on variability of Froude number as well as longitudinal bed profiles in channel and their effect of the improvement of habitat for fish. They suggested that an aspect ratio of 2-4 is more suitable for series of spur dike on the convex side of bend to achieve the maximal benefits to the ecosystem and the channel stability.

Sumi, Takebayashi et al. (2013) studied the effect of installation of T-head and L-head spur dikes in rivers with bars on suppression of the sediment deposition and spatiotemporal change of physical habitat in a natural river in Japan. They discussed about the spatial distributions of velocity and water depth and concluded that the diversity of the physical habitat is decreased by installation of groins in rivers with bars.

To put briefly, it is clear that spur dikes can offer a source of heterogeneity in rivers that have few forms of habitat diversity (Nicolas and Pont (1995) and Poizat and Pont (1996)) and assessment of these structures shows some success (Moring and Nicholson (1994), Nicolas and Pont (1995), and Poizat and Pont (1996)). Nevertheless, more evaluations are still needed to verify the benefits of such actions as ecological management tools (Hartman and Titus 2010).

2.7 Motivation of Current Study

1. Overall, the knowledge about the performance of different type of spur dikes (other than straight spur dikes) is still not adequate and the studies about this topic in literature are very few.
2. In general and despite the substantial amount of experimental researches and numerical works, there is still considerable interest and debate on how to optimize the spur dike shape, and spacing to increase their efficiency ((McCoy, Constantinescu et al. 2008)).
3. The key elements of most previous studies on spur dikes were concentrated on erosion and sedimentation processes of the channel due to installation of spur dikes, and/or flood control. They were not concerned well with their effects on aquatic organisms or the biological aspects of installing spur dikes.
4. Over the past decades, the biological communities of rivers have been well studied in literature. On the other hand, the morphodynamic processes and hydrodynamics of stream channel in the presence of spur dikes have received much attention, experimentally, numerically or in field surveys. However, quality of linking these two aspects to address the eco-hydraulic effects of spur dikes is somewhat unexplored.
5. The very rare available results of previous researches about spur dikes with different shapes in plan has turned out the fact that there are much differences between flow structure and morphological pattern affected by the plan view shape of the spur dikes. Given the fact that the deposition of sediment and silt in a river reach and the retention time for biological substances like algae are highly affected by the details of the flow field in zones of spur dikes' fields, knowledge of hydrodynamics and sediment transport in spur dikes with different head shape is yet to be comprehended.

2.8 Originality and Novelty of Current Study

- **Performance of different type of spur dikes (T-head) in flow field and erosion and sedimentation processes:**

In current study, a detailed investigation about flow field and sediment transport of spur dike with different head shape (T-head) was accomplished under different geometrical conditions (opening ratio and spur dike's height). The main outputs of this step were based on comparison between quality of performance T-head spur dikes and (conventional) straight spur dikes in terms of erosion and sedimentation processes near the bank and along the channel.

- **Ecological aspects of installing different type of spur dikes (T-head and straight type)**

Apart from the performance of spur dikes on bank protection, current study examined the ecological implications of morphodynamic processes and hydrodynamics of channel in the presence of different type spur dikes. This study examined the different types of spur dikes as an eco-friendly approach that adapts conventional spur dikes built to protect the riverbank in the past into a measure to improve fish habitats in rivers.

- **Quantification of spatial diversity for habitat due to installation of spur dikes:**

In current study, which the illustration of spatial heterogeneity of flow and bed changes over an area of channel is of main interest, a new approach to quantify the diversity of habitat in channel due to installation of different types of spur dikes was deployed. Despite the conventional methods for quantification of diversity, in current study the effect of "spatial complexity" will be considered and discussed.

3

Fixed Bed Channel Case

3.1 Introduction

As a first step in addressing the research objective outlined in Section 1.6, this chapter presents laboratory experiments and numerical simulation carried out in the fixed bed channel condition.

Given the main objectives of this research and as pointed out in Section 1.5, in both situations of bank erosion control and fish habitat improvement, there is need for the hydraulic evaluation of spur dikes as the proper devices to control scour, protect stream banks, and provide fishery enhancement. In each situation, the hydraulics of local flow often is not well-understood nor adequately considered when such bank protection or stream enhancement is undertaken. Moreover, the sediment erosion and deposition, sediment grading, temperature conditions, oxygen content and nutrient availability are directly or indirectly affected by flow structure. Thus, in this chapter a series of experiments will be done in order to shed light on the structure of flow in two simple cases of series of T-head and straight spur dikes.

Three types of opening ratios (S_s/L_s , in which S_s is opening length between spur dikes and L_s denotes the length of spur dike) have been adopted in emerged condition as well as submerged condition with two different ratios of submergence (H_w/H_s , in which H_w is height of water and H_s is the height of spur dike). These cases totally make up 12 sets of experiments.

For each case, the experiments are performed using Static point measurements for water level measurement and Large Scale Surface Particle Image Velocimetry (LSPIV) technique for quantifying the surface velocity field.

In the next stage, the experimental results are used to validate the numerical results. Using conventional numerical techniques, we investigate the 3D flow pattern around these types of spur dikes. The performance of the numerical model is checked by comparison to experimental LSPIV data.

3.2 Laboratory Experiments

3.2.1 Experimental Setup

Experiments have been conducted in a straight tilting flume with a total length of 20m, width of 1.0m and a maximum depth of 0.30m (See Figure 3-1). This flume was located at Ujigawa Open Laboratory at Kyoto University. The channel bed and side walls were made from glass. Water in the flume was supplied by a pump (see Figure 3-1). At the downstream end of the flume rectangular tailgate was used to regulate the depth of the flow. Inflow surface oscillation of water level at the entrance zone of the flume were lessened by using 10 cm thick fine filter as well as a 2.0 m long, and 5 cm thick Plasto Foam plate mounted parallel to the water surface. The flow rate was controlled with an electronic controller board and was measured by means of a magnetic flow meter (see Figure 3-1). The slope of channel was fixed to 1/1000. A schematic view of channel is illustrated in Figure 3-2.



Figure 3-1. A view of channel used for fixed bed experiments

Along one side of the flume, a simple series of two spur dikes have been installed. The spur dikes were made of gray Plexiglas (see Figure 3-3). The spur dike was 1cm thick and 15 cm long and was fixed at the bottom and side wall with waterproof glue. The spur dikes

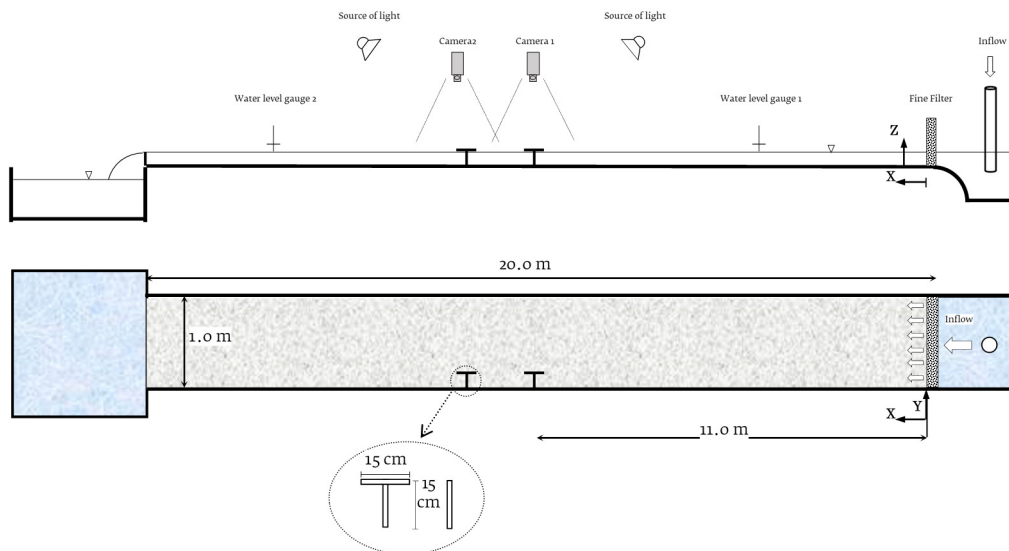


Figure 3-2. Schematic view of flume and spur dikes

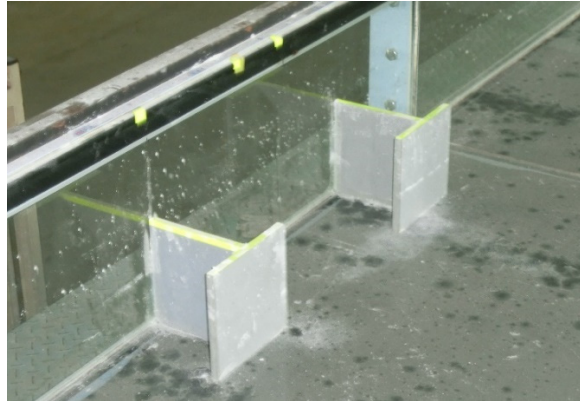


Figure 3-3. T-head spur dikes used in the fixed bed experiments

were mounted perpendicular to the channel banks. For all case studies, the water discharge of 30 lit/s and the equivalent normal depth of $h=64\text{mm}$ were applied in the flume entrance by adjusting the end tailgate. A summary of details of experimental hydraulic conditions is shown in Table 3-1.

3.2.2 Measurement Techniques

Surface velocity and water level measured during every test. Table 3-2 provides an overview of the measurements and equipment used during the experiment. After starting of the pump and giving enough time to reaching to uniform condition, the LSPIV

Table 3-1. Details of experimental hydraulic conditions in fixed-bed channel

Flow Condition	
Discharge (Q) (m^3/s)	0.030
Channel Slope	1/1000
Channel width (B) (cm)	100
Flow depth (H_w) (m)	0.064
Flow Velocity (m/s)	0.47
Shear Velocity (u^*) (m/s)	0.025
B/H_w	15.6
Re	30000
Fr	0.59

Table 3-2. Summary of measurements and measuring techniques in fixed-bed channel

Measurement	Measuring technique	Positions of measurements
Water level	Static point measurements	Upstream and downstream of spur dikes (variable points)
Surface velocity	LSPIV	Inside the spur dikes' fields

measurement was carried out for each case. Water surface profiles were also measured with a digital point gauges with an accuracy of 0.01 mm.

LSPIV Technique

LSPIV measurement is based upon visualization by camera recording of the flow. For the purpose of camera recording, floating white Polypropylene tracer particles with an average diameter of 0.06mm and a specific weight of 400 kg/m³ were used (Figure 3-4, right). To obtain good contrast with the flume bottom, some black paper sheets was attached underneath of channel bed. The particles are used to visualize the free surface velocity field only and as they are submerged for more than 90%, they are expected to follow the flow pretty well. As having a uniform distribution of particles on the water surface can be challenging sometimes, a hair dryer and a dustpan were used to provide a uniform continuous seeding of particles from an appropriate length from the upstream of the first spur dike in the series. In some cases, since direct continuous seeding of particles was not able to cover the whole desired area of study, the seeding was performed in two separate stage for upstream area and downstream part.

A set of two Sony HDR CX-590 were used simultaneously. The Camera were set to capture the video with 60 frames per second (fps) with resolution of 1920 by 1080 pixels in progressive mode. The cameras were placed on top of a movable bridge construction built over the flume 1 meter above the water surface and was directed accurately vertically downward. (See Figure 3-5, left). Consequently, the two frames with size of 85 cm alongside the flow and 55 cm in cross sectional direction were recorded at once. In each experiment case, the capturing the movies were lasted for about 30 seconds or 1700 images.



Figure 3-4. (left) The camera used for recording the continues images; (right) White PVC tracer particles

For calibration, a scaled sheet of paper was prepared beforehand and were used just before beginning of each experiment. Later, image distortion was corrected using the data of this scaled sheet. After correction of image distortion and subtraction of background information, all pairs of sequential frames containing tracer particle were spatially correlated using a free open source software in order to obtain instantaneous surface velocity



Figure 3-5. (Left) A view Bridge constructed over the flume to mount the camera;
(Right) scaled sheet used for calibration of recorded images.

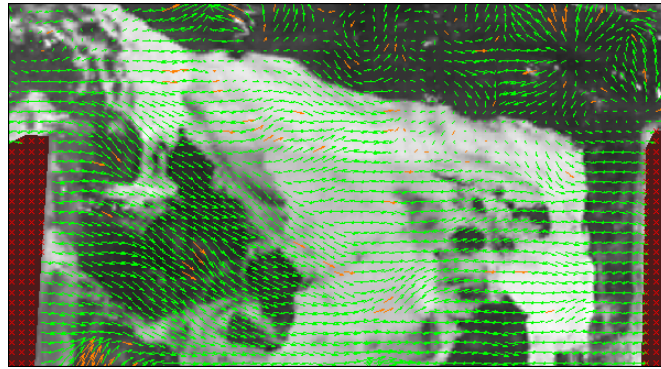


Figure 3-6. An example of output of the PIVlab software

fields. This has been done by computing the average particle displacement in each point of the flow using square correlation areas or “interrogation windows”. All these processes of image analyzing (calibration of images and removing distortion of images, subtraction of background information, setting interrogation windows, spatially correlation, and calculation of instantaneous surface velocity fields) were done using PIVlab software.

PIVlab is a free open source time-resolved PIV software that does not only calculate the velocity distribution within particle image pairs, but can also be used to derive, display and export multiple parameters of the flow pattern. There is no complete guide or manual how to use the software and then it made the user get familiar the software by many trial and errors. An example of output of the software is shown in Figure 3-6.

Table 3-3. Fixed-bed channel experimental cases (Emerged condition)

Case Name	Q (m ³ /s)	H _w (cm)	L _s (cm)	H _s (cm)	S _s	H _w /H _s	S _s /L _s	S _s /H _s
T_SL2_Emg	0.030	6.4	15	15	30	<1	2	1.4
T_SL3_Emg	0.030	6.4	15	15	45	<1	3	2.0
T_SL6_Emg	0.030	6.4	15	15	90	<1	6	4.0
I_SL2_Emg	0.030	6.4	15	15	30	<1	2	1.4
I_SL3_Emg	0.030	6.4	15	15	45	<1	3	2.0
I_SL6_Emg	0.030	6.4	15	15	90	<1	6	4.0

3.2.3 Experiment Conditions

The first spur dike was installed 11 m away from the inlet upstream boundary, which was long enough to achieve a fully developed turbulent flow before reaching the spur dikes.

Two different sets of experiments was considered. In the first sets, three cases of T-head spur dikes was studied with three different opening ratios (S_s/L_s , in which “ S_s ” is opening ratio between spur dikes and “ L_s ” is length of spur dikes). These experiments were followed by carrying out three cases of straight type with same opening ratio in order compare the performance of these two types and highlight the differences and similarities. A summary of characteristics of these cases is shown in Table 3-3.

In the next phase, for T-head submerged spur dikes, two different submergence ratios of 1.2 and 2 (fully submerged) were selected to be carried out. Since the main focus of the current study is about different shape of spur dikes and given the numerous researches about straight spur dikes in submerged condition (See Section 2.4), in this phase no experiment was carried out for submerged straight spur dike.

The submergence ratio of 1.2 represents the condition of boundary overflow and the ratio of 2 was chosen to resemble the condition of high water level (full flooding) in rivers. The summary of conditions for submerged case is pointed out in Table 3-4.

3.2.4 Results

Figure 3-7 to Figure 3-11 show the velocity vectors on the water surface and their magnitudes in each case. As can be seen, in general, in all emerged cases the three

Table 3-4. Fixed-bed channel experimental cases (Submerged condition)

Case Name	Q (m ³ /s)	H _w (cm)	L _s (cm)	H _s (cm)	S _s	H _w /H _s	Opening ratio	S _s /H _s
T_SL2_Sub1.2	0.030	6.4	15	5.5	30	1.2	2	3.6
T_SL3_Sub1.2	0.030	6.4	15	5.5	45	1.2	3	5.5
T_SL6_Sub1.2	0.030	6.4	15	5.5	90	1.2	6	10.9
T_SL2_Sub2	0.030	6.4	15	3	30	2	2	6.6
T_SL3_Sub2	0.030	6.4	15	3	45	2	3	10.0
T_SL6_Sub2	0.030	6.4	15	3	90	2	6	20.0

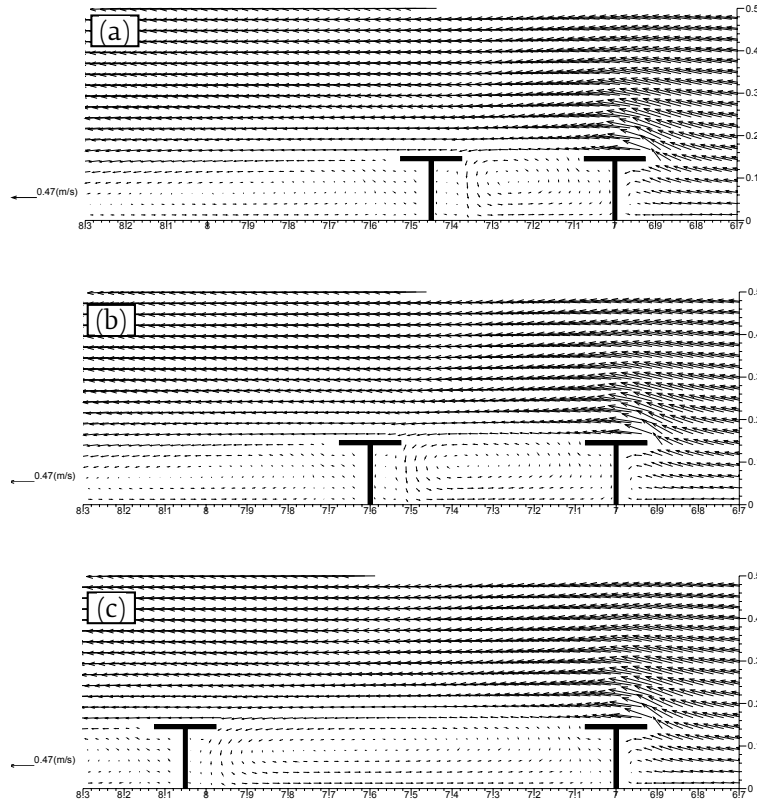


Figure 3-7. Flow velocity vectors on the water surface for T-head spur dikes

(a) $S_s/L_s=2$, (b) $S_s/L_s=3$, and (c) $S_s/L_s=6$

phenomena of the flow separation at head of spur dike, the reduction of flow at the wake of spur dike and the flow acceleration in the main channel can be clearly seen.

More precisely, regardless of the head shape, at the first spur dike of the series the flow separation is quite discernible in all cases (see Figure 3-7 and Figure 3-8). On the other hand, the flow separation in submerged cases (see Figure 3-9 to Figure 3-11) is not noticeable as it was in emerged cases. The main reason of this dissimilarity is basically due to the effect of submergence on the formation of flow separation. This means that in emerged cases, the spur dikes act as an obstacle in the flow which induce intense alteration of the flow direction once it reaches the spur dike's head.

Moreover, in all cases, at spur dikes' field, a velocity reduction region can be seen. This region is chiefly characterized by formation of reticulation gyres among the spur dikes in series.

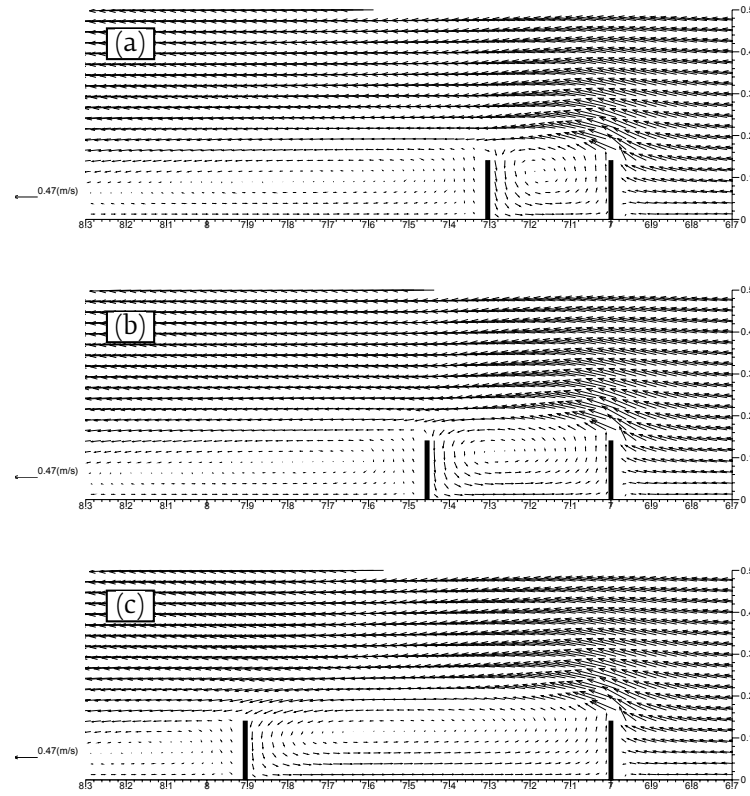


Figure 3-8. Flow velocity vectors on the water surface for straight spur dikes
(a) $S_s/L_s=2$, (b) $S_s/L_s=3$, and (c) $S_s/L_s=6$

Having glanced at Figure 3-7 and Figure 3-8 also reveals the conceivable effect of head shape on the magnitude of velocity reduction in spur dikes' field. Qualitatively, in T-head spur dikes, the magnitude of velocity vectors inside the spur dikes' fields are much smaller than the similar area in straight spur dikes. In general, for T-head spur dikes, one might expect the reduction of potential erosion near the channel bank and increase of sediment deposition in that area which can improve the protection of bank erosion and might help in providing richer environment for fish eggs.

In addition, comparing the Figure 3-12 (a) to (c) suggests that structure of the wake flow, the number, shape and extension of gyres between two consecutive spur dikes does not merely depend on the head shape, but also are determined by opening ratio between.

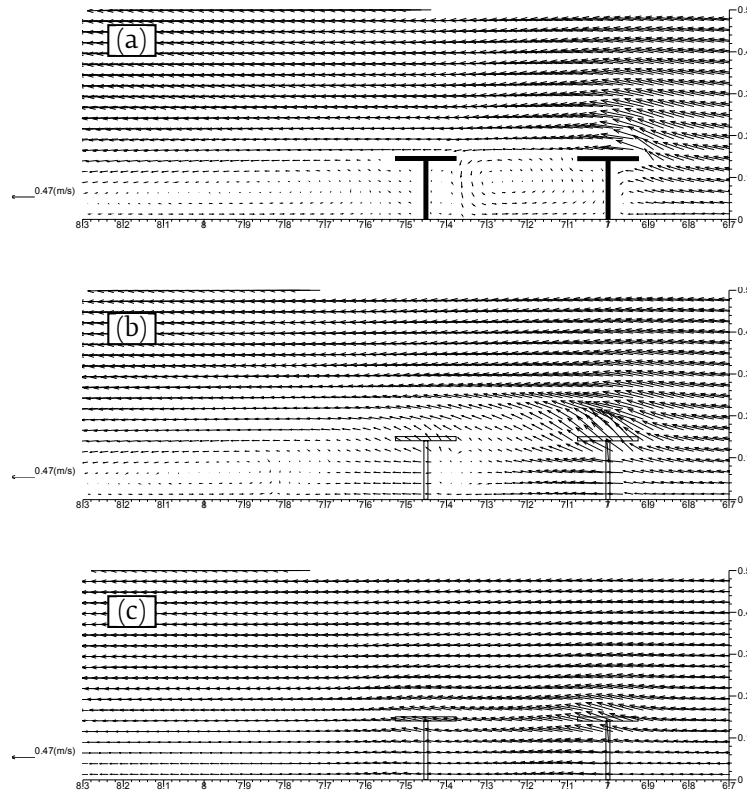


Figure 3-9. Flow velocity vectors on the water surface for T-head spur dikes ($S_s/L_s=2$) at different submergence ratio

(a) $H_w/H_s < 1$, (b) $H_w/H_s = 1.2$ and (c) $H_w/H_s = 2$

While in all cases, one main recirculating zone is visible inside the spur dikes' fields, in T-head shape spur dikes, for opening ratio equal or less than 3, there is one counter-rotating cell near the second spur dike in series. Furthermore, in T-head spur dikes, the center of recirculating zone downstream of last spur dikes in series has been shifted away far from the body of spur dike. This can be due the presence of stagnant flow just behind the wing of T-head spur dike.

As the spur dikes are submerged (see Figure 3-8 and Figure 3-9), circulating flows are not obvious on the water surface. As a matter of fact, the spur dikes in submergence condition just acts as local roughness elements and does not have any remarkable effect of water surface velocity.

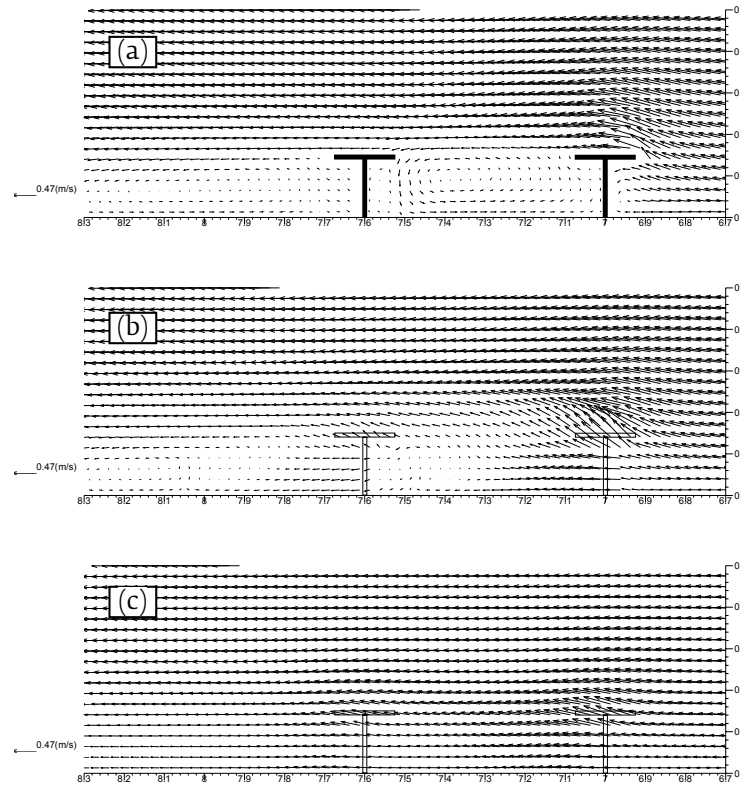


Figure 3-10. Flow velocity vectors on the water surface for T-head spur dikes ($S_s/L_s=3$) at different submergence ratio

(a) $H_w/H_s < 1$, (b) $H_w/H_s = 1.2$ and (c) $H_w/H_s = 2$

Having looked into the flow velocity in the mainstream, the acceleration of flow is obvious in all cases. The acceleration of flow in main stream ultimately has noticeable effect on the erosion of main channel which leads to increase the thalweg of channel and might be considered as potential for better navigation routes.

3.2.5 Analysis and Discussion

3.2.5.1 Time Residence and Mass Exchange inside the Spur Dikes' Field

As discussed earlier in Section 1.5, there are several physical, chemical and nutrient factors associated to abiotic attributes of a fluvial ecosystem which are of great influence on.

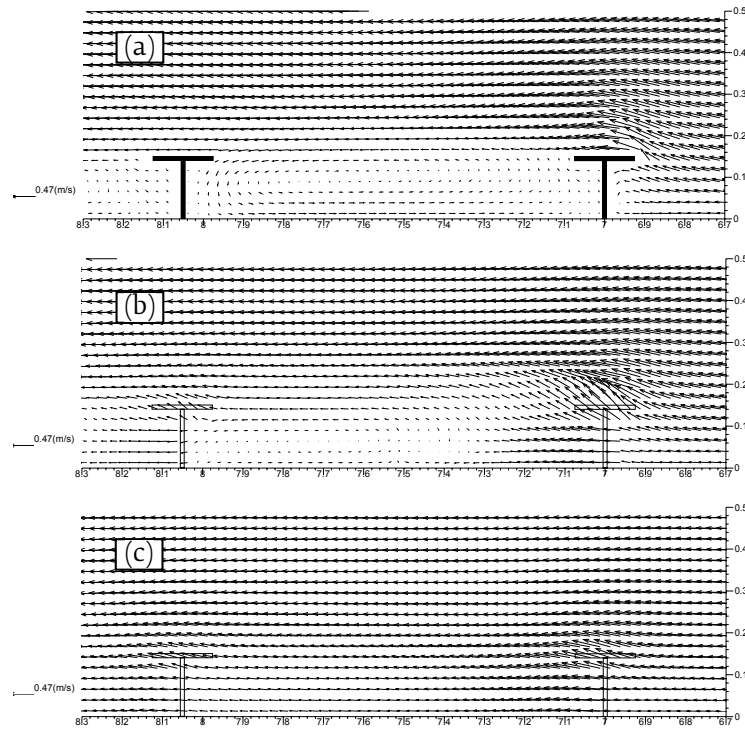


Figure 3-11. Flow velocity vectors on the water surface for T-head spur dikes ($S_s/L_s=6$) at
(a) $H_w/H_s < 1$, (b) $H_w/H_s=1.2$ and (c) $H_w/H_s=2$

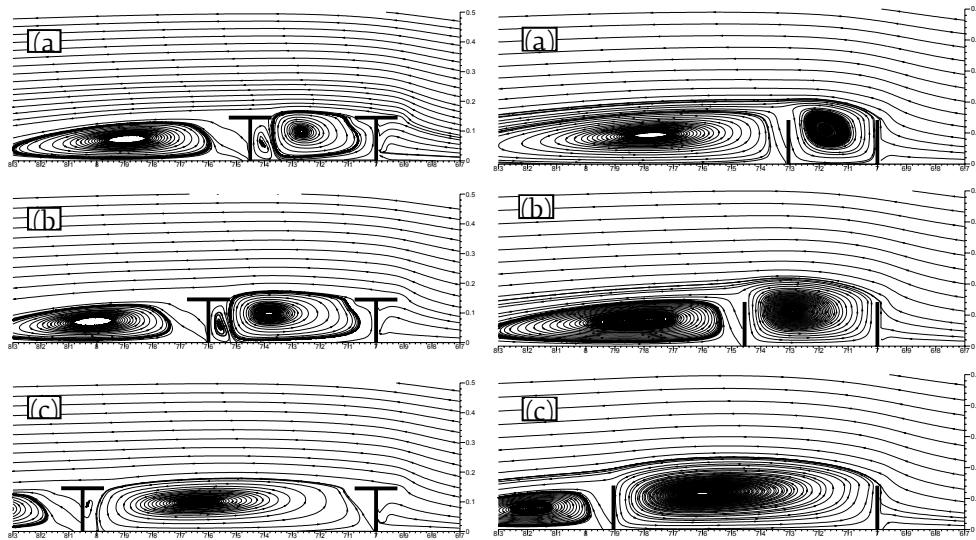


Figure 3-12. Flow streamlines on the water surface for T-head and straight spur dikes
(a) $S_s/L_s = 2$, (b) $S_s/L_s = 3$, and (c) $S_s/L_s = 6$

creating a desirable habitat for stream species. The chemical factors are mainly made up of concentrations of suspended or dissolved matters such as oxygen, inorganic and/or organic matters, etc. As an instance, phytoplanktons are kind of suspended matters in rivers which their abundance and compositions are very crucial for water quality, complex food web structures and accordingly development of sustainable ecosystem in streams.

Dynamics of suspended matters are highly affected from hydrodynamic of flow structure. There are several studies show that there is direct relation between amount of suspended matters in spur dike's fields and the age of water (residence or travel time) in dead zone areas of streams (Hein, Baranyi et al. 2003, Hein, Reckendorfer et al. 2005).

One of the most common area of stream in which the water is enforced to spiral on recirculating trajectories is fields between two consecutive spur dikes. In spur dikes' fields, the flow structure is highly three-dimensional and due to immense scale of these flows and enlarged spatiotemporal variability of flow in these regions, the direct measurement of local residence time in field surveys is extremely difficult (Englehardt 2004).

Kimura, Hosoda et al. (1997) suggested the following equation for calculating the mean residence Time (T_m) in field between consecutive spur dikes at the boundary between spur dikes' field and main channel:

$$T_m = \frac{V_D}{Q_{in}} = \frac{L_s S_s H_w}{E_{in} H_w S_s} = \frac{L_s}{E_{in}} \quad (3-1)$$

V_D is the volume of spur dikes' field and Q_{in} is the mass flux from the main stream into spur dikes' field. Eq. (3-1) means that during time of T_m , all volume of spur dikes' field has been filled up by the flow coming from the main channel. For calculating the Eq. (3-1), E_{in} should be determined. Here, E_{in} denotes the exchange velocity and can be obtained by Eq.(3-2) as follows:

$$E_{in} = \int_0^{S_s} |\bar{v}_{in}| dx \quad (3-2)$$

Using the Eq. (3-1) and (3-2) the mean residence time for series of T-head spur dikes and straight type spur dikes were calculated according to the current study's condition (see Section 3.2.3). Figure 3-13 shows the measured mean residence time in spur dikes' field for different opening ratio.

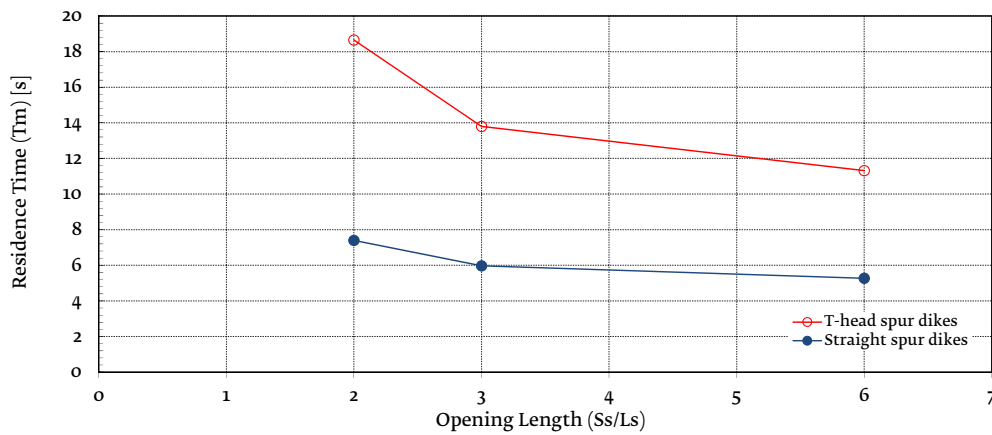


Figure 3-13. Measured mean residence time in spur dikes' field
for different opening ratios

As it can be seen, in general, T-head spur dikes have more residence time than the straight spur dikes. This means that the water will stay longer in fields of T-head spur dikes and it can be expected that the environment in T-head spur dikes' fields will benefit growth and abundance of particulate suspended matters better than the fields of straight types spur dikes. The Figure 3-13 also reveals the noticeable influence of opening ratio on time residence. With increasing the opening ratio, the mean residence time has become shorter which leads to exchanging the volume of water in spur dikes' field faster. This statement is true for both types of spur dikes, however, in T-head spur dikes the rate of decreasing with changing opening ratio is pretty much sharper. The decreasing trend is also not consistent for all opening ratio. Meaning that it is much sharper for changing opening ratio from 2 to 3 and after opening ratio of 3 the trend of decreasing in residence time becomes rather slow.

Hein, Baranyi et al. (2003) and Hein, Reckendorfer et al. (2005) in a study showed that the phytoplankton biomass in a side-arm (a natural retention zone) of a river tends to peak at intermediate water age, while at higher age the algal biomass declines due to biotic control (see Figure 3-14). Figure 3-14 also shows that the phytoplankton community composition changes over the course of this succession (Wood, Hannah et al. 2007). Although there is no prototype data for upscaling the absolute values of time residence

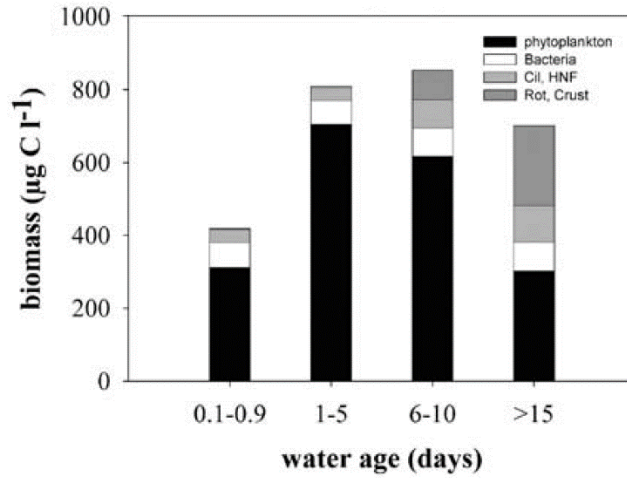


Figure 3-14. The accumulation of all functional groups of plankton in side-arms of Danube after a flood pulse (Hein, Baranyi et al. 2003, Hein, Reckendorfer et al. 2005).

calculated for the experimental data in Figure 3-13 to field data, but comparing the trend of calculated time residence for the experimental data and considering the observations of (Hein, Baranyi et al. 2003, Hein, Reckendorfer et al. 2005), it can be said that T-head spur dikes with the opening ratio of 3 is the best type and arrangement of spur dikes in terms of providing the suitable residence time for growth and abundance of plankton composition in rivers.

For better understanding of the effect of aspect ratio on the process of water exchange between spur dikes' field and main channel, mass exchange coefficient is calculated for experimental cases according to the following equation introduced by (Weitbrecht 2004):

$$k = \frac{E_{in}}{U} \quad (3-3)$$

Where E_{in} is the exchange velocity (Eq. (3-2)) and U is the time-averaged velocity in main stream.

Figure 3-15 shows the calculated mass exchange coefficient in spur dikes' field for different opening ratios. Likewise the time residence, the influence of aspect ratio is quite obvious on the mass exchange coefficient. With increasing the opening ratio, the mass exchange for both types of spur dikes has increased. The main reason of this is due to the fact that the exchange strength is mainly dominated by the intensity of large vortex

structure disturbing the boundary of spur dikes' field. These large coherent structures appear at the tip of first spur dike in series and grow over the traveling in front of spur dikes' field. Over its traveling, these large coherent structures can expand through the spur dikes' field and increasing the opening ratio can facilitate the intrusion and their affecting on the spur dikes' field.

3.3 3D Numerical Modeling of Flow Structure

3.3.1 Introduction

“Models” can be defined as a replica of a multifaceted natural reality with the ability of qualitative or quantitative prediction ((Darby and Van de Wiel 2005)). There are different ways of modeling a physical phenomenon such as conceptual models, analytical models, statistical models and numerical models. The notable advantage of numerical models is that they are capable of reproducing the spatio-temporal outputs for the studied problem. A numerical model basically works by solving the mathematical equations of governing phenomena for the studied problem over a discretized domain of the problem for different time steps. Over the past few years, by increasing the capacity of computational machines numerical models have been extensively utilizing in the study of different engineering problems. Likewise, the numerical models have been very effective tools in study of ecological implications of engineering projects in which integrating various parameters with different spatio-temporal scales are of great interest.

In this section, the simulation of hydrodynamics of flow using the numerical model SSIIM2 ((Olsen 1991)) aims to deliver information about the spatial and temporal distributions of habitat variables (water depth and flow velocity distributions) to describe the abiotic habitat conditions.

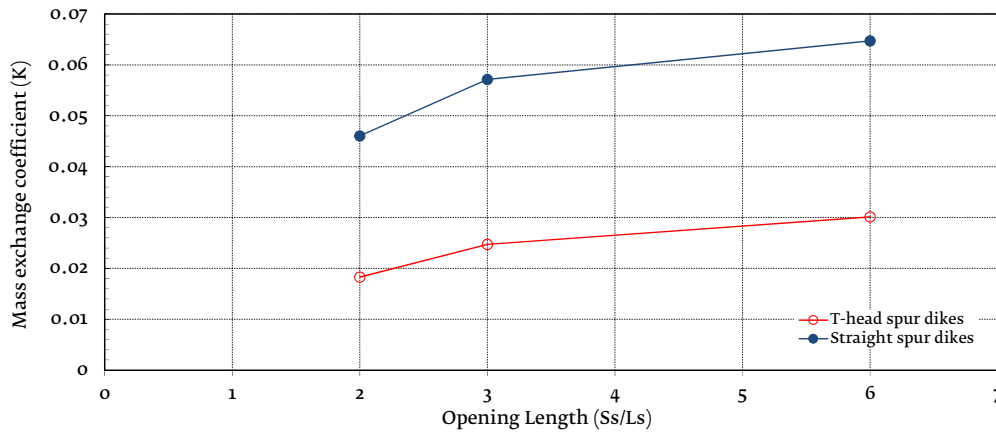


Figure 3-15. Mass exchange coefficient in spur dikes' field for different opening ratios

3.3.2 Description of 3D RANS Model

Recognition of an unknown physical phenomenon and discovery of different blind aspects of it, would be possible, in general, by means of :

- examining that phenomenon in real conditions (measuring the obvious parameters in-site), or on the other word, using field surveying
- Building the physical model of the prototype with a smaller scale and carrying out related studies on it
- Expressing the given phenomenon using theoretical relations, extracting respective differential equations, and consequently solving the mathematical equation using numerical approaches.

The major principle of any mathematical model is the conservation laws of physics (i.e. conservation of energy, mass and momentum). The governing equations for incompressible viscous turbulent fluid are expressed using the Navier-Stokes (N-S) equations and continuity equation. Depending on the conditions of each specific problem, several simplifications and assumptions are usually made in order to allow the usage of CFD models on practical applications.

The most conventional approach to model turbulent flow is the time averaging of the Navier-Stokes equations or so called the Reynolds Averaged Navier-Stokes (RANS) equations. This approach separates the instantaneous amounts of velocity and pressure into mean and fluctuating components. Mathematical representation of averaging leads to presence of unknown parameters known as Reynolds Stresses (Rodi, 1993). The resolving of Reynolds Stresses is done using turbulence modelling. RANS approach has some drawbacks. Most importantly, it lacks the capability to model anisotropic flows as well as capturing instantaneous flow dynamics. However, considering the affordable computational needs and its ability to model different engineering problems with accurate results, the RANS modelling is still most practical and popular numerical approach, specifically for riverine environment problems.

3.3.3 Governing Equations

The numerical study of flow field and sediment transport is basically possible when the governing laws of these processes is expresses in mathematical forms which is often in the form of differential equations. The details of obtaining these equations are discussed well in various literature (Schlichting 1979, Rodi 1980) .

The governing equation for incompressible, fully turbulent flow is expressed using Navier-Stokes (RANS) equations and continuity equations. Assuming the being steady of flow ($\frac{\partial}{\partial t} = 0$) and ignoring the fluctuations of specific mass ($\rho' = 0$) these equations are written as follows:

$$\frac{dU_i}{dx_i} = 0 \quad (3-4)$$

$$\frac{\partial U_i}{\partial t} + U_i \frac{\partial U_i}{\partial x_i} = \frac{1}{\rho} \frac{\partial}{\partial x_i} (-P \delta_{ij} - \rho \overline{u'_i u'_j}) + \frac{f_i}{\rho} \quad (3-5)$$

U is the averaged velocity over time t , x is the spatial geometrical scale, ρ is the density of fluid, P is the pressure, δ_{ij} is the Kronecker delta and u' is the velocity fluctuation over time during one time step δt . The term of $\overline{u'_i u'_j}$ in Eq. (3-5) is known as Reynolds stress and being modeled with the Boussinesq idea (3-6)

$$\overline{u'_i u'_j} = \vartheta_t \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) - \frac{2}{3} k \delta_{ij} \quad (3-6)$$

in which k is the turbulent kinetic energy and is calculated using Eq. (3-7).

$$k = \frac{1}{2} \overline{u'_i u'_i} = \frac{1}{2} (\overline{u_1'^2} + \overline{u_2'^2} + \overline{u_3'^2}) \quad (3-7)$$

Now the main problem is defining the turbulent eddy viscosity ϑ_t which is unknown. This is the duty of a turbulence model to determine the ϑ_t .

The most conventional turbulence models which are used for a wide range of engineering analysis is called two-equation models. In this sort of models, two independent equations are used for mixing length and turbulent kinetic energy. The most known and popular two-equation turbulence model is standard k - ϵ model. In this model, the turbulent eddy viscosity ϑ_t is expressed using the following relation:

$$\vartheta_t = c_\mu \frac{k^2}{\epsilon} \quad (3-8)$$

in which c_μ is coefficient and is determined using experimental studies. k is turbulent kinetic energy and ϵ is turbulence dissipation rate and are calculated using following equations:

$$\frac{\partial k}{\partial t} + u_i \frac{\partial k}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\frac{\vartheta_t}{\sigma_k} \frac{\partial k}{\partial x_i} \right) + \vartheta_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j} - C_D \frac{k^{3/2}}{l} \quad (3-9)$$

$$\frac{\partial(\rho\epsilon)}{\partial t} + \text{div}(\rho \bar{u} \epsilon) = \text{div} \left(\frac{\mu_t}{\sigma_\epsilon} \text{grad} \epsilon \right) + C_1 \frac{\epsilon}{k} G - C_2 \rho \frac{\epsilon^2}{k} \quad (3-10)$$

in which G is rate of production of turbulent energy k using turbulent shear stresses and C_D , C_1 , C_2 , σ_k and σ_ϵ is experimental coefficient. For standard k - ϵ turbulence model, these coefficients are shown in Table 3-5.

Table 3-5. Fixed coefficients for standard k - ϵ turbulence model

C_1	C_2	c_μ	σ_k	σ_ϵ
1.44	1.92	0.09	1.00	1.3

The second term in the left side of Eq. (3-5) represents the convective term of the equation. Discretization of convective term can be done using the finite volume method where the variable in one cell is the function of the variables in the neighboring cells:

$$c_p = \frac{a_w c_w + a_e c_e + a_n c_n + a_s c_s}{\sum a_{nb}} \quad (3-11)$$

In which c denotes the variable in the center cell p and in each of the surrounding cells (w, e, n, s represent the neighboring cells of west, east, north and south side of center cell p) and a_{nb} are weighting factors:

$$\sum a_{nb} = a_w + a_e + a_n + a_s \quad (3-12)$$

This is true for two-dimensional state and for three-dimensional state of equations the top (T) and bottom (B) sides are also included.

To solve Eq. (3-11), the coefficients a_{nb} must be known. Different first order or second order numerical schemes are used to calculate these coefficients.

. In current study two schemes of Second Order Upwind (SOU) and Power Law (POW) was tested to gain the best results.

For instance, in SOU scheme, the value of the variable in each face is determined on two upstream cells (Patankar 1980). Figure 3-16 shows the way of discretization in the scheme of SOU. In this figure the values of variable in nodes are determined and the value of variable in the western face (w) of cell p is unknown and should be calculated. This scheme uses an interpolation of the value of variable in cells ww and w too calculate the value of variable in cell w :

$$\frac{U^w - U_{ww}}{dx + 0.5dx} = \frac{U_w - U_{ww}}{dx} \quad (3-13)$$

which after simplification will lead to:

$$U^w = \frac{3}{2}U_w - \frac{1}{2}U_{ww} \quad (3-14)$$

The equation (3-12) is true when the length of cells are same. In the case of non-uniformity of cells, the coefficients of $3/2$ and $1/2$ in Eq. (3-14) will be determined

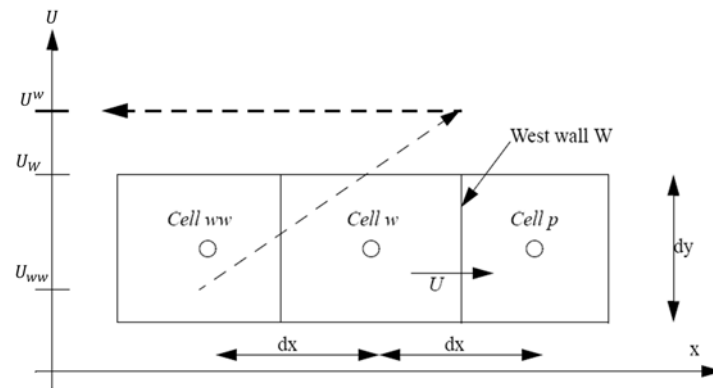


Figure 3-16. The way of calculation the value of U in west (w) side of center cell (p) using SOU Scheme

proportional to expansion ratio of adjacent cells. The flux from west side of cell p , then will be calculated as following:

$$F_W = U_W A_W \left(\frac{3}{2} U_W - \frac{1}{2} U_{WW} \right) + \Gamma_W \frac{A_W (U_W - U_p)}{dx} \quad (3-15)$$

and accordingly:

$$a_w = \frac{3}{2} U_w A_w + \Gamma_w \frac{A_w}{dx} + \frac{1}{2} U_e A_e \quad (3-16)$$

$$a_{ww} = -\frac{1}{2}U_w A_w \quad (3-17)$$

$$a_e = \Gamma_e \frac{A_e}{dx} \quad (3-18)$$

$$a_{ee} = 0$$

$$a_n = \frac{3}{2}U_n A_n + \Gamma_n \frac{A_n}{dx} + \frac{1}{2}U_s A_s \quad (3-19)$$

$$a_{nn} = -\frac{1}{2}U_n A_n \quad (3-20)$$

$$a_s = \Gamma_s \frac{A_s}{dx} \quad (3-21)$$

$$a_{SS} = 0 \tag{3-22}$$

In the Navier-Stokes equations, in addition to the parameters of velocities, the pressure parameter is also present which is unknown and should be calculated by a particular algorithm. Patankar (1980) proposed SIMPLE algorithm for calculating pressure fields based on known velocity field. The main idea behind the SIMPLE algorithm is to guess a value for

the pressure and finding an equation for the pressure correction using the continuity defect in the next time step. By applying the pressure correction to the pressure values, continuity equation is also satisfied.

3.3.4 Boundary Conditions

As discussed above, unknown variables in the cell center are determined as a function of the variables in the neighboring cells. However, as for boundary cells at the inflow, outflow, water surface and walls of the domain, the values of velocities, turbulence variables (k and ϵ) and pressure are required to be known at the beginning of the calculation.

At the inflow boundary of domain, the Dirichlet boundary condition was applied by which the values of variables are set to a certain known value, according to the characteristics of case studies. At the outflow boundary, the zero-gradient boundary condition was applied which means the values of variables were set to the values of the cell next to the cells at the outflow boundary. For the water surface, U_x, U_y, P and ϵ have zero gradient boundary conditions. U_z is set to a certain value and k is equal to zero, respectively.

As to the wall boundary, the wall law functions for rough boundary (Schlichting 1979) were utilized:

$$\frac{U}{u^*} = \frac{1}{\kappa} \ln \frac{y}{k_s} \quad (3-23)$$

where u^* is the shear velocity, k_s the bed or wall roughness.

3.3.5 Model Input

The 3D RANS model presented in Section 3.3.3 and 3.3.4 is applied to simulate the cases presented in Section 3.2.3. The flume is spatially discretized with a non-uniform unstructured grid having 482 grid cells in longitudinal, 80 grid cells in lateral and a

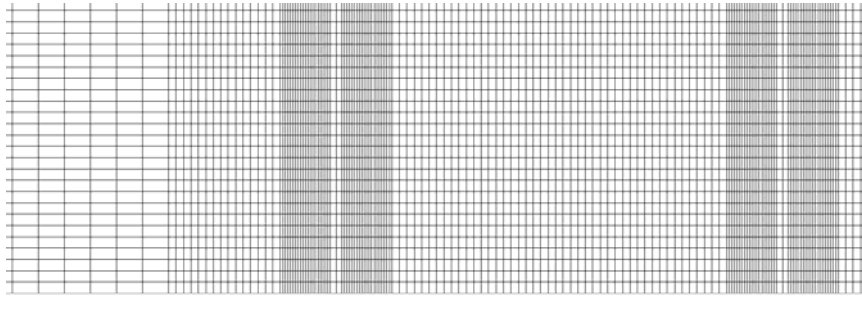


Figure 3-17. A view of the grid used for simulation of cases

maximum of 10 grid cells in vertical direction, giving a total number of 385,600 grid cells. The length of one grid cell in longitudinal direction changed from 0.05 m (in the area far from the spur dikes) to 0.003 m at regions near the spur dikes, the width 0.01 m and the height depends on water depth that defines the maximal number of grid cells in vertical location. The required criteria such as “ y^+ ” criterion near the walls and bed was checked to avoid from the instability in the results. Figure 3-17 shows a view of the grid.

Zero gradient boundary conditions were used for all variables at the outflow boundary, while velocities were specified at the inflow boundary (Dirichlet boundary condition) according to the experiment condition (Table 3-3 and Table 3-4). Wall laws introduced by Schlichting (1979) were used for the side walls and the bed. The bed roughness was set to $k_s=0.0001$ m (the bed assumed smooth as glass).

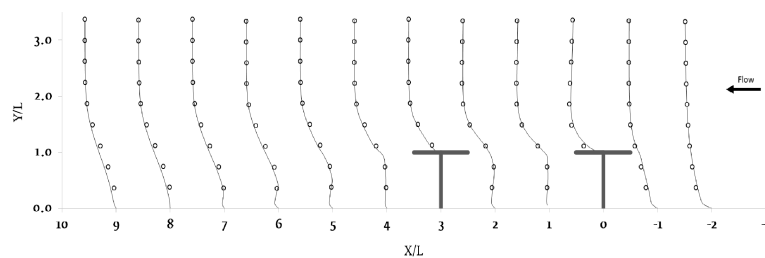


Figure 3-18. Verification of numerical simulation with experimental data
(velocity magnitude at water surface)

○ Experimental data — Numerical. results

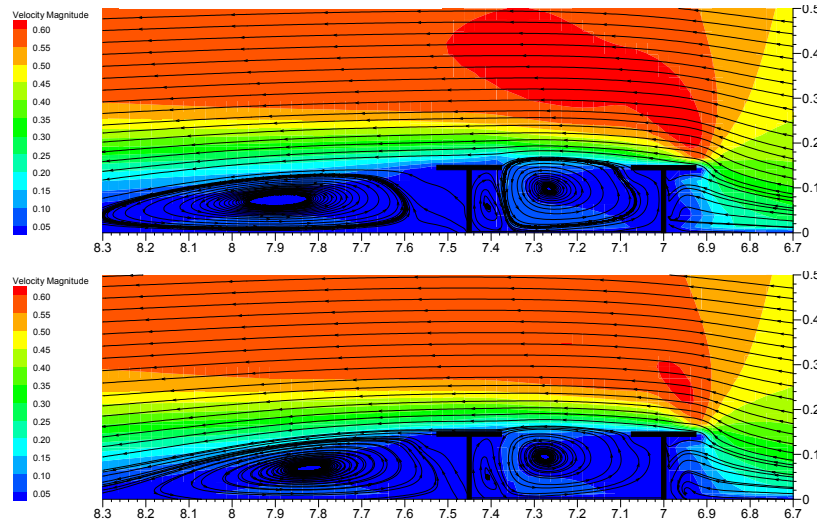


Figure 3-19. Streamline and contour of magnitude of velocity in water surface plane for experimental data (above) and numerical results (below)

3.3.6 Verification

A set of experimental case with opening ratio of 2 was chosen for verification of the modeling. The experiment was carried out at Ujigawa Open Laboratory of Kyoto University. The further details of experiment can be found in Sections 3.2.1 and 3.2.2. The numerical domain was set up according to the Section 3.3.4 and 3.3.5. To solve the governing 3-D RANS equations, the standard $k-\epsilon$ turbulence model was used to solve the turbulent stresses in the Reynolds averaged equations. Since in such cases the changes of water surface around the structure are considerable and cannot be neglected, in this study the water surface calculation was also applied in order to incorporate fully 3D turbulent modeling and free-surface flow.

For discretization of convection terms in RANS equations two approaches of second order upwind (SOU) and power law (POW) were available as they were discussed in Section 3.3.3.

Figure 3-18 shows the comparison between the simulation results and the experimental data for the velocity magnitude ($= \sqrt{u^2 + v^2}$ in which u , v are respectively longitudinal, and

transverse components of velocity) in different cross sections of upstream and downstream of the spur dikes in the plane near the water surface. It can be seen that agreements between measured and computed velocity are quite satisfactory. However, in some points the performance of the model was not well which might be due to the lack of the $k-\epsilon$ turbulence modeling to model the turbulence-driven recirculation perfectly.

3.3.7 Analysis and Discussion

In this section and after verification of the model, the effect of different head shapes on the flow structure will be discussed. Figure 3-20 shows the positions of the studied planes.

3.3.7.1 Analysis of 3D Flow Structure

3.3.7.1.1 Effect on path of streamlines of the flow

Figure 3-21 and Figure 3-22 show the path of streamlines of the flow in the plane close to the channel bed (plane 1yz in Figure 3-20) and the plane near the water surface (plane 2yz in Figure 3-20) at the upstream and downstream of the spur dikes as well as inside the spur dikes' field with opening ratio of 2.

Having a glance at the path of streamlines in the plane near the bed of T-head case shows that unlike the straight spur dikes, a reverse flow from near of the head of the spur dike is present which goes toward the bank of the channel. Conversely, in the straight spur dikes the direction of deflection of the lower level flows is mainly toward the head of the spur dikes. This fact can qualitatively lead to increasing of the danger of the erosion of the banks upstream of the first spur dikes of the T-head series. Further investigation about the path of streamlines in these two cases reveals that, however the dimensions of gyre for the straight spur dikes have not been changed a lot along the depth, the gyre near the water surface has tendency to escape from the spur dikes' field. Alternatively, for the T-head spur dikes, the characteristic of gyre inside the spur dikes' field is quite different. In the near bed surface, there are two clock-wise rotating zones: the main one which occupies almost the whole of

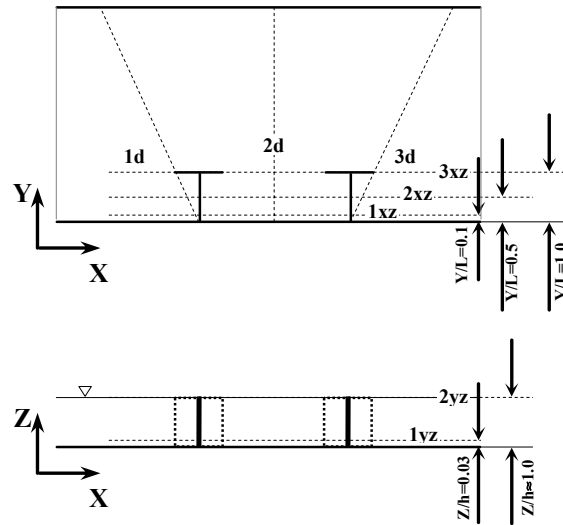


Figure 3-20. Schematic view of the position of the studied planes

the embayment and another small anti-clock-wise rotating zone which is located just upstream of the latter spur dike in the series.

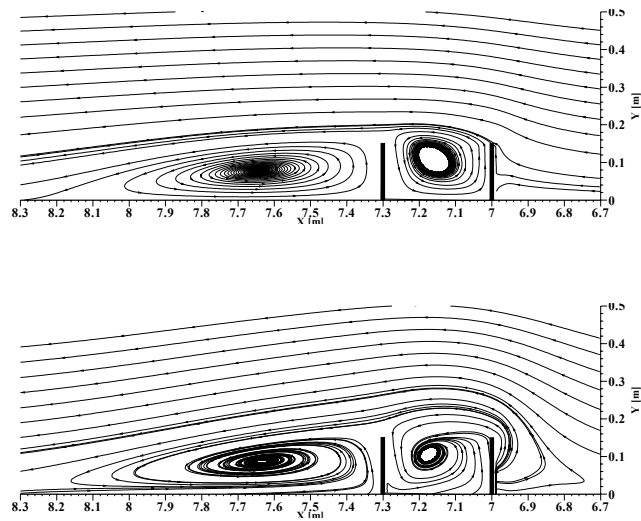


Figure 3-21. Path of the streamlines of flow in the plane near the water surface (above) and the plane close to the bed (below) in straight spur dikes ($S_s/L_s = 2$)

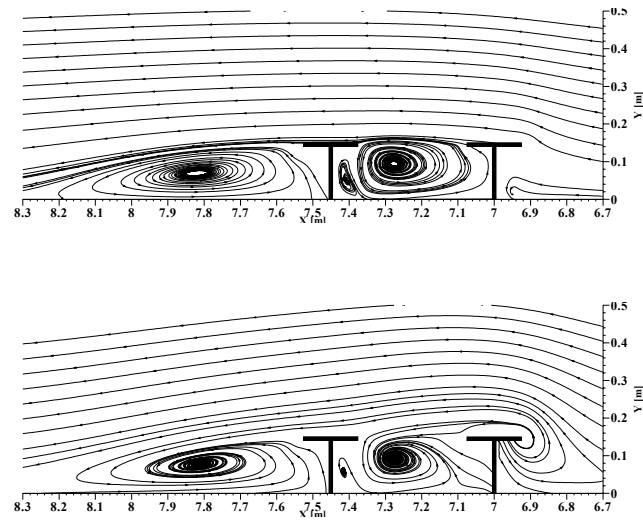


Figure 3-22. Path of the streamlines of flow in the plane near the water surface (above) and the plane close to the bed (below) in T-head spur dikes ($S_s/L_s = 2$)

Figure 3-23 shows the contour of velocity magnitude in the level of near bed as well as the level close to the water surface for both cases. In all cases the zone of maximum velocity occurs alongside of the outer zone of the shear layer. Comparison between the contour of plane near the bed for both shapes shows that in the T-head case the zone of high velocity has moved toward the opposite bank of the channel. The main cause of this fact can be the presence of the wing for T-head case. In other word, the wing of the T-head spur dike displace the high velocity zone away from the body of spur dike toward the main channel and/or opposite bank. In addition, the amount of maximum velocity magnitude has reduced for T-head spur dikes. The direct effect of this decrease can be changes in bed shear-

stress. Then it can be expected that in this case the pattern of bed-shear stress as well as the potential of the erosion would be reduced.

Generally, it can be seen that the extension of high velocity zone in series of straight type spur dikes is more than the T-head case.

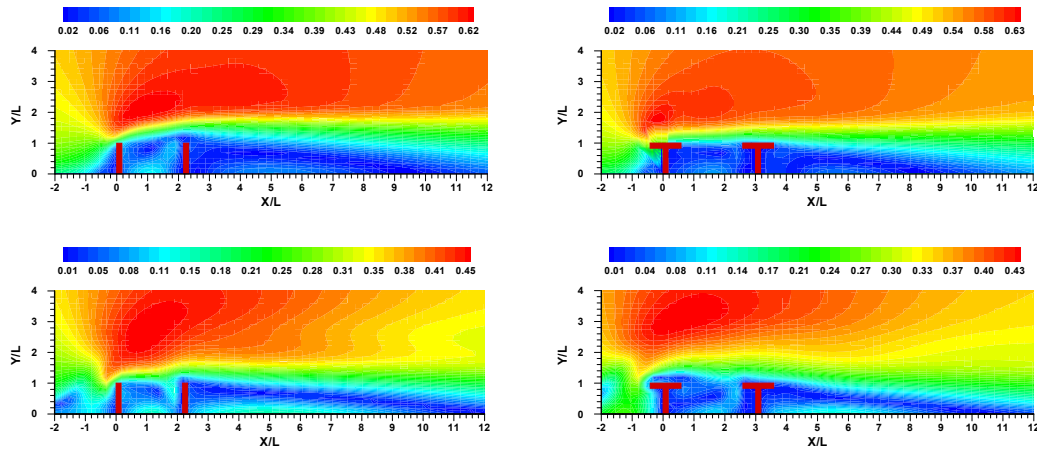


Figure 3-23. Contour of velocity magnitude in the plane near the water surface (above) and the plane close to the bed (below)

3.3.7.1.2 Effects on Formation of Horseshoe Vortices

In Figure 3-24 the distribution of vertical component of velocity around the spur dikes in the plane close to the channel bed has been shown. The goal of this illustration is delivering an image about the zone of the formation of horseshoe vortices around the spur dikes. Having seen the figure turns out that presence of two positive and negative zones near the upstream of the head of upper spur dike that is the sign of the formation of horseshoe vortex. The first point that can be seen from this figure is the ability of T-head spur dike to deviate the horseshoe vortex from the body of spur dike.

In fact, the presence of the wing in T-head spur dike has noticeable impact on the mechanism of interaction between the approaching flows near the bed and the vortex zone

upstream of the spur dike's head in order to keep the center of the vortex zone far from the first spur dike's body in the sequence of spur dikes.

3.3.7.1.3 Impact on 3D structure of vortices around the series of spur dikes

To have better understanding about the 3D structure of vortices around the series of spur dikes, it might be better to have a look on the path of streamlines in three different

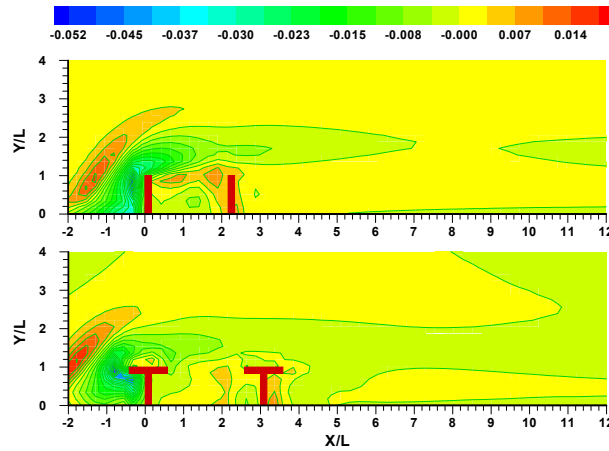


Figure 3-24. Contour of vertical component of velocity in the plane close to the bed

longitudinal sections: “1xz” (in Figure 3-20) which means the section just close to the wall; “2xz” (in Figure 3-20) and “3xz” (in Figure 3-20) which means the section tangent to the spur dikes’ heads. Figure 3-25 shows the comparison between paths of streamlines for two cases in these three sections. It is clear that the general structures of vortices in these two cases are quite different. At the upstream part of the straight type spur dikes, the approaching flows in the below levels confront to the reverse direction of downward flows and it results in formation of a clockwise rotating flow near the channel bed. Moving toward the spur dike’s head, this rotating zone weakens so that it would be disappeared near the section tangent to the spur dikes’ head; however, along this way its center goes for the body of the upstream spur dike in series. Comparing this region with its counterpart in series of T-head spur dikes shows that unlike the straight type spur dikes, a rotating zone is present at all sections ($Y/L=0.1, 0.5$ and 1.0) of T-head spur dikes. In addition, the center of this rotating

flow moves toward the bed channel by traveling from the near wall section to the section tangent to the spur dikes' heads.

By comparing the upstream part of first spur dike in series of straight type and T-head one, it could be also pointed out that due to existence of the wing in the T-head spur dike, the center of rotating flow which is the meeting point of approaching flows near the bed and reverse direction of downward flows, goes a pretty much farther comparing to the similar situation in the straight type spur dikes. This difference for the section of $Y/L=0.5$ (plane 2xz in Figure 3-20) is about $0.4X/L$ and this reveals again another effect of the presence of wing in T-head spur dikes, as it is discussed earlier. In the downstream part, but the difference due to the existence of T-head spur dike is more important. In the series of T-head spit dikes, a strong vertical clockwise rotating zone is present just downstream of the latter spur dike's body. The center of this zone that occupies almost the entire depth of water is almost fixed near the downstream edge of the spur dike's wing; however, it goes a little bit downward by going away from the wall. In the straight type spur dikes this full-size vertical gyre is confined to a small surface zone attached to the body of spur dike.

3.3.7.1.4 Effects on Turbulence Characteristic

By now the pattern of mean flow around two series of spur dikes with different head shape was discussed. To investigate turbulence characteristic as well as the structure of shear layer and horseshoe vortices Figure 3-26 is illustrated. This figure shows the path of streamline and the contour of turbulence kinetic energy (TKE) in three different sections: "1d", "2d", "3d" (See Figure 3-20).

As can be seen in Figure 3-26, in all sections of straight type spur dikes, a vertical high energetic zone can be seen. Another limited high energetic core is also available just in the

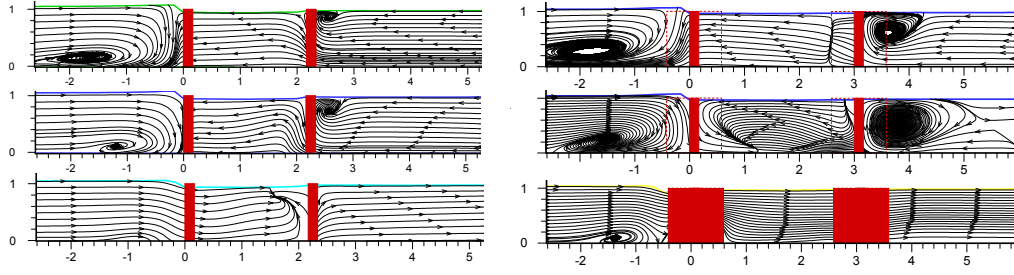


Figure 3-25. Paths of the streamlines for series of straight type spur dikes (left) and T-head spur dikes (right) in three longitudinal sections:
Above: $Y/L=0.1$; Middle: $Y/L=0.5$; Below: $Y/L=1$

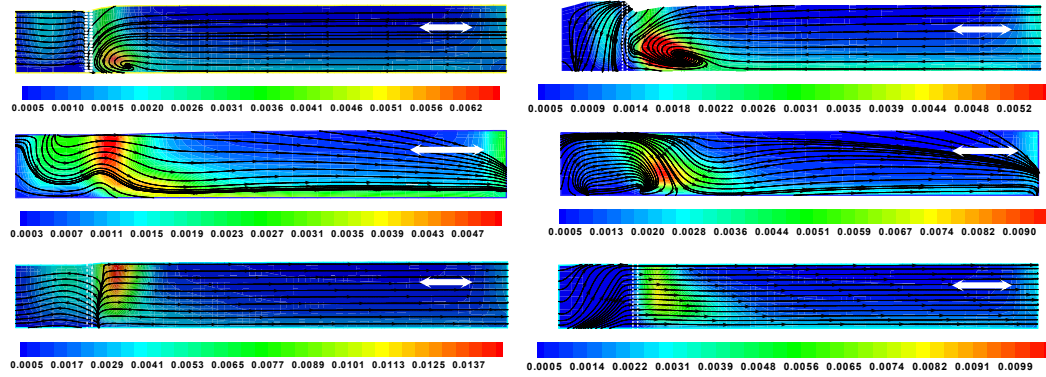


Figure 3-26. The path of streamline and the contour of turbulence kinetic energy (TKE) in three different cross sections around spur dikes' field
(left: Straight type spur dikes ; right: T-head spur dikes)
I: The plane 1d; II: The plane 2d; III: The plane 3d

section passing upstream of the first spur dike in series. In T-head series, this high energy core can also be seen in the section inside the spur dikes' field, while in the similar section of the straight type spur dikes this near bed high energy core has almost weakened.

By comparing the contour of TKE and path of streamlines in all sections in both cases, it can be seen that the position of vertical zone is in accordance with the location of shear layer

around the spur dikes' field. Moreover, the cause of formation of the second high energetic core is also related to the formation of horseshoe vortex in front of head of spur dike and near the channel bed. By this explanation and referring to the Figure 3-26, it is obvious that the depreciation of horseshoe vortices in series of straight type spur dike is faster than those of T-head ones. Because as can be seen in Figure 3-26-II, in the second section which is located inside the spur dikes' field, a horseshoe vortex is still present in the T-head spur dike, while in the straight type spur dikes the horseshoe vortex which existed in Figure 3-26-I has been disappeared along the downstream. In series of straight type spur dikes and especially in the first spur dike of series, the location of the center of horseshoe vortex is so close to the location of shear layer compared to the T-head spur dikes in which the center of horseshoe vortices is pretty much far from the shear layer.

This fact can lead to the increase of interaction between horseshoe vortex and shear layer in series of straight type spur dikes compared to series of T-head spur dikes. This increased interaction would intensify the shear stress in this type of spur dike compared to T-head. This fact is in consistency with the results discussed earlier.

4

Movable Bed Channel Case

4.1 Introduction

Compared to the other restoration structures like bank revetments, and so on, the spur dikes have been documented to be the most durable solution (Shields, Cooper et al. 1995).

Despite the long history of utilizing the spur dikes, there is still lack of knowledge about their effects on river. Even though local scour phenomena near a single spur dike has been discussed by many researchers, as it was shown in Chapter 2, discussions about the overall bed degradation in the main channel and aggradations in the spur dikes regions caused by a series of spur dikes are not sufficient yet.

Usually, spur dikes are installed in a series. The fields between successive spur dikes acts as a dead water zone, where the mean velocities are much smaller compared with the main channel and influences deposition there (Alauddin 2011).

The importance of this study can be highlighted regarding the fact that controlling bank erosion, and/or improving biodiversity are being directly affected by the shapes of these structures. Thus, in this chapter, several sets of experiments were designed and carried out to explore the suitable head shape of spur dikes in order to stabilize the

mainstream flow of a river channel through protecting the bank from erosion at high flood, and improving a diverse habitat for aquatic biota and fauna. Keeping in view the above considerations, the associated sub-objectives are pointed out as follows:

- To investigate flow structure in two types of spur dikes with different head shape in a sand bed channel.
- To study the processes of sediment transport and the variation in bed topography in the regions around the spur dikes.
- To compare the performances of the spur dikes of various head shapes to suggest the suitable one for practical purposes.

4.2 Laboratory Experiments

4.2.1 Experimental Setup

The experiments were carried out in a flume located at the Ujigawa Open Laboratory of Disaster Prevention Research Institute (DPRI), Kyoto University, Japan. The experimental setup consists of a straight rectangular flume with 10.0 m long and 0.8 m wide and 0.28 m

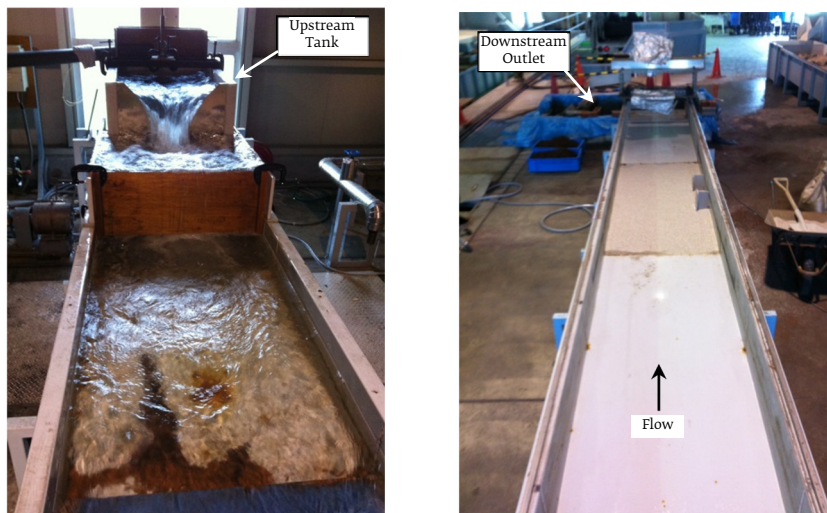


Figure 4-1. Experimental flume; (Left) Flume inlet ;(Right) Flume outlet

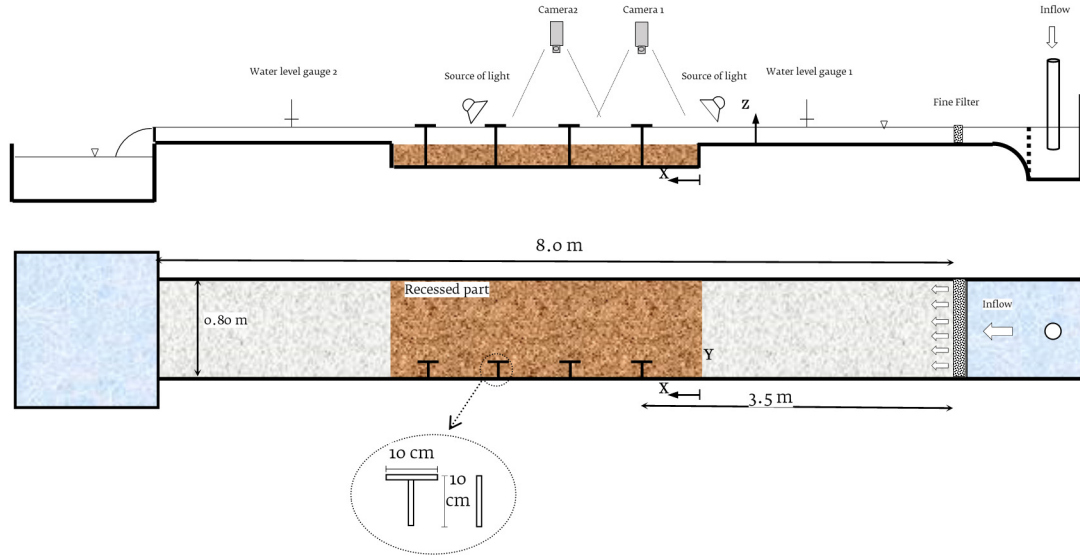


Figure 4-2. Schematic view of experimental setup; side view (top) and top view (bottom)
(not scaled)

deep. A recession area was embedded to the channel with maximum depth of 0.17 m which was applicable for movable case experiments. The bed and side walls of the flume are made of steel painted by color to avoid it from oxidizing and were hydraulically smooth. Uniform quartz sands with a median size $d_{50} = 1.78$ mm covered the recession area of the channel with a thickness of around 17 cm.

The projected length of all spur dikes models (L_s) was 10.0 cm. A set of up to 4 numbers of same spur dikes are placed on left side of the channel perpendicular to the side wall. The axis of the first spur dike was at 50.0 cm downstream from the beginning of the study area (in the recessed part of the channel filled with sand) and 3.50 downstream from inlet boundary which is theoretically sufficient to achieve a fully developed turbulent flow in the study area. The water level in the flume is controlled by a tail steel gate with 0.90 m wide and 0.33 m at the end of the outlet.

Along the experimental flume side walls, a 1.0m long movable steel frame is mounted, which carries the measurements instruments. The experimental facility and its different

parts (inlet and outlet parts, etc) are clearly illustrated in Figure 4-1 and Figure 4-2. In Figure 4-2 the x-axis is the downstream direction with $x = 0$ at the beginning of movable area (study area), y-axis is directing towards the right side in the transverse direction with $y = 0$ at the left-side where the spur dikes are placed; and z starts from the initial bed level with upward positive.

Two types spur dikes are considered in this study with different head shapes. First type was straight shape spur dikes (denoted as “I” in Table 4-1); this is the conventional type of spur dike (Figure 4-3; left). Considering the straight type experiments in current study was mainly to give a reference for comparison of the performance of T-head spur dikes with the typical shape of spur dikes and to investigate the effect of the changing the head-shapes on the impact of the spur dikes on flow structure and sediment transport.

The second type of the spur dike in this study was T-head one (Figure 4-3; right) which was the main focus of the research. As was discussed earlier, this type of spur dike with T-head shape has rarely been studied yet.

Therefore, in this research a two-step study was set up. In the first stage, the effect of opening ratio was investigated by placing the spur dikes with opening ratio (S_s/L_s) of 1, 2, 3, and 5 in different set of experiments as mentioned in Table 4-1.

In Table 4-1, “Q” is discharge of the channel, “ H_w ” denotes the height of the water above the initial flat bed of the channel, “ L_s ” is length of spur dike, “ H_s ” is the height of spur dike

Table 4-1. Movable bed channel experimental cases (Emerged condition)

Case Name	Q (m ³ /s)	H_w (cm)	L_s (cm)	H_s (cm)	S_s	H_w/H_s	S_s/L_s	S_s/H_s
T_SL1_Emg	0.02	6.7	10	8	10	<1	1	1.25
T_SL2_Emg	0.02	6.7	10	8	20	<1	2	2.5
T_SL3_Emg	0.02	6.7	10	8	30	<1	3	3.75
T_SL5_Emg	0.02	6.7	10	8	50	<1	5	6.25
I_SL1_Emg	0.02	6.7	10	8	10	<1	1	1.25
I_SL2_Emg	0.02	6.7	10	8	20	<1	2	2.5
I_SL3_Emg	0.02	6.7	10	8	30	<1	3	3.75
I_SL5_Emg	0.02	6.7	10	8	50	<1	5	6.25

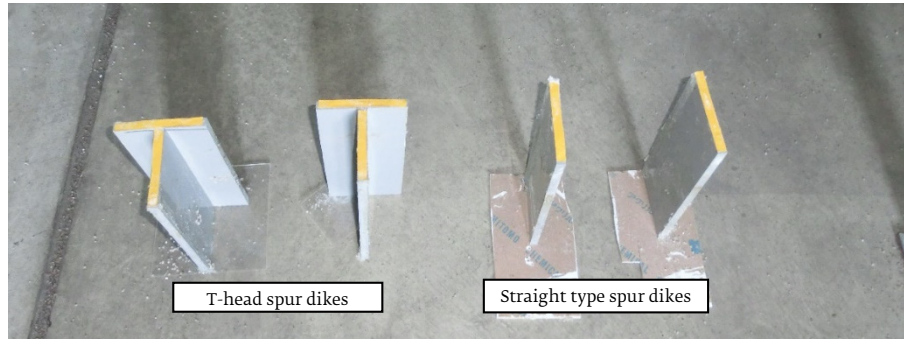


Figure 4-3. (Left) Straight spur dike, and (Right) T-head spur dikes used in the experimental setup

above the initial bed surface, and “ S_s ” represents the spaces between the spur dikes of a series. Later, in the second stage of the research and after shedding light on the effect of changing head-shape on the flow and sediment transport in the channel, several sets of experiments were set up to elaborate the performance of the specific non-typical type of spur dike (T-head shape) under the high water level with different submergence ratios ($H_w/H_s = 1.2, 1.7, \text{ and } 3.4$). As the performance of straight spur dikes in submerged condition was studied quite well by different researchers over the past years (refer to Table 2-3), the main focus of this stage of the research was merely concentrated on the study of T-head shape spur dikes. The details of the carried out experiments in the submerged condition can be seen in Table 4-2.

Table 4-2. Movable bed channel experimental cases (Submerged condition)

Case Name	Q (m ³ /s)	H_w (cm)	L_s (cm)	H_s (cm)	S_s	H_w/H_s	S_s/L_s	S_s/H_s
T_SL2_Sub1.2	0.02	6.7	10	5.5	20	1.2	2	3.6
T_SL3_Sub1.2	0.02	6.7	10	5.5	30	1.2	3	5.5
T_SL5_Sub1.2	0.02	6.7	10	5.5	50	1.2	5	9.1
T_SL2_Sub1.7	0.02	6.7	10	4	20	1.7	2	5
T_SL3_Sub1.7	0.02	6.7	10	4	30	1.7	3	7.5
T_SL5_Sub1.7	0.02	6.7	10	4	50	1.7	5	12.5
T_SL2_Sub3.4	0.02	6.7	10	2	20	3.4	2	10
T_SL3_Sub3.4	0.02	6.7	10	2	30	3.4	3	15
T_SL5_Sub3.4	0.02	6.7	10	2	50	3.4	5	25

4.2.2 Experimental Conditions

The experiments in the channel were conducted under clear-water condition. To meet this condition, the control valve of the pump and the tail gate were adjusted so that the bed shear velocity (u^*) did not exceed the critical shear velocity for initiation of motion of sediment (u^*_c) for the approach flow to avoid bed-forms at upstream of the control reach.

On the other hand, the hydraulic condition was set so that it could provide not very shallow water depth. The final condition was fixed after some trials such that except around the spur dikes, the channel bed was remained unchanged, i.e., the condition of clear- water scouring was met.

Flow uniformity is verified by comparing the free-surface slope and the flume's bed slope. In all cases, the flow discharge (Q) and approach depth (H_w) were maintained fixed. Furthermore, in the first stage of the research, in all tests, the spur dikes were emerged and the Froude number was small enough to ensure sub-critical flow condition.

Moreover, the Reynolds number is maintained high enough to ensure fully developed turbulent flow in the control section. The details of the tests undertaken, including the hydraulic and sediment particles' characteristic are presented in Table 4-3.

Table 4-3. Details of experimental conditions in movable bed experiments

Flow Condition	
Discharge (Q) (m^3/s)	0.02
Channel Slope	1/800
Channel width (B) (cm)	80
Flow depth (H_w) (m)	0.067
Flow Velocity (m/s)	0.37
Shear Velocity (u^*) (m/s)	0.028
Sediment Number	3
Sediment mean diameter (d_{50}) (mm)	1.78
σ_g	1.18
Sediment Density (g/cm^3)	2.65
B/H_w	11.94
Re	24800
Fr	0.46
u^*/u^*_c	0.86

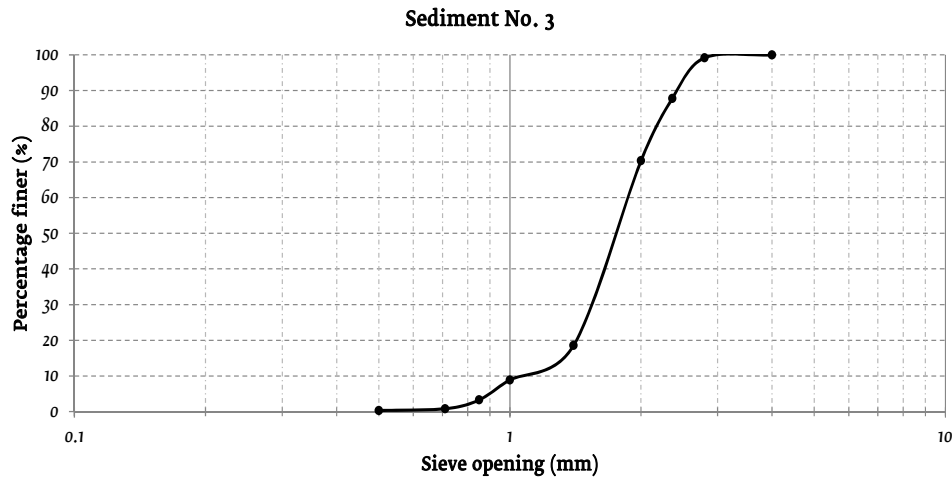


Figure 4-4. Grain size distribution of sediment used in the experiment channel

The Figure 4-4 also shows grain size distribution of sands used in the experiments obtained by sieve analysis.

4.2.3 Model Operation

The flume slope was adjusted on a slope 0.00125 m/m for all experimental cases. A calibrated V-notch weir fitted at the inlet of the flume with a Vernier point gauge (Figure 4-5) with an accuracy of ± 0.5 mm was used to control the inflow discharge. Each experimental case was extended up to 4 hours, which was the necessary time to reach the dynamic equilibrium condition based on a control test case. The control test case was carried out at the very first stage of the study by installation of a series of T-head spur dikes with opening ratio of 2. In that specific case, the maximum scour depth in the scour hole of the first spur dike in series was measured at different time intervals of 5, 10, 15, 20, 25, 30, 45, 60, 90, 120, 180, 240, 300, 360, 420, 480, 540, 600 minutes using the point gauge measurement. Figure 4-6 represents the changes of the ratio of scour hole depth over the maximum scour hole depth around the first spur dike of series in the control test case. As it can be seen, after around 4 hours from the beginning of the experiment, the scour depth was reached to 92 percent of maximum scour hole depth. Thus, the duration of 4 hour was chosen as the equilibrium time for measuring bed features of the channel bed.



Figure 4-5. V-notch weir and Vernier point gauge for controlling water discharge

Basically, the experimental operation followed the identical steps for all cases. The flume was prepared with sediment in the movable area (recessed part of the channel) where the sediment height was 17.0 cm above the channel bottom. The experiments were conducted under uniform flow conditions. The hydraulic parameters adopted for these experiments are given in Table 4-3.

Before starting the experimental run, the flume was slowly filled up with water by a plastic pipe and once the required flow depth was reached, the pump was started to run. Uniform flow condition is established by adjusting the height of tailgate at the end of the flume to desired position. The water pump monitored by a V-notch weir during the experiments which allowed checking the stability of the approach flow. The measurement apparatus are shown in Figure 4-5. During each experiment the level of water surface at different sections of the channel were measured by means of point gauge (Figure 4-7). This allowed verifying that the uniform flow condition was achieved during the experiments.

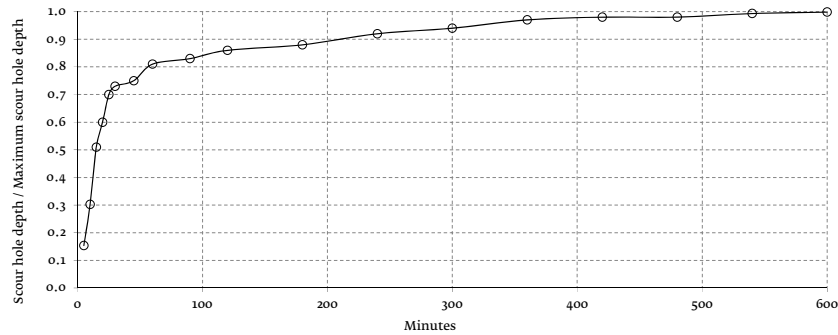


Figure 4-6. Time evolution of the maximum scour depth in the scour hole of the first spur dike of series for the control test case

4.2.4 Measurement Techniques

Several parameters measured during every test: bed profiles, water level, and bed form movement. Table 4-4 provides an overview of the measurements and equipment used during the experiment.

Table 4-4. Summary of measurements and measuring techniques
in movable bed experiments

Measurement	Measuring technique	Positions of measurements	Times of measurements
Water level	Static point measurements	Upstream- Downstream (Variable points)	after equilibrium condition
Surface velocity	LSPIV	Inside the field of spur dikes	after equilibrium condition
Bed features	Laser bed profiler	The whole movable bed area	For all cases: after equilibrium condition - For a specific case: at 5, 10, 15, 20, 25, 30, 45, 60, 90, 120, 180, 240, 300, 360, 420, 480, 540, 600 minutes by point gauge measurement
Bed-form migration	DSLR camera	Inside the field of spur dikes and in the interface region	Continuously during the all experiments



Figure 4-7. The Vernier point gauge used for measuring the water level in different cross sections along the channel.

Just after the beginning of the experiments and over the time of running the experiment, the bed-form migration was captured using two DSLR cameras mounted above the study area. Consequently, after reaching to the equilibrium state and just before turning off the pump, the LSPIV measurement was carried out for each case. Finally, after turning off the pump, the flow discharge was slowly reduced to zero. Having carefully drained the water out from the flume, scour depths at different cross-sections were measured by a laser bed profiler as will be described in detail in the following section.

LSPIV

Particle Image Velocimetry (PIV) is an efficient and powerful technique for measuring instantaneous velocity vector in a cross-section of a flow. For field measurements with large-scale flows, an extension of PIV, the LSPIV (Large-Scale Particle Image Velocimetry) is usually used. In hydraulic engineering, this technique has been applied for surface velocity measurements of water in very uniform flow fields as well as spur dikes experiments (Teraguchi 2011).

A digital video camera was used to record the images. The video camera was fixed above the flume covering an area of 2.0m (in flow direction) by 80cm (in transverse direction), where the spur dikes are located. The recorded images were transformed to remove



Figure 4-8. Set of laser displacement sensor used for measuring the final bed deformation

perspective distortion from the objective lens and then processed using PIV software. Further details of this technique can be found in Section 3.2.2.

Laser Bed Profiler

The Laser bed profiler (Keyence – LK 2500) was used to measure the final equilibrium bed deformation after each experiment for all cases (Figure 4-8). This equipment consists on a controller and a sensor head that measures the distance of one point of a bed surface to the laser displacement through a sensor installed to capture the time interval for this laser beam go and return to the source place. The output data of bed level measurements are analogical voltage values that are saved in a Personal Computer using a data collection system (A/D conversion card – Keyence NR-110 and data logger software). Then this voltage is converted into level values and the final data can be achieved. Before the bed level measurement a calibration of equipment, using 4 cylindrical steel pieces with pre-defined thickness as reference levels are used to determine the relation between the voltage registered by the equipment and the measured bed level.

For each experimental cases this calibration results is different. The bed level measurements were realized after the bed was completely dried out due to the presence of water in the eroded places could cause measurements errors (Teraguchi 2011).

For each experiment a total 200 cm reach of the channel in the movable bed area of the

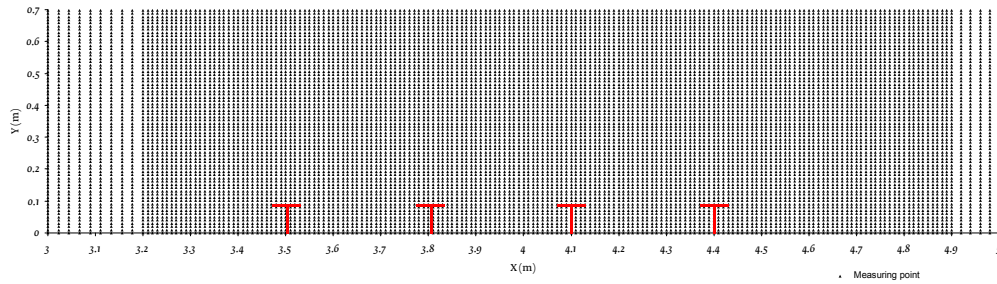


Figure 4-9 .Representation of measuring points for a case of T-head spur dikes with opening ratios of 2.0, captured by Laser Bed Profiler

flume was measured. In all cases, from the beginning section of the study area up to 20cm downstream, measurement was done with 2cm interval. From this point on to the 50 cm downstream of the last spur dike in stream, the measurement was carried out with interval of 1 cm. For the rest of the movable bed area of the channel, measurement was done with 1 cm interval. Figure 4-9 shows a representation of measuring points for a case of T-head spur dikes with opening ratios of 2.

Bed Form Migration

The area between spur dikes was continuously monitored using two standard DSLR cameras (Nikon D5000 and D5100). The cameras stored the images in memory card and were controlled by their own internal software for timing and interval shooting. The recording lasted for about 3 hours from the beginning of the experiment at a rate of 0.1 Hz (one frame per 10 seconds).

4.2.5 Experimental Results

4.2.5.1 Effect of Opening Ratio on Equilibrium Bed Variations Due to Series of Spur Dikes

Figure 4-11 and Figure 4-12 show the bed deformation of the series of spur dikes with T-head shapes and straight type with different opening ratio ($1L_s$, $2L_s$, $3L_s$, and $5L_s$).



Figure 4-10. The scaffold mounted for holding the digital cameras (right photo) which were used for monitoring bed form migration

In T-head spur dikes, the opening ration is from the downstream tip of one spur dike to the most upstream tip of the next sour dike in series. Comparing the different open ratio between these two head shapes firstly shows the considerable effect of the head shape on the bed changes.

In all Opening Ratio (OR), the overall pattern of the bed is quite different. In $OR=1$ and 2, in the series of T-head shape spur dikes, the presence of the wing of the spur dikes, made a sort of uniform pattern alongside of the spur dikes' field. While in straight type the changes has been formed right away from the banks of the channel. In other words, in T-head spur dikes, the presence of wing was able to prevent the extension of scour hole inside the spur dike's field.

In T-head spur dikes, in $OR=1$, in the first field of the spur dikes, a very limited point bar has been formed. At $OR=2$, this point bar has started moving to upstream and near the center of the spur dikes' field. By increasing the OR to 3 and not only the form, but also the location of this point bar has been fixed and furthermore, the volume and its dimensions have been started to expanding.

This trend in straight type, however, has a significant difference. Comparing different OR in straight type shows a lag in similar behavior compared to the series of T-head spur dikes. In other words, while the formation of point bar in the first field of T-shape spur dikes,

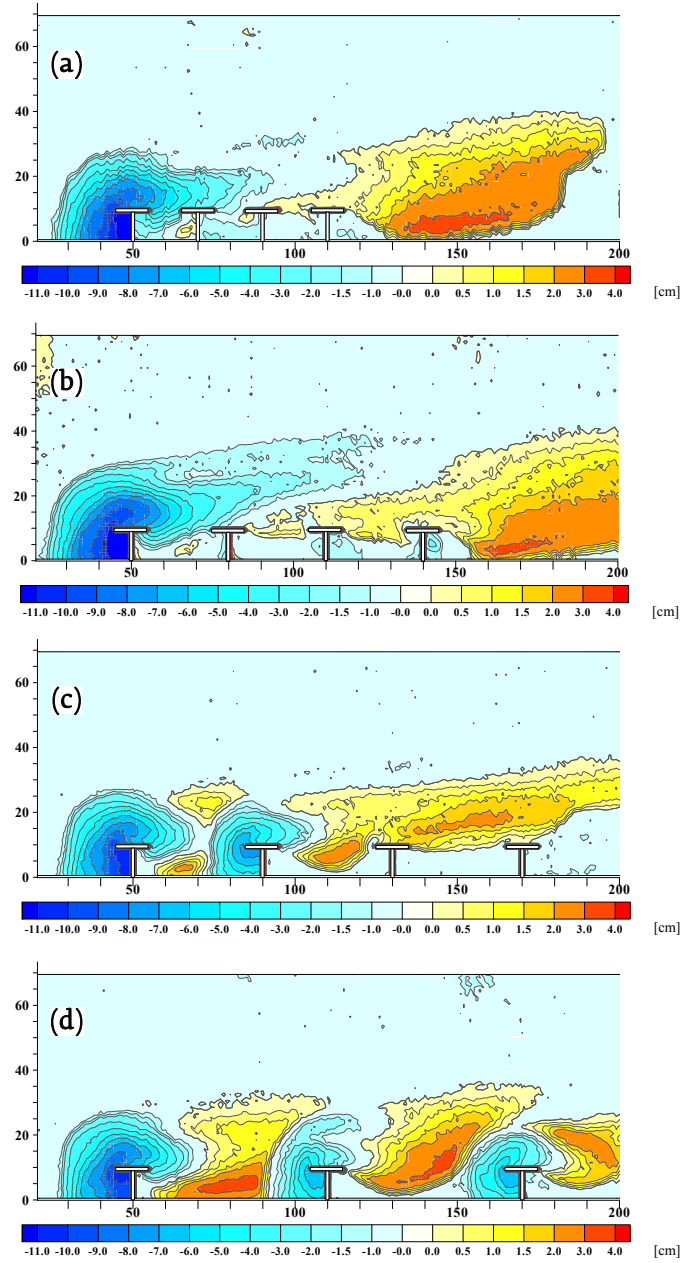


Figure 4-11. Equilibrium bed levels in a series of T-head spur dikes

(a) $S_s/L_s = 1$ (b) $S_s/L_s = 2$ (c) $S_s/L_s = 3$ (d) $S_s/L_s = 5$

All cases are emerged ($H_w/H_s < 1$)

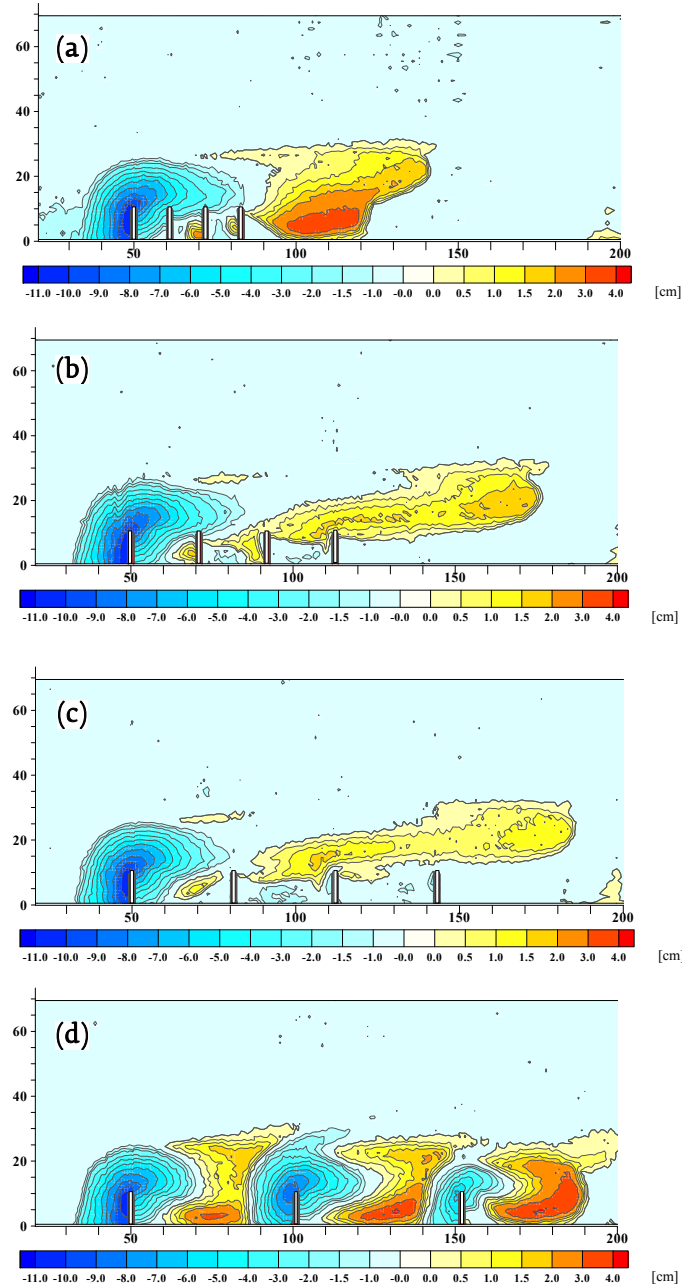


Figure 4-12. Equilibrium bed levels in a series of straight spur dikes

(a) $S_s/L_s = 1$ (b) $S_s/L_s = 2$ (c) $S_s/L_s = 3$ (d) $S_s/L_s = 5$

All cases are emerged ($H_w/H_s < 1$)

was started from OR=1 and then moved to the upstream at OR=2 and expanding from OR=3, in straight type spur dikes this trend has been observed from OR=2 (instead of OR=1).

The first implication of this difference, highlight the less effect of the opening ratios of the interface between the field and main channel on the formation of channel bed inside the field. Simply speaking, regardless of opening ratios in the interface of field and main channel, the distance between the main bodies of spur dikes has particular and clear effect on the pattern of bed changes in the series.

Comparing the second field in these two different series of spur dikes, but reveals the crucial rule of the head shape on the pattern of bed inside and in front of the field. In T-head spur dikes, before OR=3, there is no significant changes inside the field and it is just after OR=3 in which a visible point bar was formed between second and third spur dikes. While in the straight type spur dikes, the formation of point bar was started from OR=1.

The third field in the series of spur dike can be considered as a region in which there was enough length after the first spur dike in series to form a uniform flow in front of the spur dikes' field. In this particular field, in T-head spur dikes, up to OR=3, the presence of the wing has led to a uniform area alongside the field. It was just after OR=3 (OR=5 indeed), in which by increasing the OR, the flow had enough spaced to intrude to inside the spur dike's field and the wings of the spur dike were not able to prevent the formation of the point bar. In straight type spur dikes, this trend is somehow similar but with a lag in OR.

In general, the first result of this comparison highlights the particular rule of the wing in the control of sediment transport in the first and second spur dike's fields. These two fields are those ones in which the uniformity of flow has not still been formed. On the contrary, in the third field in which there was enough length to get to uniformity of flow after the installation of the first spur dikes in the upstream, this rule was relatively faded.

In OR=5, but since the spaces between spur dikes was so far, the effect of the head shape has been rather local and the general pattern of the bed changes inside the fields and alongside the interface between the fields and main channel has been rather analogous in T-type and straight type.

To put in a nutshell, it was shown that up to $OR=5$, the presence of the wing in T-head spur dikes has significant effect, specifically in the first and second spur dikes' fields. In the third field in series, however, the role of the wing was rather less important and was limited to form a uniform pattern alongside the interfaces of the field and main channel. In OR greater than 3, since the flow has enough space to intrude into the field completely, the role of head shape on the general pattern of bed variation inside the spur dikes' fields was rather local and limited.

4.2.5.2 Effect of Submergence on Equilibrium Bed Variations Due to Series of Spur Dikes

Figure 4-13 shows the equilibrium bed levels in series of T-head spur dikes with different submergence ratios. Three submergence ratios were chosen. The ratio=1.2 which denotes the boundary overflow above the spur dikes, ratio=1.7 which represents the condition of relatively high water level and ratio=3.4 which presents the condition of fully flooding in channel.

Having reviewed this figure, it clearly turns out that by increasing the overtopping ratio the general pattern of bed changes has noticeably been affected. In fact, by occurrence of overflowing, the features of bed changes have been growing less and less. This is obviously due to the fact that by increasing the water level the effect of flow on spur dikes will decrease and in other word the spur dikes can only act as local roughness element on the channel bed. Apart from this general change, there are several other interesting points. Looking into Figure 4-13 (b) reveals that by turning the spur dikes submerged, the general features of bed (such as local scour around second and third spur dikes (in opening ratio of 5) and sediment depositions in second spur dikes' field) have been significantly faded. Nonetheless, in the first spur dikes' field (between the first and second spur dikes) the amount and general extension of point bar has been remarkably increased.

This phenomenon can be due to this fact that in such a case in which the spur dikes are under a boundary overflow, the body of structure will acts as a weir and in the area just

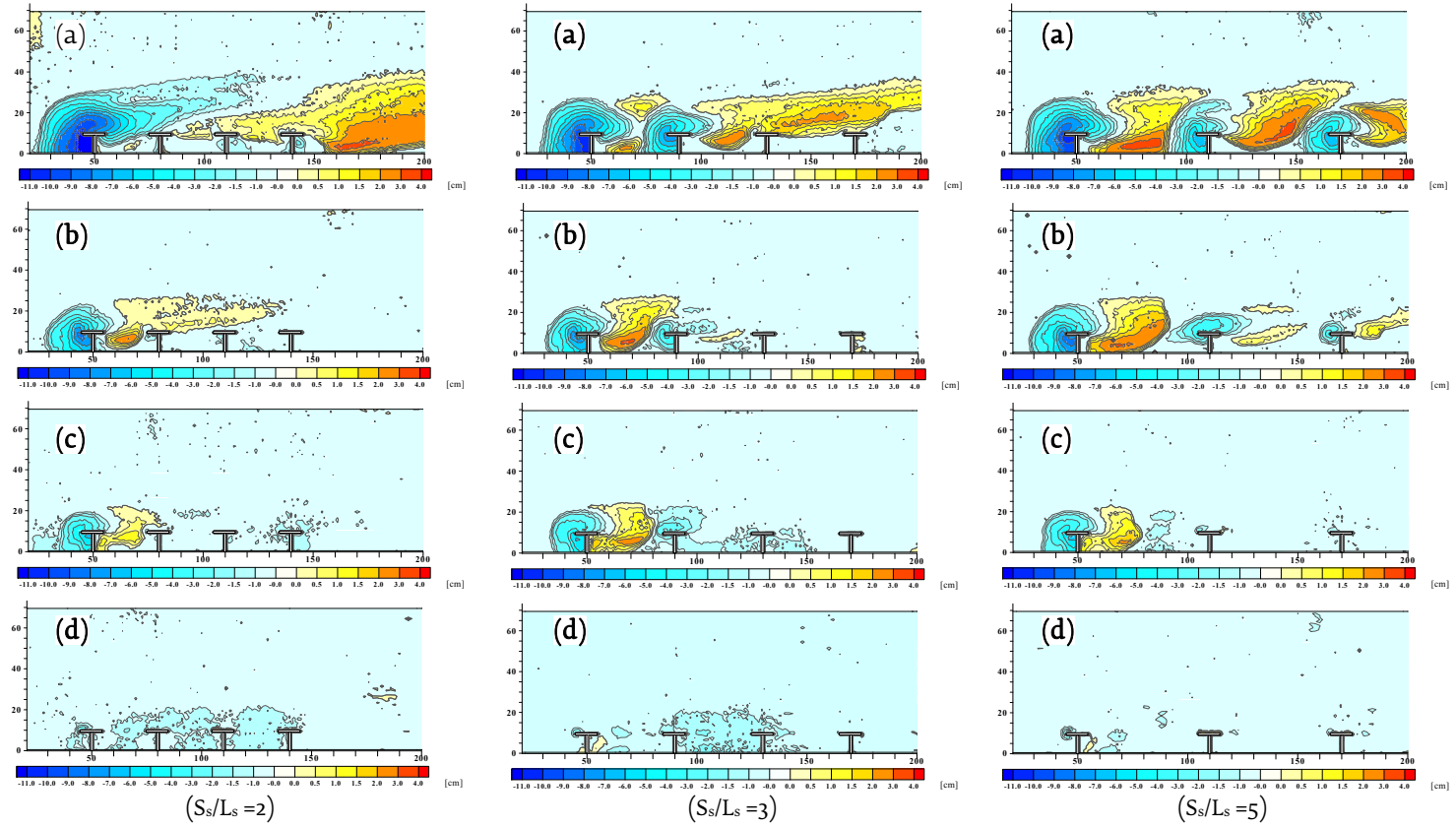


Figure 4-13. Equilibrium bed levels in a series of T-head spur dikes with different submergence ratios

(a) $H_w/H_s < 1$ (b) $H_w/H_s = 1.2$ (c) $H_w/H_s = 1.7$ (d) $H_w/H_s = 3.4$

behind the first spur dike, a relatively strong jet flow will emerged which can lead to deposition of sediment particles in this region.

Figure 4-13 (c) shows the condition of overtopping ratio of 1.7, which means the flow has flooded the spur dikes. In this case, in addition to general decay of bed features due to submergence of spur dikes (as discussed earlier), the point bar in first spur dikes' field (between first and second spur dikes) which had been formed in submergence ratio of 1.2, has been also affected and begun to decay. Here, however, the interesting point is that along with this decay, the remained of this point bar has been extended toward the area confined between downstream wing and the body of first spur dike. This extension of deposition to this area has not been observed in another cases (even in emerged cases). In addition, this occurrence had been taken place in all opening ratios. The probable reason for this phenomenon is likely due to formation of very stagnant flow in that region in condition of comparatively fully flooded.

At overtopping ratio of 3.4 in which the spur dikes are completely flooded in a very high level water, the effects of spur dikes on the channel bed has been negligible. In fact at this condition the amount of water level has been so high that the spur dikes were just as local roughness elements and was not any notable influence on bed level.

4.3 3D Numerical Modeling of Sediment Transport

4.3.1 Introduction

The simulation of sedimentation and erosion processes in fluvial environment and modelling the time dependent changes of riverbed is of great interest among the river engineering research topics. Over the past decades and along with the ever-increasing growing of computational capacities, the attentions to utilization of numerical models as strong tools in study of such processes has been tremendously rising. Although there are good numbers of researches on computing the flow structure and sediment transport in channels and natural streams, due to the high complexity of 3D turbulent flow and various

morphodynamic processes involved in such problems, there is still strong concern about improvement and development of hydro-morphodynamic models capable of simulate different sediment transport problems in rivers. On the other hand, due to the heavy computational demand required for multi-dimensional modeling of such problems, the large numbers of available numerical models in this field have been confined in academia and there is still considerable interest to verify the applicability of such models in river engineering problems.

In this section, the simulation of sediment transport and its associated transient bed deformation using the numerical model aims to deliver information about the spatial and temporal distributions of habitat variables (depth and flow velocity distributions, and distribution of erosion and sedimentation) to describe the abiotic habitat conditions. The simulated test cases were laboratory studies described in Section 4.2.

4.3.2 Governing Equation for Sediment Transport Modeling

Particles of sediment can be transported in two main transport modes: suspension and bed load. Hunter-Rouse proposed an equation (Eq. (4-1)) to define if the particle transports in suspension or bed load mode:

$$z = \frac{w}{\kappa u_*} \quad (4-1)$$

in which w is the particle fall velocity, κ is a constant and assumed as 0.4 and u_* denotes the shear velocity of flow. If the Eq. (4-1) is larger than 1, the particle is chiefly moved as bed load. In other words, in this case, the fall velocity is larger than the force due to the turbulence and it prevents the sediment particle from suspending in flow. On the other hand, if the Hunter-Rouse equation gives value of less than 1, this means that the particles are transported in suspension mode.

4.3.2.1 Bed Load Calculation

The amount of bed load was calculated by van Rijn (1984)'s equation as follows:

$$\frac{q_{bed}}{d^{1.5} \sqrt{\frac{g(\rho_s - \rho_w)}{\rho_s}}} = 0.053 \frac{T_i^{1.50}}{D_*^{0.3}} \quad (4-2)$$

in which T_i is the transport parameter defined as:

$$T_i = \left(\frac{\tau - \tau_{crit}}{\tau_{crit}} \right)^{1.50} \quad (4-3)$$

and D_* the particle parameter is:

$$D_* = d \left(\frac{(\rho_s / \rho_w - 1)g}{g^2} \right)^{1/3} \quad (4-4)$$

The mass q_{bed} from Eq. (4-2) can be converted to concentration using Eq. (4-5):

$$c_{bed, bed\ load} = \frac{q_{bed}}{aU_{bed}} \quad (4-5)$$

in which a is a reference height assumed to half the height of the first cell close the bed and U_{bed} is the velocity in the first cell close to the bed. The boundary conditions for computations of sediment transport are arbitrary value at the upstream boundary defined by user and zero gradients for the outlet and the walls.

The bed changes are computed from the deficit between the inflowing and outflowing sediment fluxes assuming validity of sediment continuity for the bed cell. The volume of the erosion and/or deposition, then, will be calculated for each time step based on vertical bed elevation which is obtained by dividing the difference between the inflowing and outflowing sediment fluxes by the submerged density of the sediments (1320 kg/m^3).

4.3.2.2 Moving Direction of Sediment Particles

In the case of erosion around spur dikes, the direction of moving a sediment particle might be different from the direction of the bed shear stress. So far, several attempts have been made to calculate the transverse bed load transport. In current study, the equation of Engelund (1981) was utilized. In this equation, the drag force was considered a function of the relative flow velocity, i.e. the longitudinal drag on a sediment particle was balanced by both the friction and the lift force (Ruther 2006). Accordingly, the deviation angle Ψ between direction of the sediment transport and the direction of flow near bed can be calculated as:

$$\tan \psi = \frac{0.6}{\sqrt{\theta}} \frac{\partial z}{\partial n} \quad (4-6)$$

in which $\frac{\partial z}{\partial n}$ is the transverse slope of the channel bed, z is the bed elevation and n represents the radial coordinate. θ is defined as:

$$\theta = 0.4\theta^2 + 0.06 \quad (4-7)$$

4.3.2.3 Effect of Sloping Bed

In scour hole around spur dikes, the slope of bed is likely to become very steep. Then the incipient motion of sediment particles is not only a function of hydrodynamic forces, but also additional gravity and tractive components must be taken into account to correct the critical shear stress obtained from the Shields graph (τ_0) (Bihs and Olsen 2011).

In current study, two different equations were adopted in order to consider the effect of sloping bed on the reduction of the critical bed shear stress. In both relations, the reduction factor (r) is calculated. The reduction factor (r) is used to give the modified critical shear stress (τ_c) using the multiplying with the initial critical shear stress (τ_0):

$$\tau_c = r \cdot \tau_0 \quad (4-8)$$

Lane (1955) proposed a relation for calculating r in which he considered solely the effect of side slopes. Precisely speaking, in his relation, he only used the angle perpendicular to the flow direction, and the transversal angle α and on the other hand, the angle in flow direction, and the longitudinal angle θ were assumed as zero:

$$r = \sqrt{1 - \frac{\tan^2 \alpha}{\tan^2 \varphi}} \quad (4-9)$$

Dey (2001) proposed another empirical expression for consideration of effect of bed slope on reduction of critical shear stress. The advantage of Dey's formula was that he incorporated both the transverse angle α and the longitudinal angle θ in the equation of reduction factor:

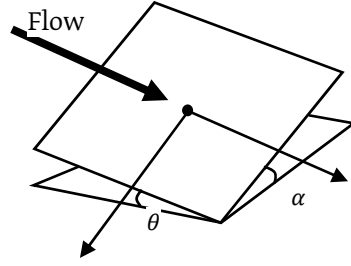


Figure 4-14. Longitudinal and transversal angles on a sloping bed cell
(Bihs and Olsen 2011)

$$r = 0.954 \left(1 - \frac{\theta}{\varphi}\right)^{0.745} \left(1 - \frac{\alpha}{\varphi}\right)^{0.372} \quad (4-10)$$

4.3.3 Model Input

For modeling, according to the details of experiments in Sections 4.2.2 and 4.2.3, numerical domain was prepared for a 8 m long, 0.8 m wide straight flume, in which a false floor was set in the flume with a recess of 2.0 m long and 0.17 m deep. The first spur dike of series with a length of 0.1 m was located at 50 cm downstream of the recess. A discharge of 20 lit/s was used at the upstream boundary and the downstream normal depth was fixed to 6.7 cm. The mean diameter of particles was also applied as 1.78 mm.

One of the most important and time-consuming part of numerical modeling is preparing an appropriate grid network. In that regard, a non-uniform grid was used in which the sizes of grids near the bodies of spur dikes were finer than the regions far from the spur dikes. The grid was made up of 468*80*10 cells in longitudinal, cross sectional and vertical directions respectively. For preparing the mesh, the size of cells was adjusted so that the required criteria such as y^+ criterion ($y^+ = \frac{U^*y}{\vartheta}$ in which y is the distance of the center of the cell located in the fully turbulent region from the wall, U^* is the shear velocity, and ϑ is kinematic viscosity equals to 10^{-6}) near the walls and bed was checked to avoid the instability in the results. A computer with a 3.2 GHz processor (4 cores) was used to run the numerical models.

4.3.4 Verification

Three sets of experimental cases with opening ratios of 1, 3 and 5 were selected for verification of the modeling. All sets were carried out at Ujigawa Open Laboratory of Kyoto University. The further details of experiment can be found in Sections 4.2.2 and 4.2.3. The numerical domain was set up according to the Section 4.3.5. To solve the governing 3-D RANS equations, the standard $k-\epsilon$ turbulence model was used to solve the turbulent stresses in the Reynolds averaged equations. Since in such cases the changes of water surface around the structure are considerable and cannot be neglected, in this study the water surface calculation was also applied in order to incorporate fully 3D turbulent modeling and free-surface flow.

The cases with opening ratios of 1, 3 and 5 were considered respectively, in this way that the modeling begun with the case with opening ratio of 1 and if the results was in fair agreement with experimental data the modeling with similar configuration was utilized for cases with opening ratios of 3 and 5 separately. In case the numerical results for latter two cases were not satisfactory, the configuration and/or numerical approaches were changed in order to attain the better results.

For discretization of convection terms in RANS equations two approaches of second order upwind (SOU) and power law (POW) were available as they were discussed in Section 3.3.3. In addition, since the observations of experimental results had turned out the bed slope in areas such as scour holes was relatively large choosing an appropriate formula for reduction of the critical bed shear stress of particles on a sloping bed was of great importance.

The modeling was started for case with opening ratio of 1. The POW approach was chosen for discretization method and Lane (1955) formula (Eq.(4-9)) was taken for reduction of critical bed shear stress. The results of numerical simulation are illustrated in Figure 4-15. As it can be seen, the results are in fair agreement with experimental data. Almost all features including the scour hole and its pattern of extension, as well as the big point bar downstream of last spur dike near the channel bank was modeled pretty well.

In the next step, the same numerical configurations were used to model the cases with

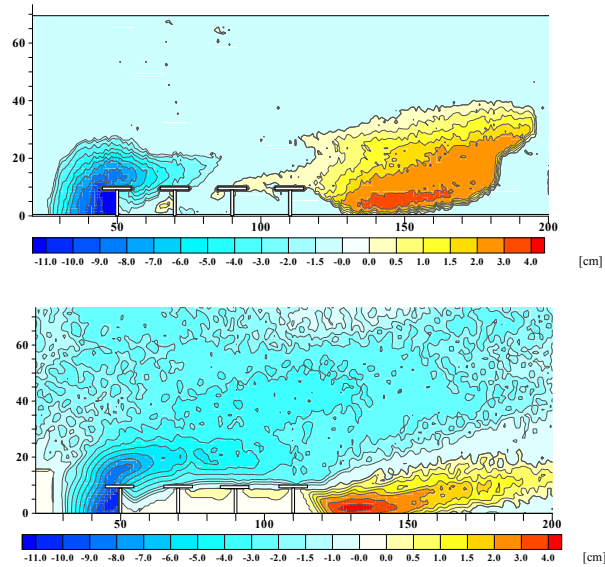


Figure 4-15. The comparison between experimental data (above) and numerical result (below) for cases with $S_b/L_s=1$. (POW, Lane (1955)'s formula were used)

opening ratios of 3 and 5 respectively. Figure 4-16 shows the outputs of the models. In these cases, apart from the features which were visible in first case, the appearance of scour holes for spur dikes other than the first one and the development of point bars inside and/or in front of the spur dikes' fields were of great importance to address. This figure turns out that the models were unable to reproduce both these features. Specifically, the scour holes of second and third spur dikes were almost failed to be modeled.

Consequently, it was tried to change the approach for discretization of convection term in RANS models from POW to SOU and the formula for reduction of critical bed shear stress from Lane (1955) to Dey (2001) (Eq. (4-10)). In this step, the study was limited on cases with opening ratios of 1, 3 and if the results were acceptable the modeling would go on in cases with opening ratio of 5. Then the attempt was specially made to reproduce the scour hole of second spur dike.

Figure 4-17 shows the results of the modeling with new approaches for discretization of convection term in RANS models as well as the new formula for reduction of critical bed shear stress.

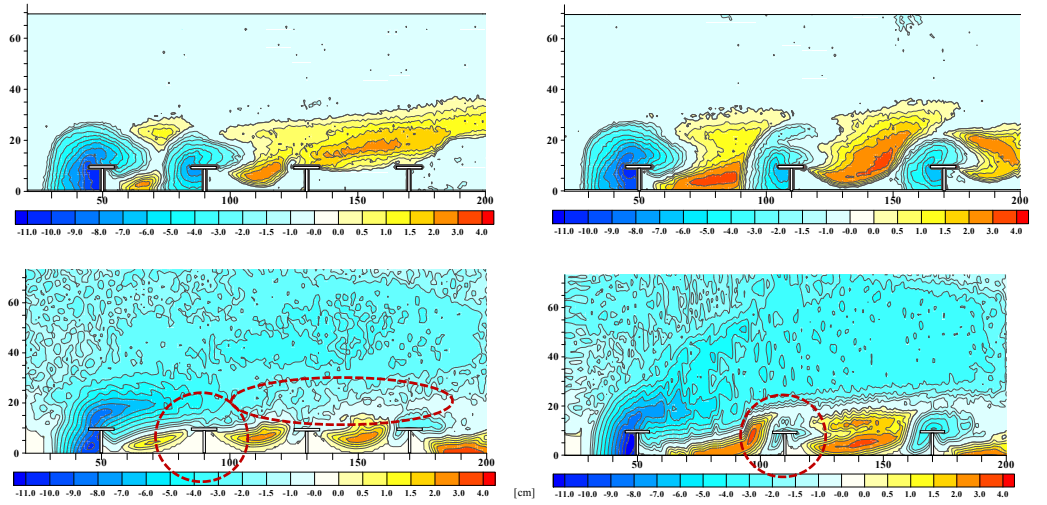


Figure 4-16. The comparison between experimental data (above) and numerical results (below) for cases with $S_s/L_s = 3$ (left) and $S_s/L_s = 5$ (right). (POW, Lane (1955)'s formula were used)

As can be seen in Figure 4-17 (right), this approaches all were successful to model the feature of cases with opening ratio of 1 (as it was in the previous stage). However, in modeling the case with opening ratio of 5, all methods were unable to reproduce the second scour hole. In the next step, another attempt was made by refining the mesh, especially in the area between first and second spur dikes. To do so, a new mesh was made in which the size of grid was decreased from 1 cm to an average value of 3 mm for the aforementioned area between first and second spur dikes (Figure 4-18).

The results of modeling for different numerical approaches are shown in Figure 4-19. The figure obviously shows that in case of deploying second order upwind (SOU) along with using Dey's empirical formula in a fine mesh for critical areas the model was relatively able to reproduce the second scour hole of the series of spur dikes. However, there are several deficiencies in the results. The shortage in quality of pattern of scour hole in plan (lack of proper extension of second scour hole toward the bank), and the occurrence of scouring for

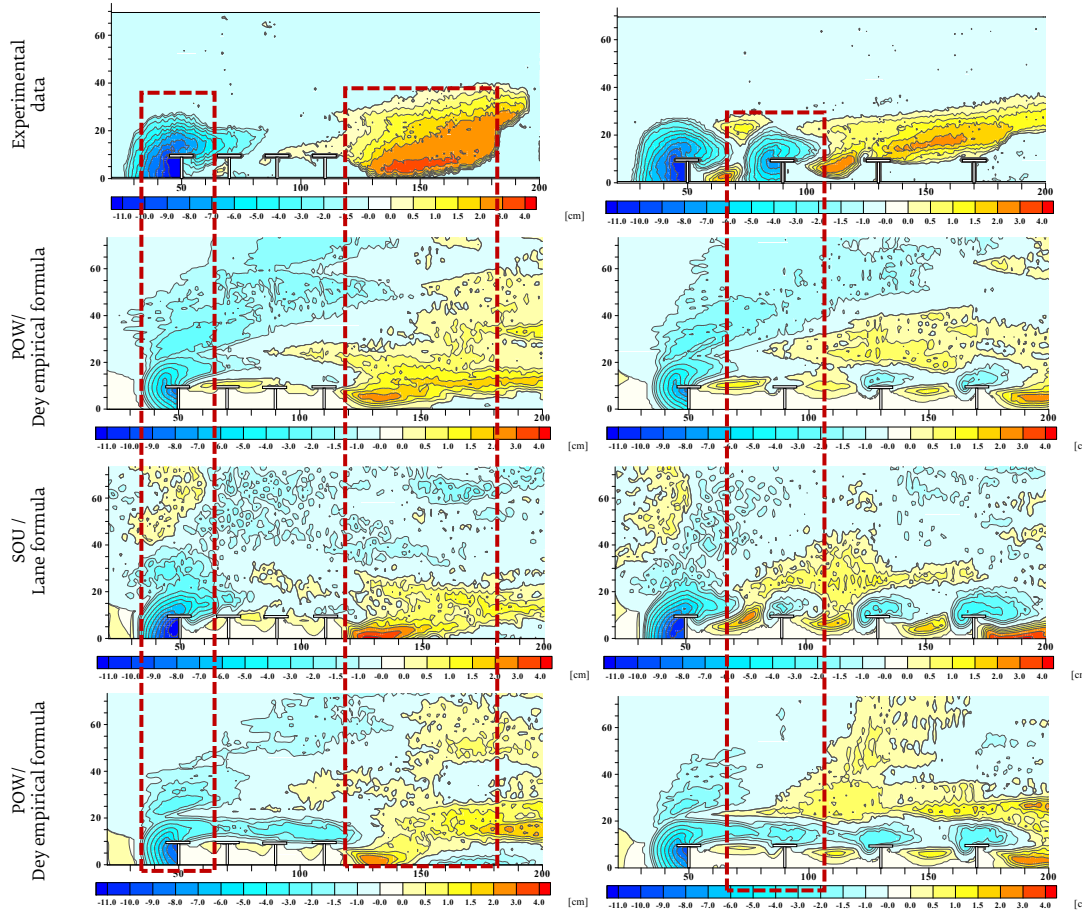


Figure 4-17. The comparison between experimental data and numerical results for cases with $S_s/L_s = 1$ (left) and $S_s/L_s = 3$ (right); different numerical approaches were used.

third and fourth spur dikes of series unlike the observation in experimental data are of most significance issues.

In order to solve these issues and to improve the results many trials and errors were done to achieve better results. Having examined the residuals of RANS equations, k and e , it turned out that the residuals for k and e are quite high. Then the relaxation factors were lowered to get over this problem. Figure 4-20 shows the results of modeling after lowering the relaxation factors.

As can be seen in this figure, the scour hole of second spur dike has been modeled pretty much well. The pattern of its extension has been improved quite well. In addition, the problem of occurrence of scouring in third and fourth spur dikes has been solved. In terms

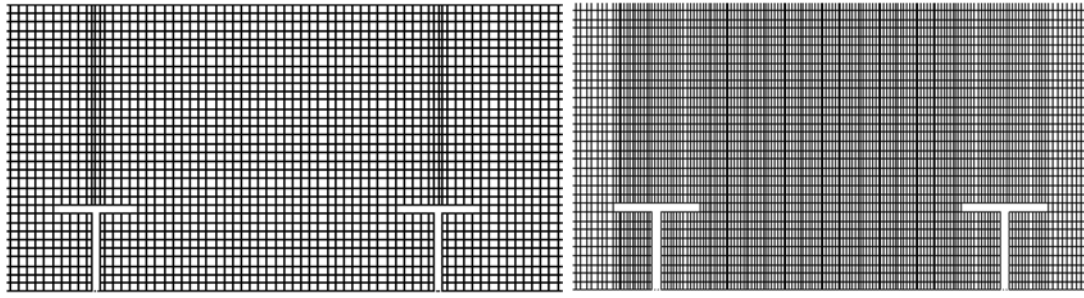


Figure 4-18. The old (left) and new fine mesh (right) deployed for the area between first and second spur dikes

of the deposition area in front of spur dikes' field (between third and fourth spur dikes) the results are comparatively acceptable. The only major shortage in numerical results is in presence of a moderately large deposition area in main channel. In observation of experiment, the main channel was eroded thoroughly and this shows an inconsistency with numerical results.

In following, it was tried to adjust the model to resolve the latter discrepancy by doubling the number of computational mesh in transverse direction from 1 cm to 0.5 cm, changing the bed roughness from 6d₅₀ to 10 d₅₀. Nevertheless, no major improvement was observed (Figure 4-21).

In following, it was tried to adjust the model to resolve the latter discrepancy by doubling the number of computational mesh in transverse direction from 1 cm to 0.5 cm, changing the bed roughness from 6d₅₀ to 10 d₅₀. Nevertheless, no major improvement was observed (Figure 4-21).

However this shortage in numerical model is present, as the focus of the current study is study of implication of spur dikes, and as to experimental observation (and given the clear water condition that was applied in experiment runs) that implication mainly is limited to the area around the spur dikes, the results of numerical models for reproduction of features due to installation of spur dikes are in fair agreement with experimental data.

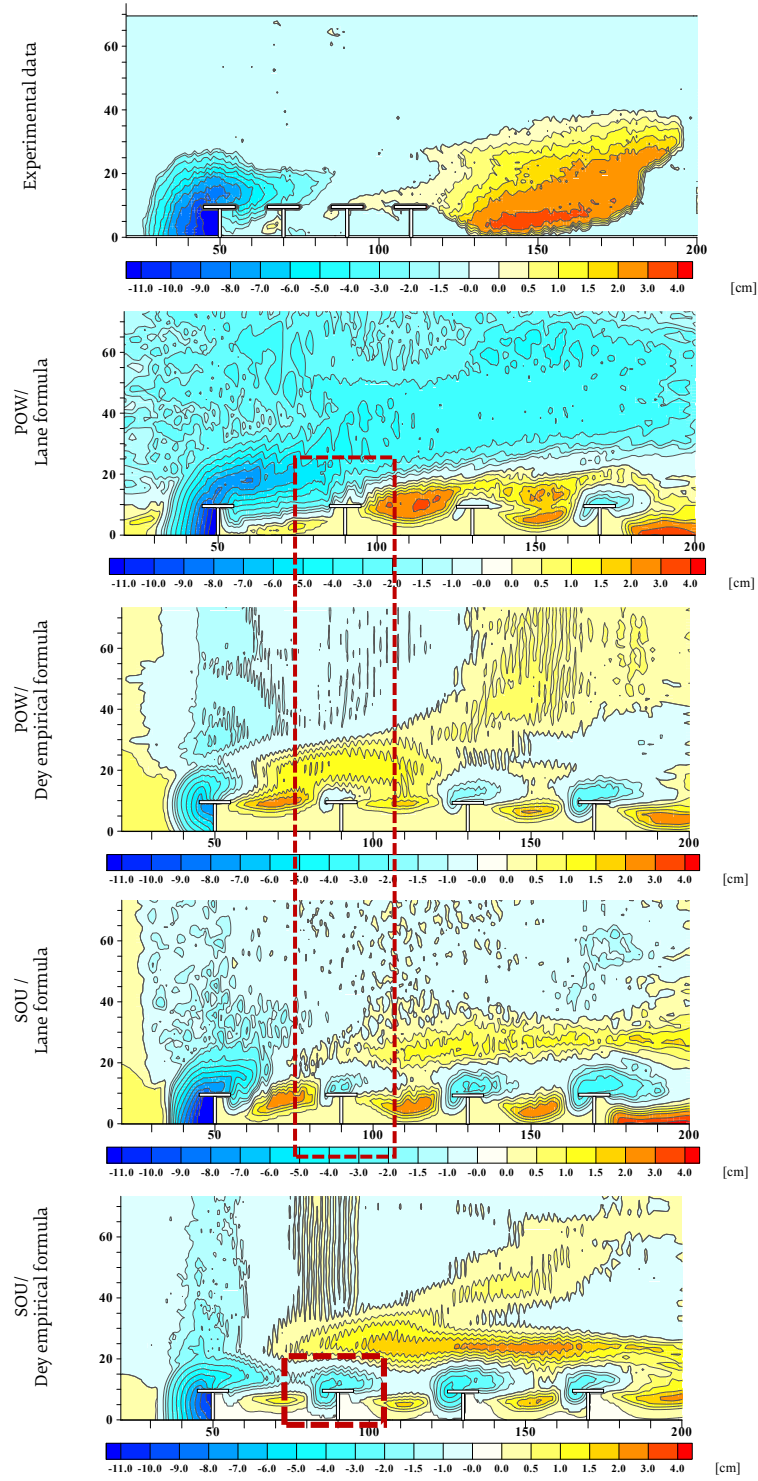


Figure 4-19. The comparison between experimental data and numerical results for case with $S_b/L_s = 3$ modeled in fine mesh

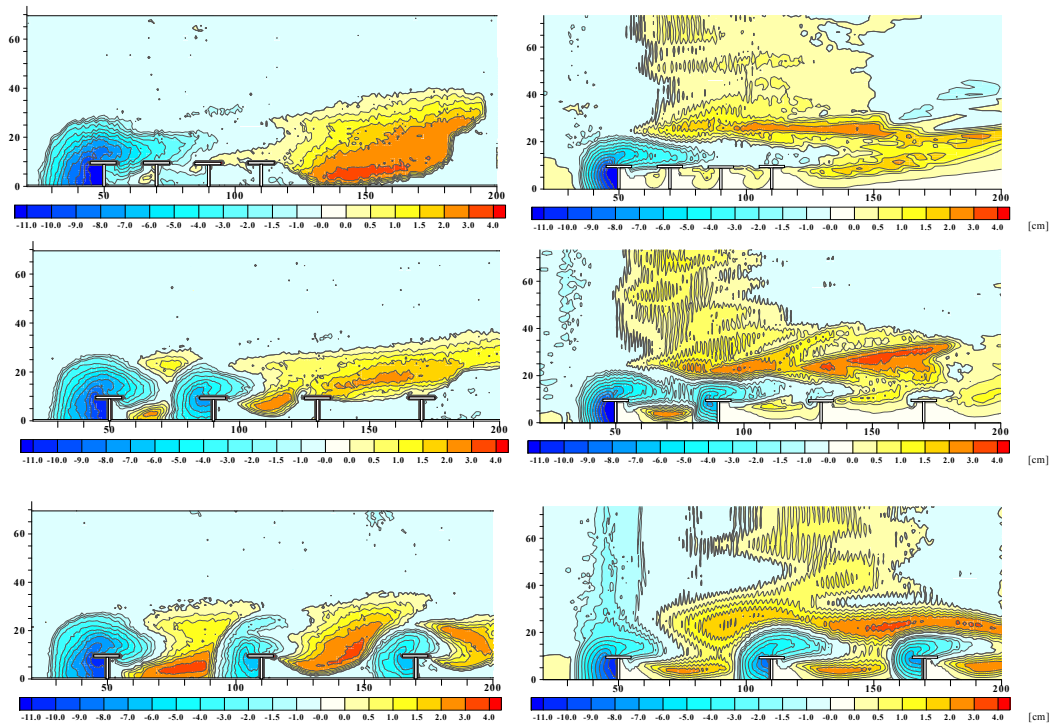


Figure 4-20. Final numerical results for case with $S_s/L_s=1$ (above), $S_s/L_s=3$ (middle) and $S_s/L_s=5$ (below)

(Right column: experimental data; left column: numerical results)

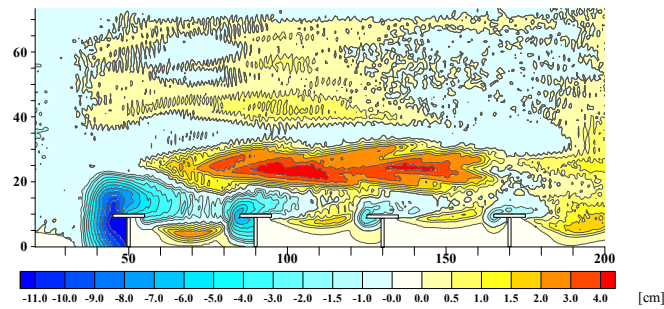


Figure 4-21. Numerical results for case with $S_s/L_s=3$ modeled in a finer mesh produced by doubling the number of transverse cells

Figure 4-20 also shows the results of same numerical configuration for experimental cases with opening ratios of 1 and 5. Having looked into that figure, it is clear that the model was able to simulate those cases with fine agreement as well.

4.4 Analysis and Discussion

In-stream habitat structures such as dams, spur dikes (or deflectors), and cover structures have been used extensively in restoration projects to create pool habitat for fish (Biron, Robson et al. 2004). A popular structure for providing habitat is spur dike. The optimum design for these structures should consider two main parameters (Kuhnle and Alonso 1999):

- (1) Maximizing benefits to aquatic habitat, and
- (2) Minimizing shear stress at the banks to reduce potential bank erosion.

In this section, our objectives were to examine how the head shape of spur dikes, as well as submergence ratio, affect fish habitat and the potential for bank erosion.

4.4.1.1 The Potential for Bank Erosion

As it was noted earlier in Chapter 1, the most common purpose of installation of spur dikes in rivers is to prevent the erosion and collapsing of a bank especially during the floods. In addition, in case of installation of spur dikes in series, recirculation gyres form between spur dikes and consequently it is very important to design series of spur dikes with proper intervals to ensure the security of channel bank as the strong reverse flow may cause erosion of bank.

Apart from the direct negative effect of bank erosion on collapsing the sides of rivers, the stream bank erosion has another side ecological impact by which it can degrade in-stream aquatic habitats by increasing the sediment load in rivers and changing the physical features of habitats and their functions. When this happens, the river loses its capability to transport its sediment that causes it to become wide and shallow. Once these changes begin the stream channel can become braided, quality habitat is lost and the increased sediment can reduce overall biological productivity ((USDA) 2012).

To assess the “potential bank erosion” in current study, a method of Kuhnle, Alonso et al. (2002) was adopted in which they quantified the “potential bank erosion” by calculating the volume per unit length of scour below the initial bed surface in a 0.01-m-wide transect

collected 25 mm away from the channel bank alongside the spur dike. In other words, it was assumed that significant erosion of the bed near the bank would lead to bank erosion in a natural stream (Kuhnle, Alonso et al. 2002).

Effect of Head Shape

Calculated “potential bank erosion” for different types of spur dikes are summarized in Table 4-5. Figure 4-22 also shows the variation of potential bank erosion for spur dikes with different head shapes. As it can be seen, the potential bank erosion varied for T-head spur dikes than straight type ones. This figure indicates that near bank scouring of bed was in general greater in T-head spur dikes, except for aspect ratio of 3 in which the near bank bed erosion was almost of the same depth for both types of spur dike. For same opening ratio, the difference between potential bank erosion in T-head spur dikes varied from 0.90 to 1.4 times of straight spur dikes. Overall, T-head spur dikes showed less capability for stability of bank after installation of spur dikes.

Table 4-5. Potential bank erosion for experimental cases (Emergent condition)

Case Name	H_w/H_s	S_s/L_s	Volume of	Volume per Unit Length
			Near Bank Bed Erosion (cm ³)	(cm ³ /cm of bank)
T_SL1_Emg	<1	1	276.88	1.38
T_SL2_Emg	<1	2	271.08	1.36
T_SL3_Emg	<1	3	177.52	0.89
T_SL5_Emg	<1	5	302.17	1.51
I_SL1_Emg	<1	1	194.12	0.97
I_SL2_Emg	<1	2	216.94	1.08
I_SL3_Emg	<1	3	194.30	0.97
I_SL5_Emg	<1	5	220.50	1.10
T_SL2_Sub1.2	1.2	2	181.78	0.91
T_SL3_Sub1.2	1.2	3	167.63	0.84
T_SL5_Sub1.2	1.2	5	174.03	0.87
T_SL2_Sub1.7	1.7	2	143.06	0.72
T_SL3_Sub1.7	1.7	3	157.84	0.79
T_SL5_Sub1.7	1.7	5	145.72	0.73
T_SL2_Sub3.4	3.4	2	137.18	0.69
T_SL3_Sub3.4	3.4	3	126.14	0.63
T_SL5_Sub3.4	3.4	5	108.36	0.54

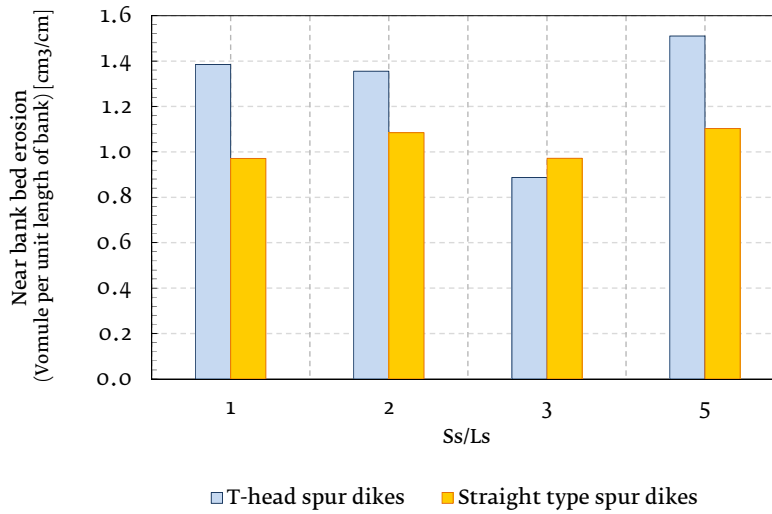


Figure 4-22. The potential bank erosion for T-head and straight type spur dikes with different opening ratios (all cases are emerged), calculated based on experimental data

Effect of Opening Ratio

Having noticed the effect of opening ratio on potential bank erosion, another interesting point is revealed. Opening ratio of 3 acts as a boundary in performance of spur dikes in terms of potential for bank erosion. In other words, near bank bed erosion is the lowest for spur dikes with opening ratio of 3 for both types of spur dikes and it can be said that this opening ratio can have the best performance when the prevention of bank erosion is of the main interest for the installation of spur dikes. This finding is true for both types; however, for T-head spur dikes, the value of potential bank erosion is slightly smaller than straight spur dikes and this case can be chosen as the most suitable type of spur dikes for protecting the bank against erosion.

For both types of spur dikes, the greatest magnitude of near bank scour is associated with opening ratio of 5 and it would be expected that in this opening ratio, the bank erosion and channel instability increase which consequently can have damaging effect on physical habitat in rivers as well.

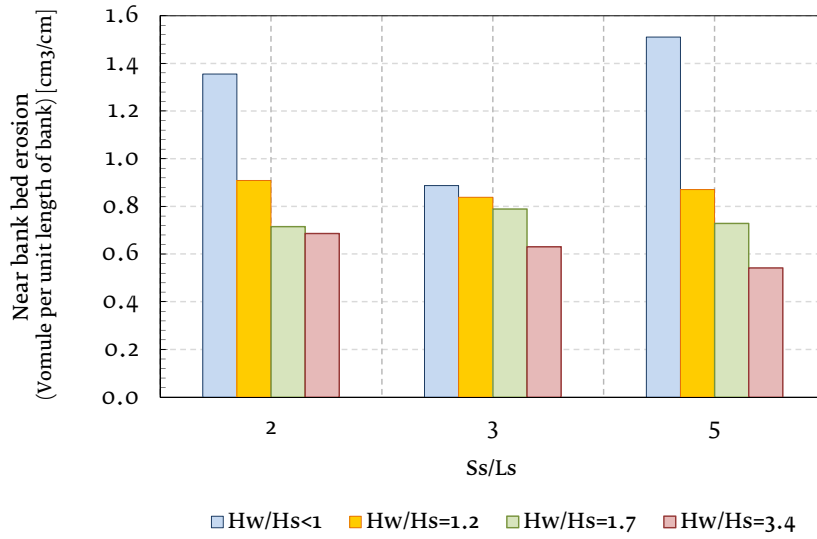


Figure 4-23. The potential bank erosion for T-head spur dikes with different submergence ratios, calculated based on experimental data

Effect of Spur Dike's Height

Figure 4-23 shows the potential bank erosion for T-head spur dikes with different spur dikes's height (H_w/H_s). For all opening ratios, a greater potential bank erosion is observed for same opening ratio when the height of spur dike is increased. This reduction in case with opening ratio of 3 is relatively small (1.05 times) and in contrary, for aspect ratios of 2 and 5 the potential erosion for bank was 1.49 and 1.73 times greater when the flow condition shifts from low water ($H_w/H_s < 1$) condition to high water ($H_w/H_s = 1.2$) condition.

Moreover, Figure 4-23 shows that in peak water condition ($H_w/H_s = 3.4$), in opening ratio equals 2, there is small change in near bank bed erosion. On the other hand, for opening ratios greater than 3, even in high water condition ($H_w/H_s = 1.7$) increasing the height of flow has comparatively considerable influence on potential for bank erosion. The average erosion volume per unit length was 1.25 and 1.34 times greater in peak water condition ($H_w/H_s = 3.4$) than high water condition ($H_w/H_s = 1.7$) for opening ratios of 3 and 5 respectively.

In overall, it can be said that the case with opening ratio of 3 is expected to be more stable by changing flow height in high water and/or peak water conditions.

4.4.1.2 The Potential for Physical Habitat Improvement

There a quite good number of works on ecological aspects of spur dikes carried out in field surveys in which they tried to find a direct link between “abundance of different species” in stream, and “biotic” and/or “abiotic” habitat characteristics due to installation of spur dikes (Bischoff and Wolter 2001, Eggers, Kleinwächter et al. 2003, Garcia, Brauns et al. 2005).

In contrast, another group of researches predicted the effectiveness of such in-stream structures by examining the quality of “biotic” and/or “abiotic” habitat characteristics.

In laboratory, due to limitations of experiments, direct measuring of the effect of biotic and/or abiotic habitat characteristics on abundance of species is very difficult. Thus, the approach that is often being taken into consideration is the one in which the impact of such structures on providing the favorable environment for growth of different aquatic species is examined indirectly. In other words, the key approach of the research in this type of studies is examining the effect of spur dikes on “habitat characteristics”.

A “habitat” is the environmental surrounding that is composed of multiple dimensions representing “biotic” and “abiotic” components and their dynamic and static characteristics that are directly or indirectly related to the use of a location by an organism (Beyer, Haydon et al. 2010). This definition of habitats includes both abiotic (physical) and biotic (biological) features (Jowett 1997). Nevertheless, a major advantage of the physical habitat-view in the investigation of ecological friendly environments in stream is that the physical characteristic of habitats can often be described and quantified in detail (especially in laboratory) as profound knowledge about physical processes is available compared to biological processes (Jørgensen and Bendoricchio 2001). Moreover and more importantly, the rationale for physical habitat assessment in streams is that physical parameters influence biological structure and function (Harding 2009).

The physical factors comprise variables describing hydro-morphodynamic processes such as “flow variations”, “space availability”, “bed diversity and heterogeneity”, “particle size distribution” and etc. (Noack 2012). There is extensive literature which demonstrates

that the quantity and quality of physical habitat determines the successful colonization and maintenance of populations (of species) (Harding 2009). For instance, it is widely known that spawning habitat is influenced by “flow variations” (i.e. water depth, and flow velocity) (e.g. (Kondolf and Wolman 1993)). Water depth is of importance regarding the providing sufficient maneuverability for spawning process. As to flow velocity, a maximum velocity is needed to hold position over redds (Redd is a spawning nest that is built by fish, especially salmon, in the gravel of streams), and minimum velocity is required for downstream transport of fines during digging process by fish (Noack 2012).

“Space availability” is also another crucial factor forasmuch as fish behavior, selection of most suitable spawning site, redd density, and competition are highly affected by space availability (Noack 2012). The amount of required space depends mainly on body size and behavior of the spawners and the area required per redd, but on the quality of the spawning area (Noack 2012). For example, if spawning grounds are only moderately suitable it may force female fish to make several redds leading to an increased competition among the females (Bjornn and Reiser 1991).

Finally, the last but not least, the “spatial and temporal diversity” and heterogeneity is of significance as all-aforementioned physical factors should be characterized by a highly temporal and spatial variability in order to reflect the balanced dynamic behavior of a river (Noack 2012).

In this sub-section, first “the availability of physical habitat’s space” due to installation of different types of spur dikes will be discussed using examining the volume, the planar area and surface area of scoured zones around spur dikes.

In the next sub-section, the influence of spur dike’s type on “spatial diversity of habitat” will be discussed. Thus, after introducing the effective physical factors on evaluation of variability of habitat in streams induced by spur dikes, the different available criteria for quantifying the concept of “diversity” for physical habitat will be scrutinized and the advantage and disadvantage of each criteria will be shown. A new approach for quantifying the diversity of physical habitat will be described and the performance of T-head and

straight spur dikes to provide a channel with more diverse bed will be investigated using the new approach.

Finally, in the last sub-section, to provide further information about the potential for physical habitat improvement, the effect of different types of spur dikes and their arrangement on formation of sequence of pool-riffle that is of much importance in assessment of physical habitat's characteristics will be analyzed.

4.4.1.2.1 Effect of Spur Dike's Type on Habitat's Space Availability

As it was noted earlier, "space availability" is one of crucial factor in providing favorable physical habitat since fish behavior, selection of most suitable spawning site, redd density, and competition are highly affected by space availability.

Space availability can be characterized by depth, volume, and extension of pools along the channel. Depth of pool was found to be positively correlated to fish biomass (Schwartz and Herricks 2008). Large pools can also serve as shelter, feeding place, or the place for hiding and resting as well as for overwintering of adult fish. Depending on dimensions of pools, they may also serve as low water refugia (Elliot 2000).

In this sub-section, availability of habitat's space in channel is appraised by calculating "volume", "planar extension", and actual "surface" area of scoured zones due to installation of spur dikes. To neglect the effect of general scouring in channel, the scoured levels were considered just for levels lower than 1 cm below the initial bed surface.

Effect of Head Shape

The volumes of scour areas below level "-1" cm for T-head spur dikes as well as straight spur dikes are depicted in Figure 4-24. The volumes of scour holes differ markedly for T-head and straight spur dikes. Overall, T-head spur dikes had been able to make larger scour holes. This difference however highly depends on the arrangement of installation of spur dikes and the spacing between them in series. On average, the volume of scour hole in T-head spur dikes are 1.5 times greater than scour holes of straight spur dikes.

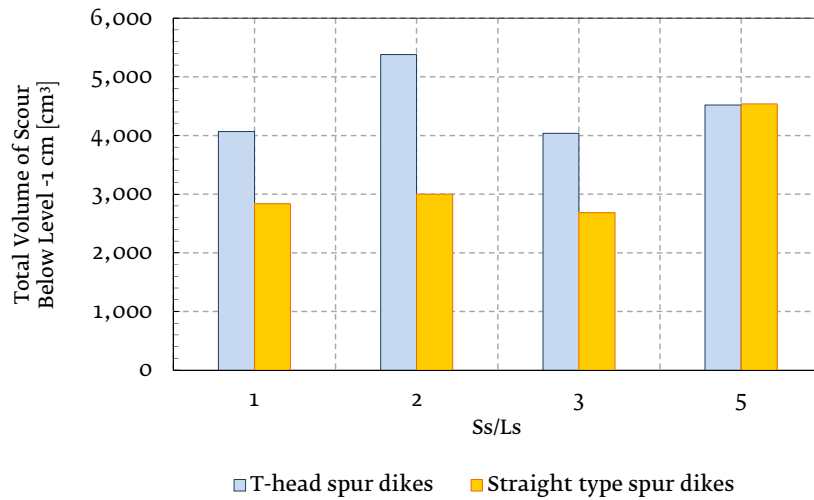


Figure 4-24. The volume of scour below level “-1” cm in T-head and straight type spur dikes with different opening ratios (Ss/Ls), calculated based on experimental data

In order to measure the variation in planar extent of scour zones, the planar area of levels below “-1” cm is presented in Figure 4-25. On average, the planar extension was 1615 cm^2 (range: $1272\text{-}2209 \text{ cm}^2$) for T-head spur dike and 1129 cm^2 (range: $896\text{-}1565$) for straight spur dikes and consequently the spur dikes with T-head shape had better performance in providing wider pools in plan along the channel. Similar to the volume of scour areas, the head shape, however, has different effect on planar extension of pools depending on the spacing between spur dikes in series.

Head shape of spur dikes also affected “surface area” of scoured zones below level “-1” cm (Figure 4-26). The difference between surface area and planar area (Figure 4-25) is that the former term represents the actual surface of scoured area that is made up of the inclination of bed slopes in pools, while the latter term just reflects the horizontal planar extension of scoured zones along the channel. In general, except for opening ratio of 5 in which there is no considerable impact of head shape, T-head spur dikes were the better choice in providing the deeper and broader pools. The surface areas of levels below “-1” cm in T-head spur dikes are in average 1.61 times (range: $1.25\text{-}1.49$) broader than scoured areas due to straight spur dikes.



Figure 4-25. The planar area of scour zones below level “-1” cm in T-head and straight type spur dikes with different opening ratios (Ss/Ls), based on experimental data

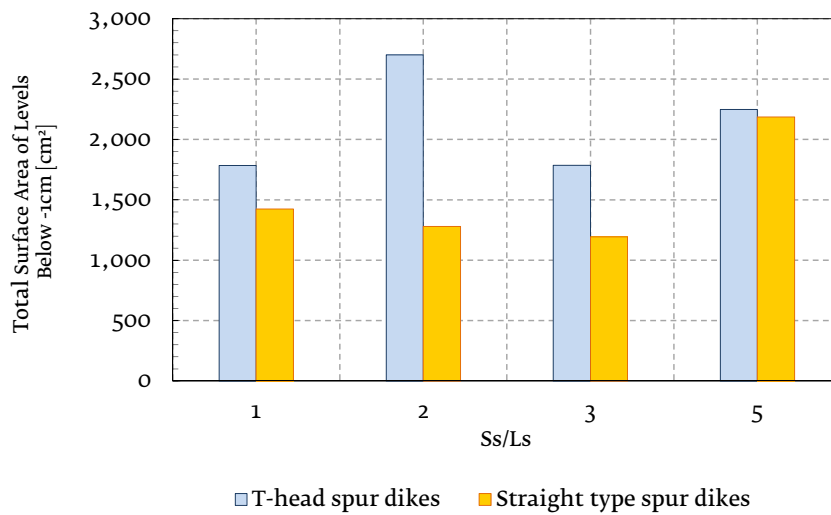


Figure 4-26. The surface area of scour zones below level “-1” cm in T-head and straight type spur dikes with different opening ratios (Ss/Ls), based on experimental data

To summarize, T-head spur dikes can give larger scoured area than straight spur dikes do, specifically for opening ratios of less than 3.

Effect of Opening Ratio

For the same type of spur dike, the volume of scoured areas differs largely by changing in spacing between the spur dikes in series (Figure 4-24). The difference, however, is not changing linearly. While the volume of scour areas for opening ratios of 1 and 3 for both types of spur dikes are almost of the same value, the volume of scour areas in opening ratio equals 2 increases. This increase specifically in T-head spur dikes is very sharp (1.30 times versus 1.05 time in straight type). Another interesting point is that after opening ratio of 3, the volume of pools has increased again, but both types the absolute value is pretty much identical. This means that in this opening ratio (5) the performance of spur dikes are quite similar in terms of providing larger scoured spots.

Concerning the planar extensions of pools along the channel Figure 4-25 shows that the trend of variations for T-head spur dikes is following the same tendency of the changes in volume of scoured areas (Figure 4-24). Nevertheless, for straight spur dikes the situation for opening ratio of 2 is different and by increasing the spaces between straight spur dike the planar extension of pools is consistently decreasing from opening ratio of 1 to 3 with about 22 percent smaller pools. For opening ratio of 5, however, Figure 4-25 indicates that the value of planar extension of scoured area has increased sharply again comparing with the corresponding values of opening ratio of 3, i.e. 1.30 time for T-head and 1.7 time for straight types of spur dikes.

In overall, opening ratio of 2 for T-head spur dikes has the best performance in proving largest pools in channel. For straight spur dikes, the greatest pools were observed in opening ratio of 5.

Effect of Spur Dikes' Height

Figure 4-27 (a) to (c) presents the volume, planar extension, and surface area of pools for different T-head spur dike's heights. For the same opening ratio, the larger volume was observed for the case where flow was below spur dike's height.

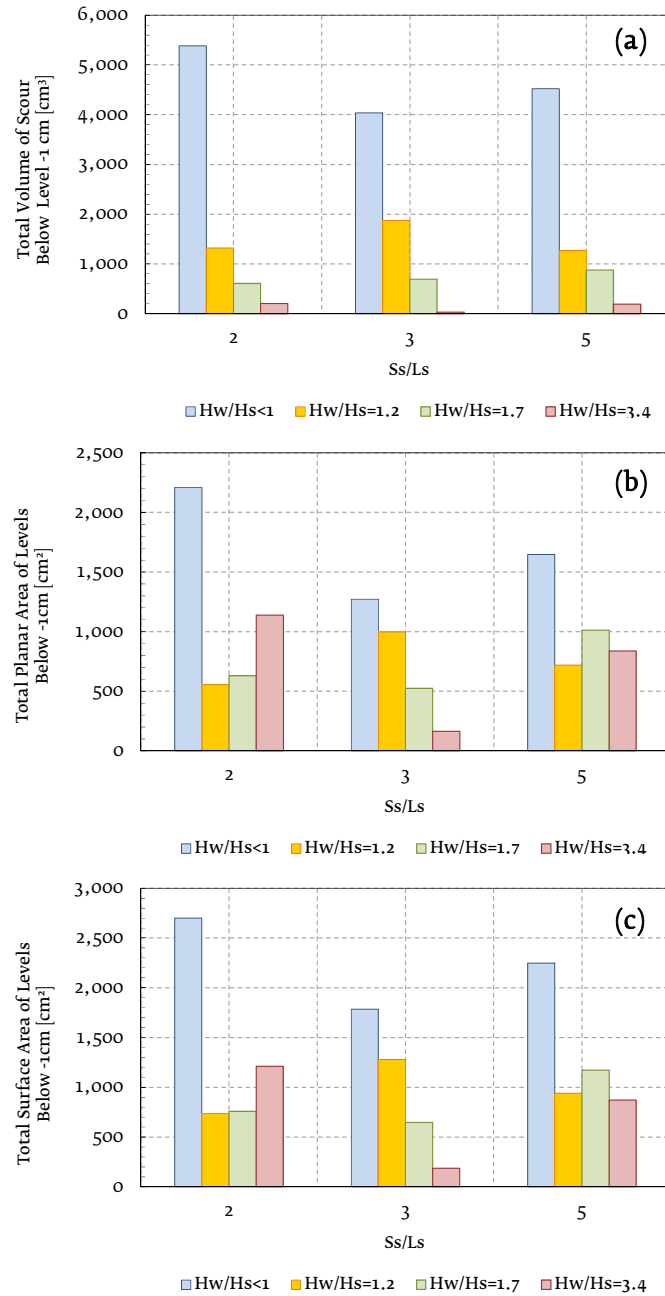


Figure 4-27. (a) The volume, (b) planar extension, and (c) surface area of pools for T-head spur dike's with different heights (H_w/H_s), based on experimental data

On the other hand, by decreasing the spur dike's height, once over topping happened the volume of scour was reduced noticeably. This value has changed from 5381 cm³ to 1320 cm³ (4 times smaller) for opening ratio of 2, 4034 cm³ to 1877 cm³ (2 times smaller) for opening ratio of 3 and from 4521 cm³ to 1268 cm³ (3.5 times smaller).

Though, by reaching flow to the spur dike's height and overtopping of flow, the volume of pools was decreased, looking into the planar area of scoured holes in opening ratio of "2" suggests that they become wider in plan. The planar area for scour was "2" time greater for overtopping ratio of "3.4" than the boundary overtopping ratio of "1.2". In opening ratio of "3", however, the planar extension of pool steadily decreases with reducing the spur dikes' height and it becomes 6 time smaller for overtopping ratio of "3.4" than of "1.2". The planar dimensions of pools when the opening ratio of spur dikes is "5" did not show a direct relation with changing of spur dike's head. Once the spur dikes get submerged the planar size of pool becomes 2.3 times smaller and by increasing the height of flow it first gets 1.4 times greater at $H_w/H_s=1.7$ and then it decreases again in peak water condition of $H_w/H_s=3.4$.

4.4.1.2.2 Effect of Spur Dike's Type on Flow Suitability

A wide range of variability required for flow features in order to improve the living environment of aquatic biota and fauna in stream. The typical fish assemblage requires a high variability in depth, flow velocity and substrates (Sukhodolov, Bertoldi et al. 2009). While it turns out that the density of deep pools, and scour holes determines the carrying capacity and the standing stock of adult fish (Fette, Weber et al. 2007), in contrast, juvenile recruitment depends on the availability of shallow, flow-protected nursing habitats (Sukhodolov, Bertoldi et al. 2009). As for velocity, it turned out that fish larvae of 6-15 mm total length perform burst and critical swimming speeds ranging from 0.06 - 0.20 m/s and 0.05 - 0.13 m/s, respectively (Wolter and Arlinghaus 2003, Wolter and Arlinghaus 2004) and consequently even comparably low flow velocities may limit the availability of habitats for larval, juvenile and small fishes (Sukhodolov, Bertoldi et al. 2009).

The direct outcome of these facts will accordingly be highlighting the remarkable range of flow features which can be considered as proper criteria in assessing the suitability of stream habitat as living environment of aquatic biota and fauna.

In current study, since there is no prototype data for model adjustment, the study of absolute values of the water depth and the flow velocity cannot directly be the center of attention. On the other hand, “Froude number” and “velocity/depth ratio” are suggested as easy-to-measure indices which provide an objective method of classifying habitat type and provide a base for between-river comparisons in terms of their suitability for aquatic habitat (Jowett 1993).

Froude number has been recognized as a criterion to distinguish between pools and riffles as fundamental ecological units of alluvial rivers (Wolman 1955, Jowett 1993). Its potential utility is demonstrated by the similarity of the Froude numbers calculated for habitats described in studies by Allen (1951) and its relationship to benthic invertebrate abundance for some species (Orth and Maughan 1983, Jowett, Richardson et al. 1991, Jowett 1993).

Wetmore, Mackay et al. (1990) showed the distribution of *Brachycentrus occidentalis* and *Simulium vittatum*, both filter feeders (animals that feed by straining suspended matter and food particles from water, typically by passing the water over a specialized filtering structure), was best explained by Froude number, with individuals of these species being found at high Froude numbers (0.6–0.7) (Kemp, Harper et al. 2000).

It also turned out that “velocity/depth ratio” and “Froude number” showed the most significant differences between habitat types. Pool habitat was associated with velocity/depth ratios of less than 1.24 and Froude numbers less than 0.18, riffles with velocity/depth ratios of more than 3.20 and Froude numbers in excess of 0.41, and run habitat with intermediate values (Jowett 1993) (Figure 4-28).

Chibana and Tamai (2002) and Chibana, Tsujimoto et al. (2004) suggested values of 0.1, 0.4 and 0.6 for Froude number to distinguish retarded habitat, swift flow habitat and suitable habitat according to their investigations on a kind of Japanese dace (*Tribolodon*

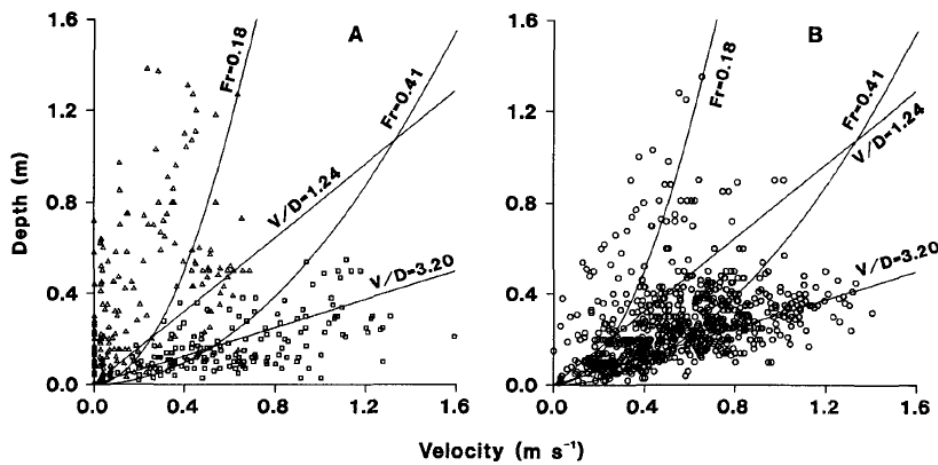


Figure 4-28. Classification of pool, run, and riffle habitats by velocity /depth ratios (V/D) of 1.24 and 3.20 and Froude numbers (Fr) of 0.18 and 0.41; illustrating the separation of pool (triangles) and riffle (squares) habitat (A) and the range of velocities and depths classed as run (circles) habitat (B) (Jowett 1993).

hakonensis) (Zhang, Nakagawa et al. 2013). A summary of recommended ranges for flow parameters in previous studies is shown in Table 4-6.

In current study, the overall suitability of the habitat was examined by study of, first, suitability of flow parameters in order to provide different habitat types using the recommended ranges of flow parameters which they were turned out to be suitable for river

Table 4-6. The recommended ranges of flow parameters by previous researchers

Reference	Flow parameter used for assessment of habitat	Recommended range	Notes
Wetmore, Mackay et al. (1990)	• Froude number	0.6–0.7	High individuals of filter feeders
Jowett (1993), Danehy and Hassett (1996), Panfil and Jacobson (2005)	• Velocity/Depth (V/D) ratio • Froude number	Pool: $Fr < 0.18$ and $V/D < 1.24$ Riffle: $Fr < 0.41$ and $V/D < 3.2$ Run: intermediate values	Classification of habitat types
Chibana and Tamai (2002), Chibana, Tsujimoto et al. (2004)	• Froude number	0.1 0.4 0.6	Retarded habitat, swift flow habitat and suitable habitat for a kind of Japanese dace

ecology, and second, by examining the spatial heterogeneity (diversity) of habitat. The former will be discussed in this sub-section and the latter will be addressed separately in sub-section 4. 4.1.2.4.

Froude number (Fr) was calculated according to the following equation (Gordon, McMahon et al. 2004):

$$Fr = \frac{V}{\sqrt{gD}} \quad (4-11)$$

where V is mean flow velocity, g is acceleration due to gravity and D is water depth. Mean flow velocity was adopted using calculating depth averaged velocity (DAV) in each point along the depth. For each cases, the 500 points were chosen among the results of numerical simulating of flow in scoured bed condition in an area confined between 0.3 meter upstream of the first spur dike in series and the end of movable bed area in channel. The width of area was also limited to 0.3 meter beginning from spur dike-side channel bank toward the main channel.

Effect of Head Shape

Figure 4-29 shows histograms of Froude number at different types of spur dikes. The frequency distribution was generated by dividing the Froude values into classes, using an inter-class increment of 0.05 (Kemp, Harper et al. 2000, Clifford, Harmar et al. 2006). Figure 4-30 also illustrates the scatterplot of velocity and depth at area around spur dikes with different head shapes. Here, data are classified into four Froude number groupings and each grouping is displayed in a specific color. The ranges of groupings are adopted according to the recommended ranges of flow parameters by previous researchers (Wetmore, Mackay et al. 1990, Jowett 1993, Chibana and Tamai 2002, Chibana, Tsujimoto et al. 2004) which were considered as suitable criteria for assessment of habitat (See Table 4-6). In addition, to aid the analyses, the values of Froude numbers of 0.18 and 0.41 along with ratios of velocity over depth equal to 1.24 and 3.20 are plotted by solid and dashed lines, respectively. These values are the recommended flow parameters by Jowett (1993) for

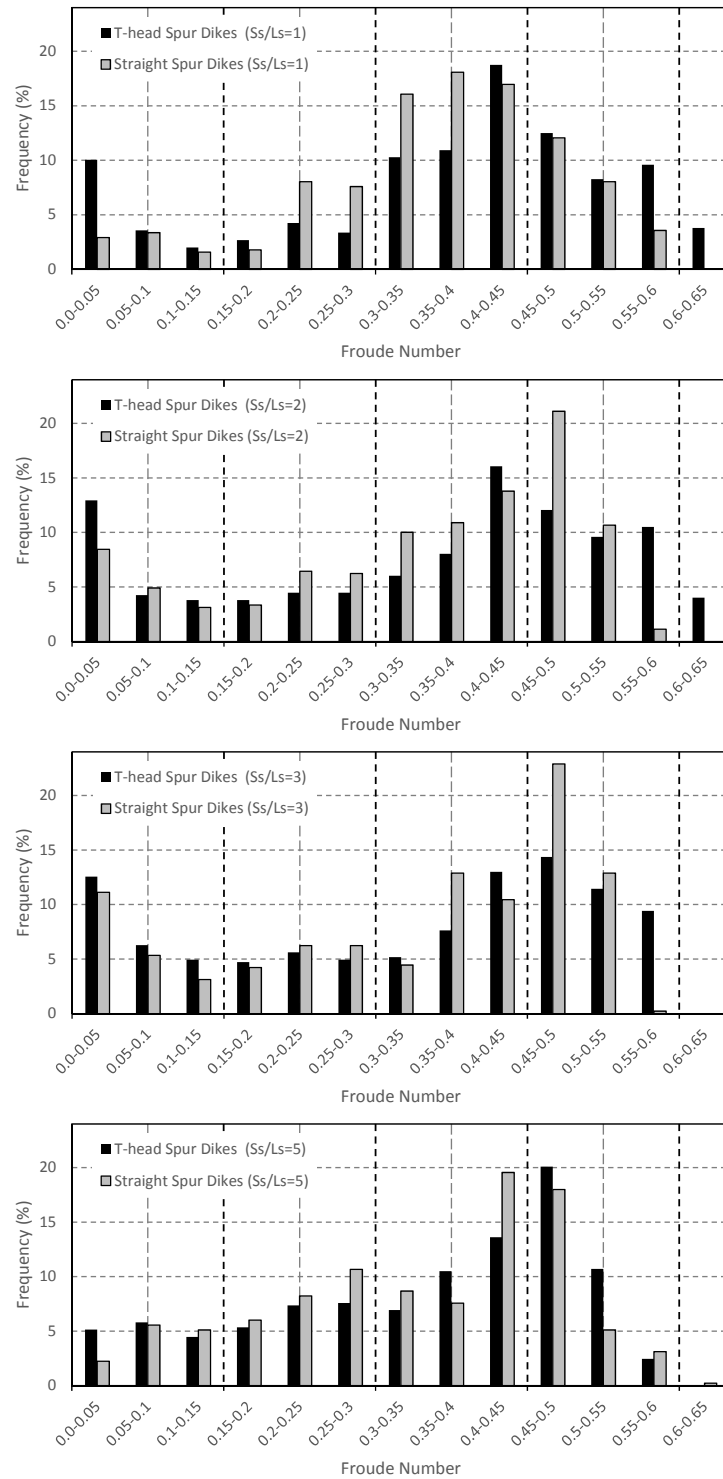


Figure 4-29. Histograms of Froude number at different types of spur dikes, calculated based on results of numerical modeling

classification of habitat types (Pool: $Fr < 0.18$ and $V/D < 1.24$, Riffle: $Fr < 0.41$ and $V/D < 3.2$ and Run: intermediate values; See Table 4-6).

The Figure 4-29 reveals that the distribution of Froude number is dependent on head shape. In range of $Fr = 0.0 \sim 0.15$, representation of retarded habitat type, T-head spur dikes showed the higher frequency. For $Fr = 0.15 \sim 0.30$ which is to be faster flowing area the straight type spur dikes showed higher frequency. In $Fr = 0.30 \sim 0.45$ which is assumed as values for providing suitable habitat for kind of Japanese dace, the performance of T-head spur dikes and straight type spur dikes were different based on the opening ratios between spur dikes. Furthermore, for higher Froude number the T-head spur dikes had generally better performance so that for $Fr > 0.6$ which is supposed to be a good flow condition for presence of filter feeders, the straight spur dikes showed zero frequency, whereas T-head spur dikes represent a few number of spots with this value of Froude number.

Scatterplot of distribution of velocity over depth data in Figure 4-30 also demonstrates the both types of spur dikes were able to disrupt the monotony of flow in channel to some extent. Nevertheless, comparison of distribution of velocity over depth for T-head (Figure 4-30 (a) to (d)) with straight type spur dikes ((Figure 4-30 (e) to (h)) revealed that in straight spur dikes the presence of an area with the water depths close to the approach flow depth is quite obvious. In contrast, the wider distribution of water depth as well as velocity for T-head spur dikes obviously suggests the better performance of T-head spur dikes to improve the flow variation in these cases.

The frequency of different habitat types in case of presence of T-head spur dikes and straight spur dikes is plotted in Figure 4-31 (above).

The two most common habitats (pool and riffle) were defined based on ratio of flow velocity over water depth along with Froude number according to Jowett (1993). Overall, the number of pools and riffles were greater in T-head spur dikes. However, the range of difference is not identical and it is highly affected by the opening ratios between spur dikes. Pool habitats in T-head spur dikes ranged from 22% to 29% of all habitats and riffles made up of 40% to 45% which means as a whole riffles were more frequent in study area.

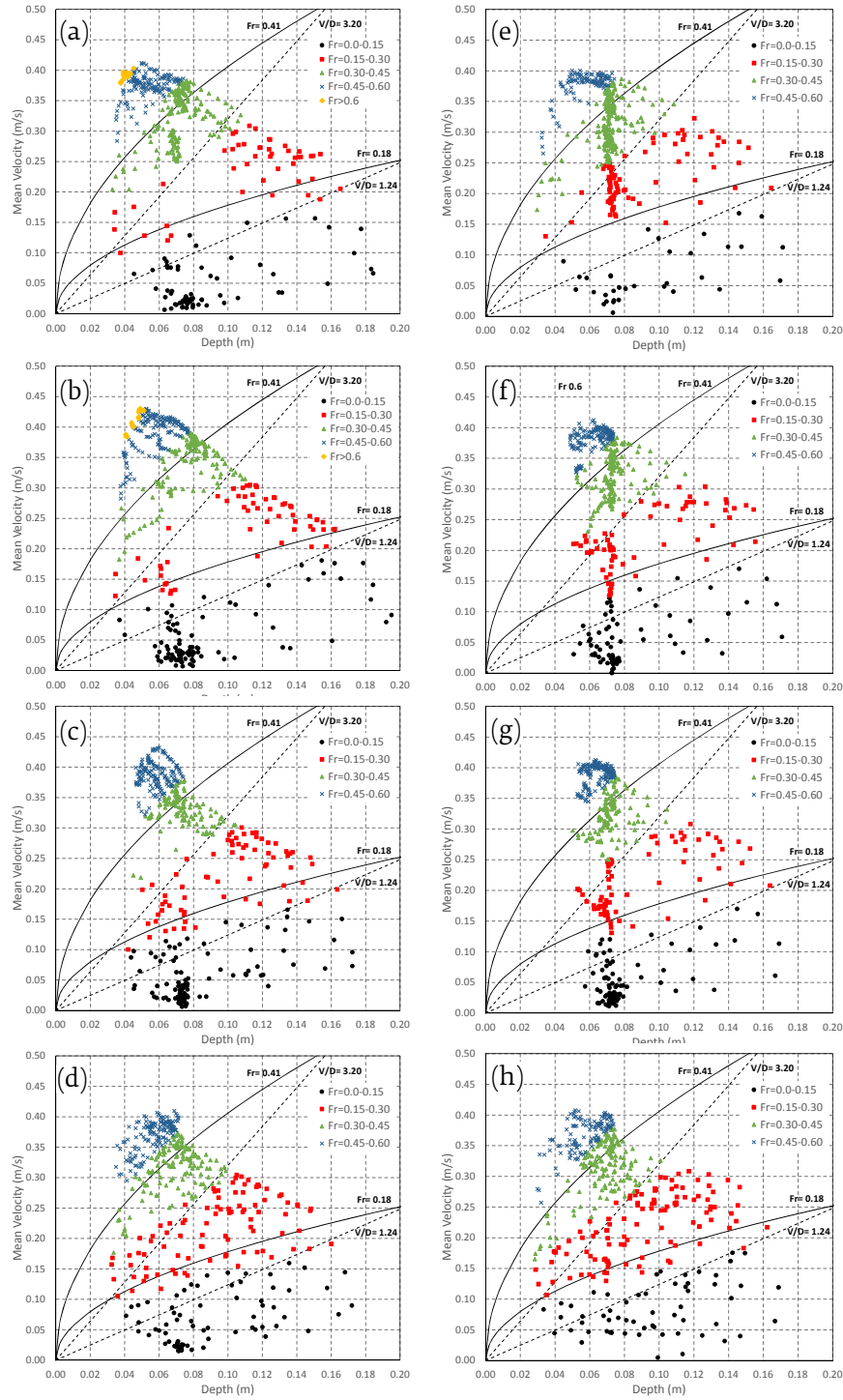


Figure 4-30. The scatterplot of velocity and depth data around spur dikes with different head shapes and opening ratios (Right: T-head, Left: Stiaight type; (a,e) Ss/Ls=1, (b,f) Ss/Ls=2, (c,g) Ss/Ls=3, (d,h) Ss/Ls=5), calculated based on results of numerical modeling

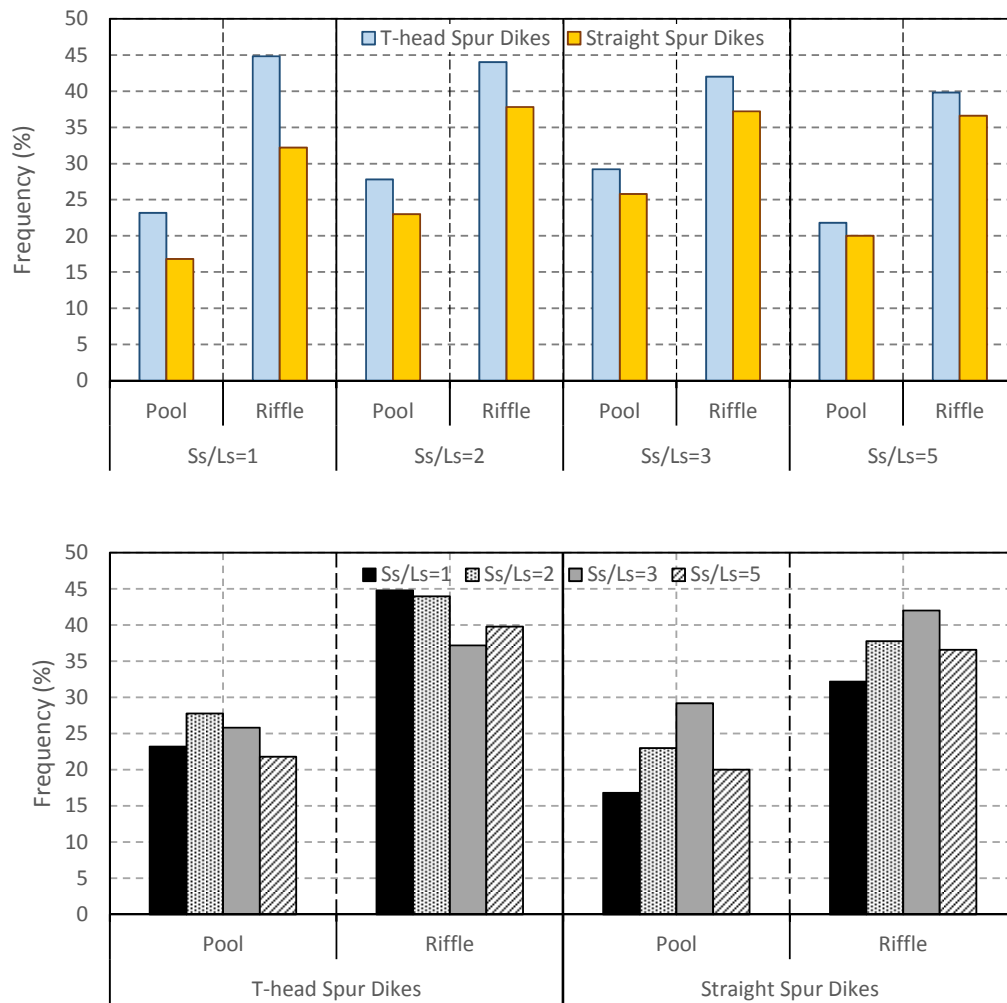


Figure 4-31. Histograms of habitat types at spur dikes with different head shapes (above) and opening ratios (below), calculated based on results of numerical modeling

On the other hand, in straight type spur dikes, the number of pools habitat were in a range from 16% to 26% and riffle habitats varied from 32% to 38% which likewise T-head spur dikes is more frequent habitat type around the spur dikes. Pools are the primary habitat for large fish in non-flood seasons when water is shallower and fish are easily captured (Zhang, Wei et al. 2013). Riffle areas and their immediate surroundings are important as a spawning area for many river fish (Zhang, Wei et al. 2009). The greater number of these two fundamental

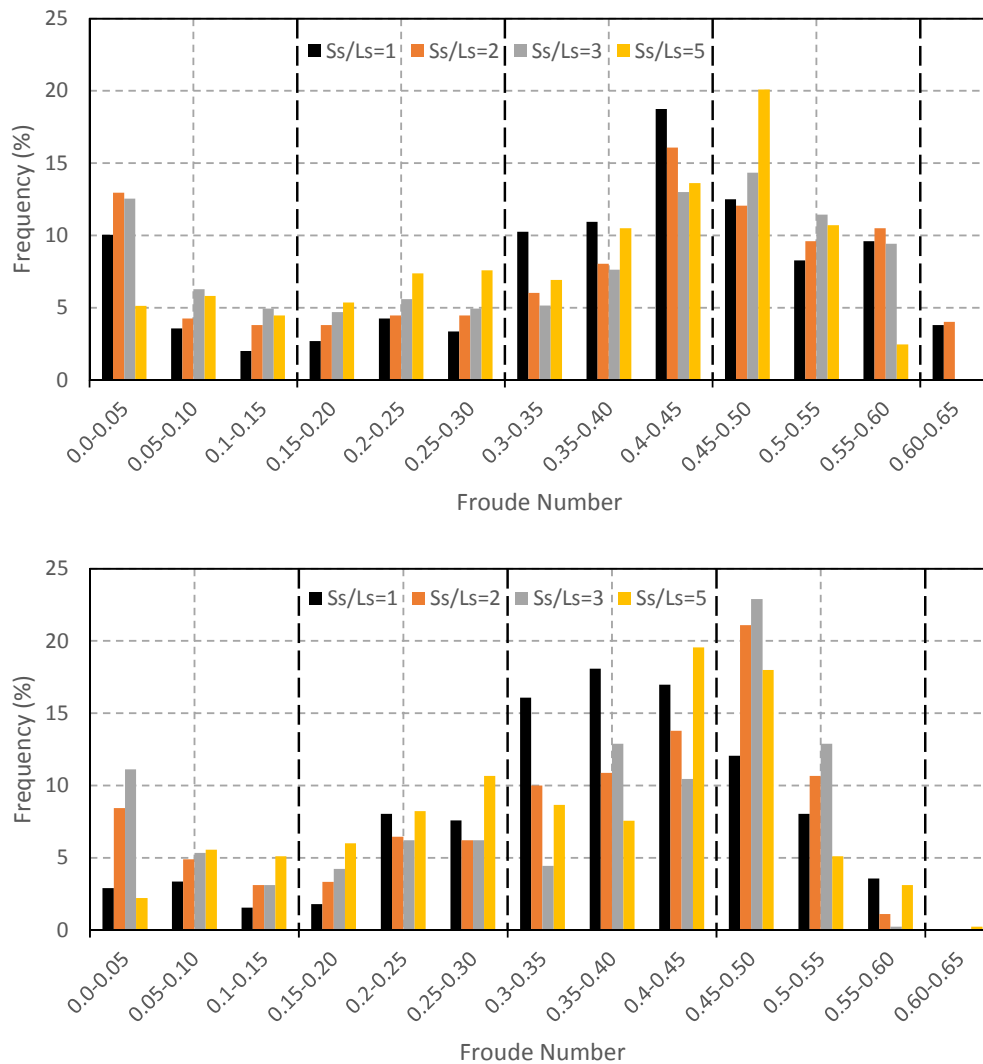


Figure 4-32. Histograms of Froude number at spur dikes with different opening ratios (Above: T-head spur dikes; Below: Straight type spur dikes), calculated based on results of numerical modeling

habitat in case of T-head spur dikes proves the better capability of them in enhancement of suitable physical habitats in streams after installation of the T-head spur dikes.

Effect of Opening Ratio

For similar type of spur dikes, the frequency of Froude numbers changes quite a lot by changing the opening ratio (Figure 4-32). For $Fr=0.0\sim0.15$, in general the opening ratios of 3 had the highest frequency. For faster flow of $Fr=0.15\sim0.30$, in general the best performance

was observed in opening ratio of 5 for both T-head and straight spur dikes. In ranging $Fr=0.30-0.45$, however, the highest frequency was generally obtained in opening ratio equals to 1. For $Fr=0.30-0.45$, the performance of T-head and straight differs. In T-head spur dikes, the opening ratio of 5 was basically able to produce higher frequency of swift flows, except for higher Froude numbers greater than $Fr=0.55$ in which the performance of opening ratio of 5 decreases substantially and better results were seen in opening ratios of 1 to 2. These high values of Froude number were observed of importance for filter feeders in stream (Table 4-6). In straight spur dikes, in contrast, the highest frequency of in this range of Froude number ($0.45-0.55$) was seen in opening ratio of 3. For greater Froude number of swift flows, specifically for the values higher than $Fr=0.6$, this type of spur dike failed to provide any suitable spot.

As for the capability of providing variable flow, Figure 4-30 also suggest the noticeable effect of opening ratio. In T-head spur dikes, the most dispersed distribution of the water depth and the flow velocity was observed after the installation of the spur dikes with opening ratio of 5. In straight spur dikes, for in opening ratio of less than 5, while the velocities vary a lot, the corresponding water depths are limited to the approach flow depth in many studied spots. Similar to T-head spur dikes, the widest distribution of flow features also turned up to be in opening ratio of 5.

Identifying two most common habitat types using combining data on water depth and flow velocity with Froude number (Figure 4-31) turned out that pool habitat was more frequent in opening ratios of 2 and 3 for both types of spur dikes (with 27% and 25% of frequency in case of T-head spur dikes and 23% and 29% for straight spur dikes).

The riffle habitats, however, were observed most in case of opening ratio 1 and 2 for T-head (with 45% and 44% of frequency) and 2 and 3 (with 37% and 42% of frequency) for straight spur dikes.

As a result, an opening ratio of 2 for spur dikes with T-shape head and 3 for straight spur dikes can be suggested to enhance ecologically suitable habitat types in stream.

4.4.1.2.3 Pool-Riffle Sequence for Different Types of Spur Dikes

One substantial factor that can be of help in improving the heterogeneity and variety of stream habitat and subsequently increasing local biodiversity is the presence of pool-riffle sequence in river. Pools are areas with enough depth that have fairly slow water flow. Riffles, on the other hand, are shallow areas characterized by faster flow and larger substrate size (Keller 1992). This sequence of pools and riffles provides a heterogeneous physical environment that is utilized by many different types of organisms (Howe 1997). Pools and riffles provide refuge from high velocity waters and extreme temperatures, spawning sites for salmonid fishes, and attachment sites for benthic invertebrates and plants (Gore and Shields Jr 1995). The complexity of pool-and-riffle sequences offers the wide variety of habitat types needed to support a diverse community of aquatic species (Howe 1997).

In this sub-section, effect of spur dike's type on perturbation of channel morphology is examined by assessing the bed profile along a longitudinal section in the interface between spur dikes' fields and main channel.

Effect of Head Shape

The longitudinal bed profile along the interface between spur dikes' fields and main channel is illustrated in Figure 4-33 for spur dikes with different head shapes. The formation of channel morphology differs noticeably for spur dikes with different head shape. Overall, T-head spur dike could induce greater perturbation on channel bed. For both types of spur dikes, the first half of study reach was mostly occupied by a big pool made due to first spur dikes in series. Nonetheless, even in this part of channel, the number of pool-riffle units formed by T-type spur dikes is greater. In spur dikes with T-head shape, the second half channel bed underwent from perturbation of spur dikes, while in straight spur dikes, except for one case (with opening ratio of 5), the second half of channel experienced a few small changes in bed levels. In general, it turns out that T-head spur dikes could show better performance in increasing the frequency of pool-riffle units, specifically in the second half of channel, and as increasing the number of pool and riffle directly affects the chance of

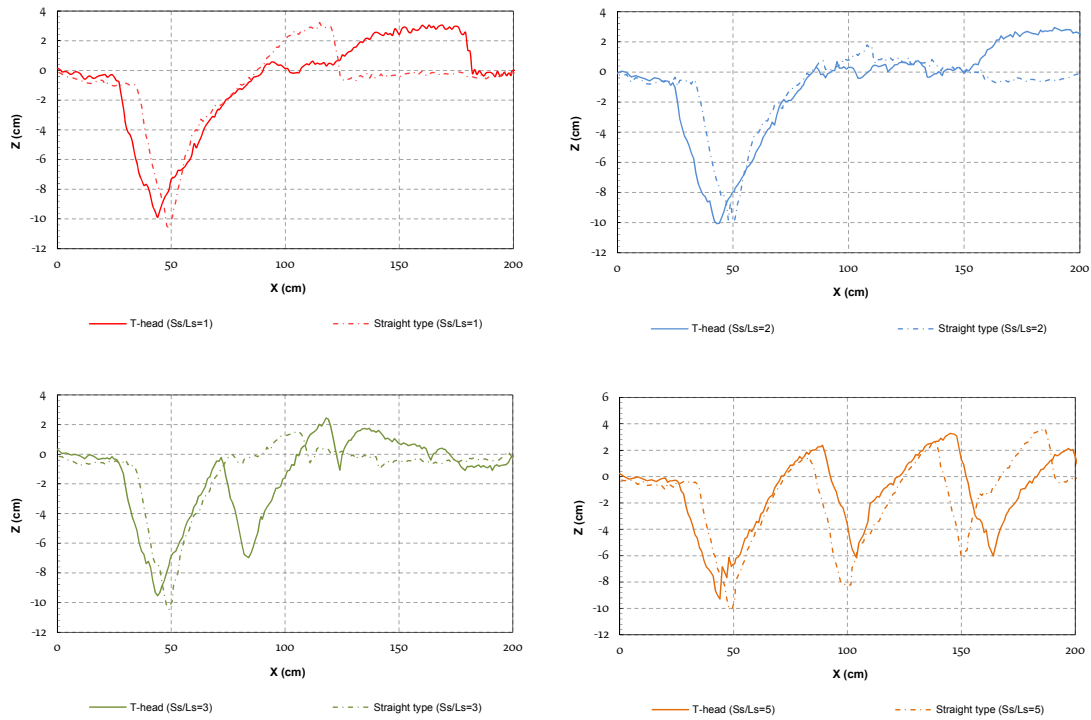


Figure 4-33. The longitudinal bed profile along the interface between spur dikes' fields and main channel, calculated based on data of experimental results

potential favorable physical habitat along the river, it is expected they can improve complexity and heterogeneity of habitat types required for biodiversity.

Effect of Opening ratio

Figure 4-34 shows the effect of different opening ratios on the formation of channel morphology in T-head and straight spur dikes. The figure indicates a strong relation between aspect ratio and number of pools and riffles in front of series of spur dikes. For T-head spur dikes the frequency of appearance of pools and riffles increases with increase of opening ratio. The intensity of this effect, however, is not identical for all opening ratios. Having increased opening ratio from 1 to 2, the number of pool-riffle units is not increased substantially. On the other hand, the effect of opening ratio is specially seen in opening ratio of 3 which could induce greatest number of pools and riffles in channel.

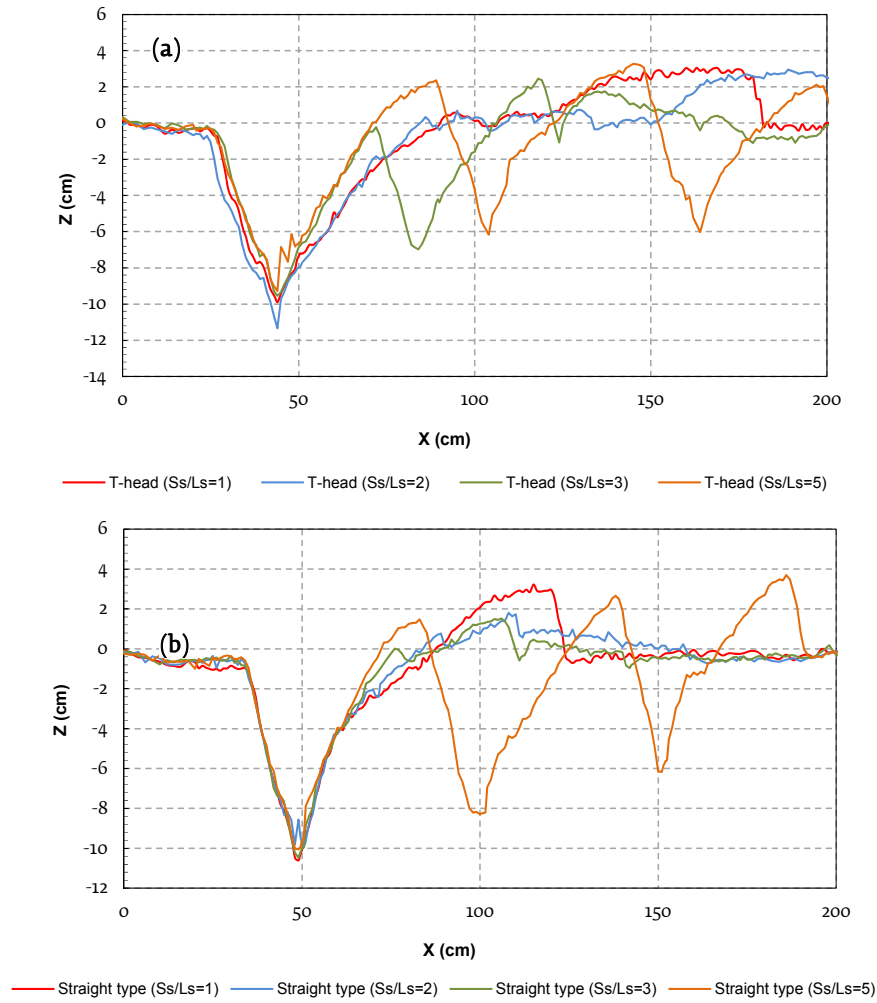


Figure 4-34. The effect of different opening ratios on the formation of channel morphology in (a) T-head and (b) straight spur dikes, calculated based on data of experimental results

In addition to the factor of number, increasing opening ratio resulted in increasing the difference in bed elevation between pools and the downstream riffle crest (or so-called residual depth of pool) which is of importance in assessment of features of pool-riffle sequences. As for straight spur dikes, in contrast, except for opening ratios of 5 the changing in opening ratios (from 1 to 3) did not show any great influence on the formation of pool-riffle sequence. This result did not follow the observation of (Zhang, Nakagawa et al. 2013) who reported that the number of pool-riffle was increased by increasing opening ratio of

series of straight spur dikes installed in convex and concave sides of a 90-degree curved channel. The discrepancy between our findings and those of (Zhang, Nakagawa et al. 2013) maybe a result of existence of a strong secondary flow and its predominant effect on the bottom flow between the convex side and the concave side of curved channel which could result in amplification of the effect of existence of spur dikes on the perturbation of channel bed.

Overall, the finding here turns out that T-head spur dikes with opening ratio of 3 has a great potential in improving the complexity of bed profile in terms of frequency of pool-riffle units in channel.

4.4.1.2.4 Effect of Spur Dike's Type on Spatial Diversity of Habitat

As mentioned earlier, all biologically-relevant-physical-factors of habitat should be characterized by a highly “temporal and spatial variability” in order to reflect the balanced dynamic behavior of a river (Noack 2012).

Habitat heterogeneity is essential for fish populations. A loss of heterogeneous habitat has been found to negatively affect fish and invertebrate populations in both diversity and abundance (Madejczyk, Mundahl et al. 1998, Langler and Smith 2001, Pretty, Harrison et al. 2003, Hartman and Titus 2010)

Heterogeneous habitats provide two major benefits. First, they may provide refugia from predation and environmental variables such as river flows. Prey cover decreases the ability of predators to both see and catch prey (Savino and Stein 1989, Walters, Lynch Jr et al. 1991, Lehtinen, Mundahl et al. 1997, Takemon and Nakanishi 1998, Hartman and Titus 2010). Second, heterogeneity tends to create higher overall productivity and concentrates food sources for many different species (Hartman and Titus 2010).

To date, however, there has been little success in creating an accepted, uniform methodology for comparing aquatic habitat diversity that is both “quantitative” and can be used to compare among the wide variety of habitat structures found in aquatic systems (Shumway, Hofmann et al. 2007).

Quantification of Diversity

So far, several studies have dealt with the issue of quantifying the habitat diversity. The standard deviation has been a prevalent way of expression of diversity that is simply the square root of the “variance”. Jowett and Duncan (1990) used the coefficient of variation of flow (an expression of standard deviation as a percent of the mean), and the ratio of mean to median flow (a measure of the skewness of the flow frequency distribution) to describe the overall variability of the flow quantitatively. Kondolf (1996) calculated the coefficient of variation for depth in the specific site for measuring the heterogeneity of habitat types and assumed that if the heterogeneity (or precisely speaking, coefficient of variation) were high biodiversity would be high as well.

McCoy and Bell (1991) proposed two axes to identify habitats uniquely: an axis of habitat complexity, which measures variation in absolute abundance of individual structural features, such as crevices and an axis of habitat heterogeneity, which measures variation in qualitatively different physical features, such as plants. Willis, Winemiller et al. (2005) used five different measures to quantify habitat complexity.

The main drawback of these approaches in addressing the diversity of habitat is that there are two main factors which should have been taken into account when measuring diversity. These two factors are “richness” and “evenness”. Richness is a measure of the number of different kinds of data present in a particular dataset. For example, species richness is the number of different species present. However, diversity depends not only on richness, but also on “evenness”. Evenness compares the similarity of the number of each

Table 4-7. Two samples of dataset with different diversity

Data-type	Sample 1	Sample 2
A	25	97
B	25	1
C	25	1
D	25	1
Standard deviation	0	48
Coefficient of variation	0	1.92

of data type. Table 4-7 shows two samples of dataset. By naked eye, it is obvious that the diversity of sample 1 is richer than sample 2.

Table 4-7 also shows calculated diversity by “standard deviation” or “coefficient of variation” for two samples of data and it suggests more value of diversity for sample 2 than sample 1 that is obviously an inconsistent result. In the samples of Table 4-7, while data have same “richness” (4 class or types) and same total number of individuals (=100), the first sample has more “evenness” than the second one does.

Precisely speaking, the main reason behind the deficiency of conventional ways (coefficient of variation, standard deviation and etc.) as an appropriate criterion to represent diversity quantitatively is that all those approaches measure just the evenness and the richness of data is neglected.

Over the past decades, a number of diversity indices have been developed which mathematically consider the concepts of richness and evenness together. Each of those indices, has its advantages, and may have more or less addressed on richness or evenness. “Shannon's Diversity Index” has been widely used as a measure of diversity (Hughes 1978, Rankin 1995, Schwartz and Herricks 2007, Chung, Bae et al. 2012). In several studies about assessment of habitat, it was also applied to quantify habitat diversity in a natural stream (Gorman and Karr 1978, Zhang, Wei et al. 2013). “Shannon's Diversity Index” is most often calculated as follows:

$$SDI = - \sum_{i=1}^n p_i \log p_i \quad (4-12)$$

which SDI denotes Shannon's Diversity Index, n is number of studied classes, and p_i is proportional abundance which is:

$$p_i = \frac{N_i}{N} \quad (4-13)$$

in which N_i is number of entities of given class (i) and N is the total number of entities.

Although Shannon's Diversity Index makes up of richness of data (n) and evenness of data (p_i), the fundamental problem of the equation is that it is not explicitly representation of “spatial” diversity of data over an area which is of importance in examining the dynamic behavior of a river.

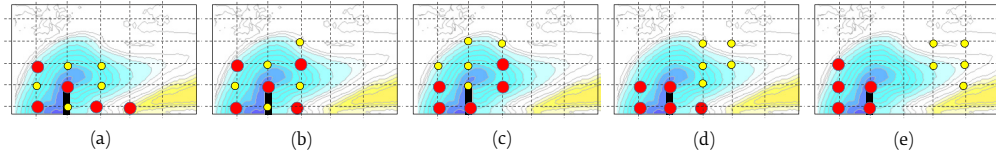


Figure 4-35. Example of different grain size distributions around an individual straight spur dikes (the bold line: spur dike; red and yellow dots: sampling points with two different mean diameter; background: the schematic bed changes around spur dike)

Figure 4-35 shows an example of different grain size distributions around an individual straight spur dikes in an assumed channel. Red and yellow dots represent sampling points of bed substrate with two different mean diameters. In Figure 4-36 the diversity index was calculated according to the Shannon's Diversity Index for each of those cases. With naked eye, it is obvious that diversity among those patterns is quite different, while the Shannon's Diversity Index gives unique index for all of them and does not reveal such a difference. This is a major weakness of the Shannon's Diversity Index (and similar index as well) in application for quantifying diversity index in practical cases. In current study, which the illustration of spatial distribution of flow variation and bed changes over an area is of main interest, deployment of new approach to quantify the diversity of habitat in channel due to installation of different types of spur dikes is necessary.

So far a few researchers have been trying to work out this deficiency of Shannon Diversity Index and similar approaches (Batty 1974, Gorelick 2006).

Claramunt (2005) proposed a method for entropy based clustering of data mining in the field of “knowledge discovery and data mining” by which he considered the average distances between patches of the same category of dataset and patches of different categories in that dataset. In other words, in order to reach the idea of “Spatial Diversity Index”, these two general rules were adopted (Wang and Wang 2011):

- Rule 1: when different entities are closer, diversity increases.
- Rule 2: when similar entities are closer, diversity decreases.

Stating these rules in quantitative expressions, the Eq. (4-12) will appear:

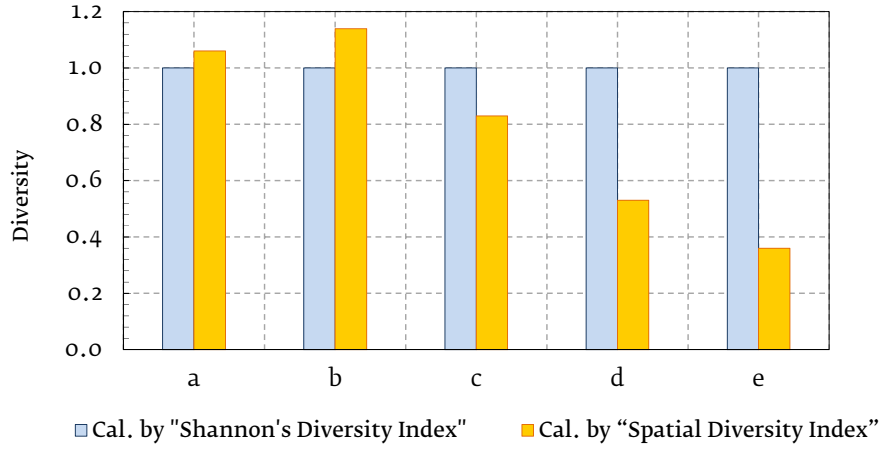


Figure 4-36. Values of Diversity index according to Shannon's Diversity Index

$$SDI = - \sum_{i=1}^n \frac{d_i^{int}}{d_i^{ext}} p_i \log p_i \quad (4-14)$$

in which d_i^{int} represents the average distance between the entities belonging to a given class i and d_i^{ext} denotes the average distance between the entities of a given class i and the entities of all the other class than i and are calculated as below:

$$d_i^{int} = \frac{1}{N_i * (N_i - 1)} \sum_{\substack{j=1 \\ j \in C_i}}^{N_i} \sum_{\substack{k=1 \\ k \neq j \\ k \in C_i}}^{N_i} dist(j, k) \quad \text{if } N_i > 1, \text{ otherwise } d_i^{int} = \alpha \quad (4-15)$$

$$d_i^{ext} = \frac{1}{N_i * (N - N_i)} \sum_{\substack{j=1 \\ j \in C_i}}^{N_i} \sum_{\substack{k=1 \\ k \neq j \\ k \notin C_i}}^{N - N_i} dist(j, k) \quad \text{if } N_i \neq N, \text{ otherwise } d_i^{ext} = \beta \quad (4-16)$$

and $dist(j, k)$ is the distance between two entities j and k . α is constant relatively small and β is a constant relatively high. In fact, in Eq. (4-14) the fraction of $\frac{d_i^{int}}{d_i^{ext}}$ is denotes whether the data over an area are “clustered” or “dispersed”.

The values of Diversity Index according to Eq. (4-14) are shown in Figure 4-36. The results show that these values are in consistent with general impression of diversity one might get from Figure 4-35. Therefore, in current study, the Eq. (4-14) is adopted in order to examine the spatial diversity and heterogeneity of flow and habitat in channel due to installation of different spur dikes.

Assessment of “Habitat Diversity”

“Habitat diversity” defined as the heterogeneity in the arrangement of physical and biological structure in the habitat surveyed (Lassau and Hochuli 2004). As for physical features of habitat, habitat diversity can be defined in various ways based on different abiotic characteristics. Several studies classified habitat as to Froude number (Jowett 1993, Danehy and Hassett 1996, Panfil and Jacobson 2005). In contrary, some researches discussed that areas with very different velocities and depths combinations may exhibit similar Froude numbers which may obscure important contrasts in habitat, such as those between channel margin and channel centerline environments (Clifford, Harmar et al. 2006). One solution to that was considering three most common habitats in streams (pool, run and riffle) as measures to define habitat diversity (Krueger and Frothingham 2007, Zhang, Wei et al. 2013). Zhang, Nakagawa et al. (2013) also used longitudinal bed profiles in addition to Froude number to highlight the influence of installation of spur dikes in a 90 degree channel bend on channel diversity.

Indeed, none of those criteria can solely represent the required habitat diversity for a biologically dynamic stream. Thus, in order to examine the habitat diversity due to installation of different types of spur dikes in current study, first the habitat diversity was investigated based on Froude number. In following, the spatial heterogeneity of bed variation (or depth) was also discussed for different types of spur dikes.

Finally, as discussed earlier, in order to compensate the limitation of Froude number to depict a comprehensive interpretation of habitat diversity in streams, habitat diversity was studied for the two most common habitats (pool, and riffle) which were defined based on combination of water depth and flow velocity along with Froude number. The description of these two habitat types was adopted according Table 4-6. Definition of Froude number (Fr) was adopted using Eq. (4-3) and for each case the diversity was studied using the data of 500 points in an area confined between 0.3 meter upstream of the first spur dike in series and the end of movable bed area in channel. The width of area was also limited to 0.3 meter beginning from spur dike-side channel bank toward the main channel.

Spatial Diversity of Habitat for Different Types of Spur Dikes

Effect of Head Shapes

Froude number discerns tranquil flow from broken and turbulent flow. Low values of Froude number are characteristic of pool habitats and higher values of riffle habitats (Allan and Castillo 2007, Harding 2009, Hauer and Lamberti 2011). To study the heterogeneity of habitat in the study area, in this first step, the classification of habitat was adopted using inter-class increment of 0.05 for values of Froude number (Kemp, Harper et al. 2000, Clifford, Harmar et al. 2006). In fact, it is assumed that a different class of Froude number is associated to different habitat types (Kemp, Harper et al. 2000).

The spatial diversity of Froude numbers in T-head spur dikes and straight spur dikes for different opening ratios was calculated using Eq. (4-14) and is plotted in Figure 4-37 (a). All Froude numbers were calculated using the simulated values of flow field by numerical model. If Froude number is regarded as indication for habitat types (Kemp, Harper et al. 2000), both types of spur dikes displayed relatively good values of habitat diversity with the spatial diversity index ranging from 2.01 to 3.15. Another impression of Figure 4-37 (a) is ability of straight spur dikes in providing Froude numbers with higher spatial diversity in study area. This superiority, however, is remarkable for opening ratio of below 3 and for spaces between spur dikes equals or greater than 3, the diversity of flow in both types are rather same.

Figure 4-37 (b) shows the spatial diversity of bed levels in T-head spur dikes and straight spur dikes. The T-head spur dikes could generally result in a bed with more diverse levels. The difference in diversity between T-head and straight spur dikes, however, is largely affected by spaces between spur dikes. In average, T-head could generate 17% more heterogeneous bed in study area than straight spur dikes.

The greatest effect of head shape on diversity of bed levels was also observed in opening ratio of 3 in which it could induce 40% increase in diversity of bed in study area. For opening ratio of 2, however, the diversity of bed levels is similar for both T-head and straight spur dikes.

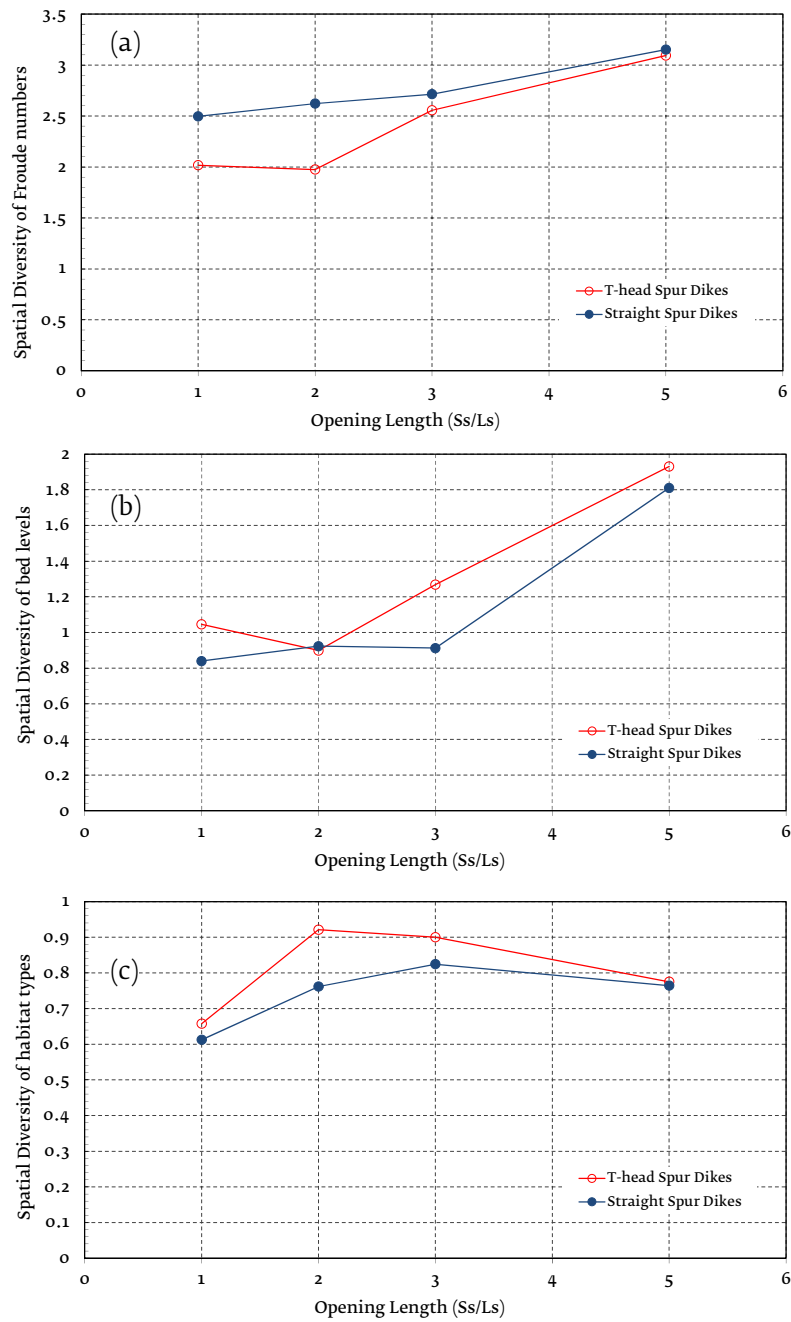


Figure 4-37. The spatial diversity of (a) Froude numbers (based on data of numerical modeling), (b) bed levels (based on data of experimental work) and (c) habitat types (pool and riffle) (based on data of numerical modeling) in T-head spur dikes and straight spur dikes for different opening ratios

Spatial diversity for two major habitat types (pool and riffle) was also quantified and the results are shown in Figure 4-37 (c). Generally, the T-head spur dikes provided better spatial distribution of pools and riffle over the study area. This better performance of T-head spur dikes differs for different opening ratio and is 20% at maximum for opening ratio of 2. In contrast, for opening ratios of 1 and 5 the capability of these two head shapes were relatively same. Habitat heterogeneity is essential for fish population as to providing higher overall source of food for different species and refugia from predation and harsh river flows. In this regard, the T-head spur dikes turns out to be better choice for ecology of stream.

Effect of Opening Ratio

By changing the opening ratio for same head shape of spur dike, there are several interesting points according to the Figure 4-37.

In straight spur dikes, the rate of changing in spatial distribution of Froude number (Figure 4-37 (a)) is constantly growing by increasing the opening ratio. On the other hand, in T-head spur dikes, for opening ratios equal and less than 2 there is no significant change in spatial diversity of Froude. Nonetheless, for opening ratio of 3 and above, the rate of diversity soars and is continuously rising by increasing the opening ratio. In overall, the opening ratios of 3 – 5 for both head shapes showed the best performance to enhance more diverse habitat.

Concerning spatial diversity of bed levels (Figure 4-37 (b)), in straight spur dikes, the diversity of bed for opening ratio of 1-3 is rather same which agrees with observations of Figure 4-12. Alternatively, the diversity of straight spur dikes will steadily increase for opening ratios of 3-5. As for T-head shape, however, after a little drop in opening ratio of 2 compared to 1, the greater bed diversity was observed for higher opening ratios in range of 2-5. The constantly increasing rate of diversity for opening ratio of 3 to 5 for T-head spur dikes might be due to the fact that for this range of opening ratios the enough room for formation of scour holes around all spur dikes and deposition of point bars in spur dikes' field was available between spur dikes.

In general, opening ratio of 5 in both head shapes of spur dike was the best case in terms of providing spatially heterogeneous bed over the study area affected by presence of spur dikes.

For the different head shape of spur dikes, the spatial diversity of pool and riffle (Figure 4-37 (c)) shows different variation for changing in opening ratio. While for both head shapes the minimum diversity for these two fundamental habitat types was observed in opening ratio of 1, the maximum diversity of habitat types was found to be in case with opening ratio of 2 for T-head spur dikes and 3 for straight spur dikes. In other words, in opening ratio of 2-5 for T-head spur dikes and 3-5 for straight spur dikes, the greater opening ratio gives less diversity of habitat types. Overall, an opening ratio of 2-3 for both head shape of spur dike may be recommended to advance the spatial distribution of ecologically suitable habitats in rivers.

4.4.1.3 Temporal Development of Channel Morphology Due to Series of Spur Dikes

Figure 4-38 shows the temporal changes of bed due to installation of T-head spur dikes over two hours. The beginning time in all images is set to 12:00:00 and the direction of flow is from right to left. As can be seen in this figure, just a short moments after beginning of the experiment (Figure 4-38, minute 12:01:00), in the region around the upstream tip of the first spur dike's wing, the erosion has begun.

Referring to the Section 3.3.7, it turns out that this point is the most high stress region of channel in fixed bed condition. Then this observation is in consistent with the result of fixed bed channel study. Elapsing time, developing this small scour hole by a set of 3D vertical horse show vortices causes the depth of scouring hole in the region increases (Figure 4-38, minute 12:03:00) and in the next stage, the transport of the eroded sediment particles along the direction of shear flow leads to formation of the ridge of point bar just in front of spur dike's field (Figure 4-38, minute 12:05:00).

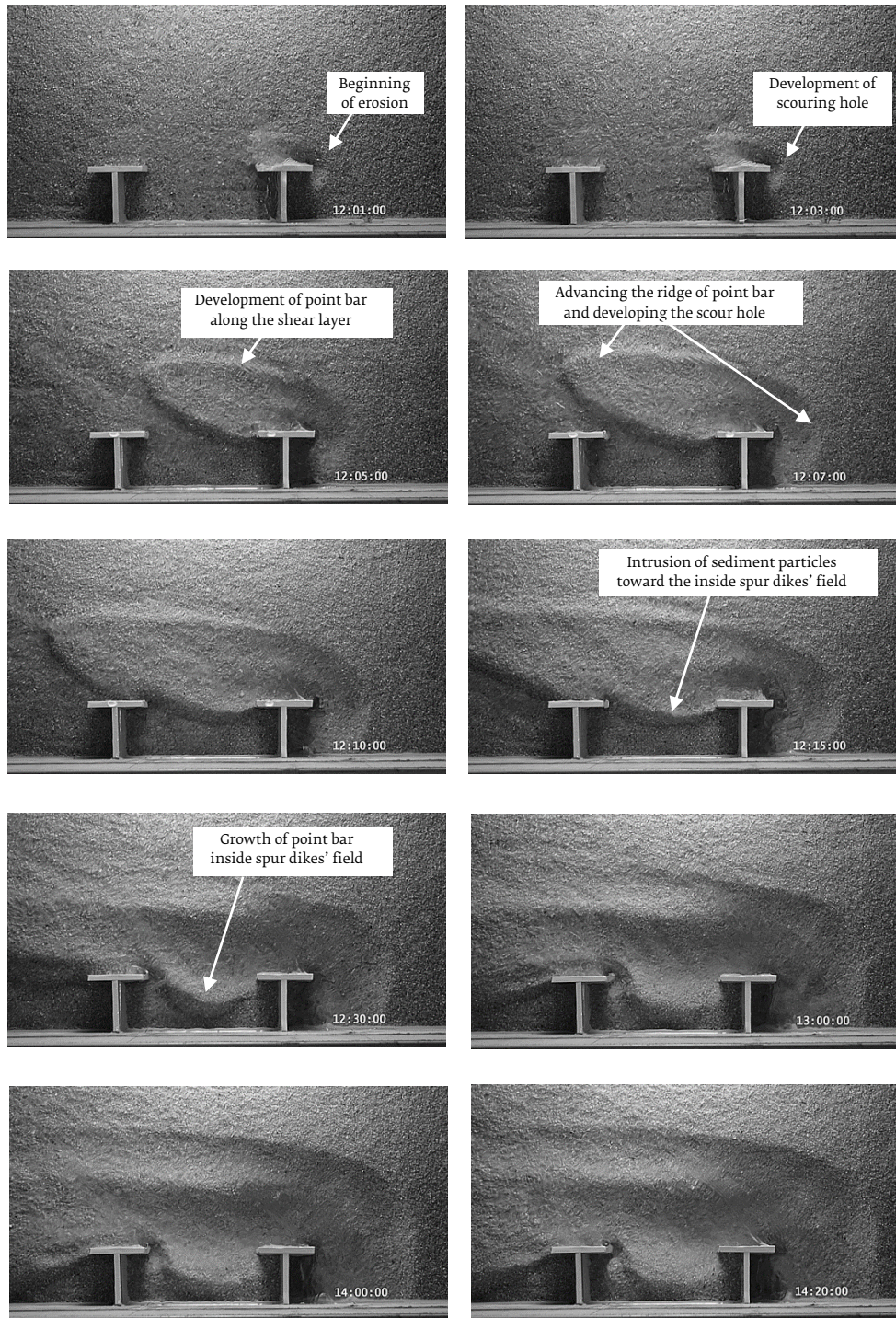


Figure 4-38. Temporal changes of bed level due to the series of T-head spur dikes
(The beginning time in above images is set to 12:00:00)

From this moment on, the development of scour hole's dimensions and advancing the crest of point bar which chiefly follows the direction of flow in front of the spur dikes took place together (Figure 4-38, minute 12:10:00).

Another interesting point here is that, it is just after the point bar passed the second spur dike, when the direct of sediment particles deviated their path towards the inside of spur dikes' field (Figure 4-38, minute 12:15:00). From this moment on (15 minutes after beginning of the experiment) the main phenomenon is the growth of point bar inside of the spur dikes' field (Figure 4-38, minutes 12:30:00). 30 minutes after the beginning of the experiment, almost all phenomena due to spur dikes has been shaped and the rest of experiment led to reaching the equilibrium state of those ones.

Conclusion and Recommendations

In this study, laboratory experiments and numerical simulation of flow structure and sediment transport in series of spur dikes with different head shapes (T-head and straight type spur dikes) were carried out. In the first stage, several series of experiments were done in order to shed some light on the structure of flow in two simple cases of series of T-head and straight spur dikes in fixed bed channel. Following on, using validation of 3D RANS numerical model, the 3D flow pattern around these types of spur dikes was elaborated in detail. In the second stage of the study, some sets of experiments were accomplished to study sediment transport in series of T-head spur dikes in emerged and submerged condition. In this stage, the numerical model was also utilized to examine the performance of this type of spur dike and its distinctions with typical straight type of spur dike.

In this chapter, the conclusions of different parts of current study will be given and the recommendation for future studies will be presented in the following.

5.1 Conclusions

The most important conclusions of current study are summarized as follows:

5.1.1 Fixed Bed Channel Case

- Examining the results of experimental data for fixed bed channel showed that in all emerged cases the three phenomena of the flow separation at head of spur dike, the reduction of flow at the wake of spur dike and the flow acceleration in the main channel can be clearly seen.
- It turned out that in T-head spur dikes, the magnitude of velocity vectors inside the spur dikes' fields are much smaller than the similar area in straight spur dikes.
- While in all cases, one main recirculating zone is visible inside the spur dikes' fields, in T-head shape spur dikes, for opening ratio equal or less than 3, there is one counter-rotating cell near the second spur dike in series.
- The length and width of the recirculation zone (reattachment length) for the T-head spur dike is less than those amounts of straight spur dikes.
- The presence of the wing of the T-head spur dike has significant effects on the formation of horseshoe vortices around the spur dikes in the series.
- The existence of the wing can increase the stability of the body of the spur dike against the erosion because of the moving the high-stress (energetic) regions away from the body.
- In general, for T-head spur dikes, one might expect the reduction of potential erosion near the channel bank and increase of sediment deposition in that area which can improve the protection of bank erosion and might help in providing richer environment for fish eggs.

5.1.2 Movable Bed Channel Case

- The presence of wing in T-head spur dikes has significant effects on the bed changes. In all opening ratios the presence of the wing of the spur dikes, made a sort of uniform pattern alongside of the spur dikes' field and wing was able to prevent the extension of scour hole inside the spur dike's field.

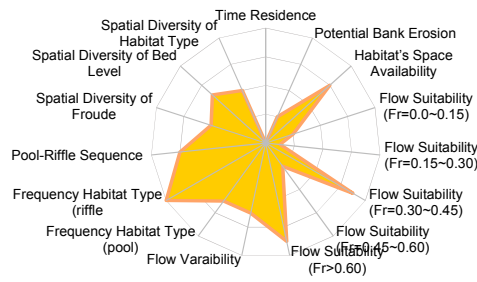
- Comparing different OR in straight type shows a lag in similar behavior compared to the series of T-head spur dikes. In other words, while the formation of point bar in the first field of T-shape spur dikes, was started from OR=1 and then moved to the upstream at OR=2 and expanding from OR=3, in straight type spur dikes this trend has been observed from OR=2 (instead of OR=1).
- In T-head spur dikes, before OR=3, there is no significant changes inside the field and it is just after OR=3 in which a visible point bar was formed between second and third spur dikes. While in the straight type spur dikes, the formation of point bar was started from OR=1.
- In general, the first results of this study highlight the particular rule of the wing in the control of sediment transport in the first and second spur dike's fields.
- In submerged conditions, in general, by occurrence of overflowing, the features of bed changes have been growing less and less. However, in overtopping ratio of 1.2 (which denotes boundary-flooding condition) in the first spur dikes' field (between the first and second spur dikes) the amount and general extension of point bar has been remarkably increased. It might be due to fact that in such a case in which the spur dikes are under a boundary overflow, the body of structure will acts as a weir and in the area just behind the first spur dike, a relatively strong jet flow will emerged which can lead to deposition of sediment particles in this region.
- In terms of maximizing benefits to aquatic habitat's space availability, in all opening ratios, T-head spur dikes can give larger scoured area than straight spur dikes do, specifically for opening ratios of less than 3, that means they are potentially more beneficial in terms of space availability for fish habitat.
- For the same type of spur dike, opening ratio of 2 for T-head spur dikes has the best performance in proving largest pools in channel. For straight spur dikes, the greatest pools were observed in opening ratio of 5.

- In terms of effect of spur dike's type on flow suitability, T-head spur dikes showed the higher frequency for different range of Froude numbers ($Fr=0.0\sim0.15$; $0.15\sim0.30$; $0.30\sim0.45$; >0.6). Moreover, the wider distribution of water depth and velocity for T-head spur dikes obviously suggests the better performance of T-head spur dikes to improve the flow variation in these cases. The greater number of two fundamental habitat (pool and riffle) in case of T-head spur dikes also proves the better capability of them in enhancement of suitable physical habitats in streams after installation of the T-head spur dikes.
- For the same type of spur dike, pool habitat was more frequent in opening ratios of 2 and 3 for both types of spur dikes (with 27% and 25% of frequency in case of T-head spur dikes and 23% and 29% for straight spur dikes). The riffle habitats, however, were observed most in case of opening ratio 1 and 2 for T-head (with 45% and 44% of frequency) and 2 and 3 (with 37% and 42% of frequency) for straight spur dikes. As a result, an opening ratio of 2 for spur dikes with T-shape head and 3 for straight spur dikes can be suggested to enhance ecologically suitable habitat types in stream.
- It turns out that T-head spur dikes could show better performance in increasing the frequency of pool-riffle units, specifically in the second half of channel, and as increasing the number of pool and riffle directly affects the chance of potential favorable physical habitat along the river, it is expected they can improve complexity and heterogeneity of habitat types required for biodiversity. In addition, opening ratio of 3 could induce greatest number of pools and riffles in channel.
- In terms of bed diversity, analysis of spatial diversity of bed levels in T-head spur dikes and straight spur dikes for different opening ratios turned out that the T-head spur dikes could lead to more diverse bed for all opening ratios.
- The greatest effect of head shape on diversity of bed levels was also observed in opening ratio of 3 in which it could induce 40% increase in diversity of bed in study area.

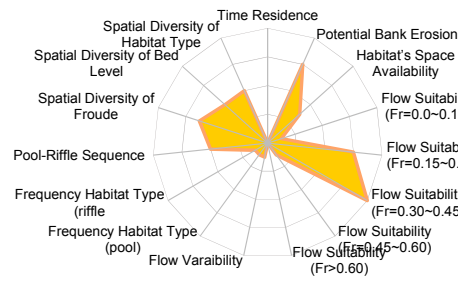
- For the same type of spur dike, opening ratio of 5 in both head shapes of spur dike was the best case in terms of providing spatially heterogeneous bed over the study area affected by presence of spur dikes.
- Straight spur dikes are more competent in providing Froude numbers with higher spatial diversity in study area. This superiority, however, is remarkable for opening ratio of below 3 and for spaces between spur dikes equals or greater than 3, the diversity of flow in both types are rather same.
- The T-head spur dikes provided better spatial distribution of pools and riffle over the study area.
- For the same type of spur dike, overall, an opening ratio of 2–3 for both head shape of spur dike may be recommended to advance the spatial distribution of ecologically suitable habitats in rivers.
- Temporal changes of temporal changes of bed due to installation of T-head spur dikes over time showed that the beginning point of erosion in T-head spur dike is region around the upstream tip of the first spur dike's wing.
- The deviation of sediment particles' movement towards inside the spur dikes' field begun no sooner than when the point bar passed the second spur dike.
- 30 minutes after the beginning of the experiment, almost all phenomena due to spur dikes has been shaped and the rest of experiment led to reaching the equilibrium state of those ones.
- The numerical modeling of sediment transport in series of T-head spur dikes showed that the best results was achieved by using Dey empirical formula for reduction of critical shear stress in sloping bed along with SOU discretization approach. The selection of appropriate mesh along with controlling instability of solution is of great importance. These issues were met in current study by refining an appropriate mesh and introducing suitable relaxation factor to the model.

To have a better imagination of the performance of each type of spur dike, star plots of each case are shown in Figure 5-1. In this figure, in each plot, for any specific studied parameter

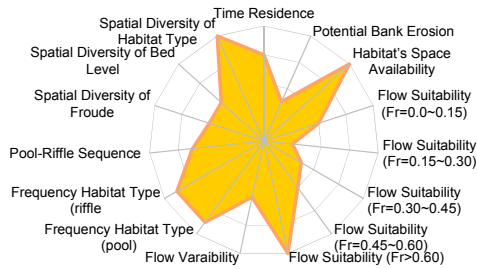
Conclusion and Recommendations



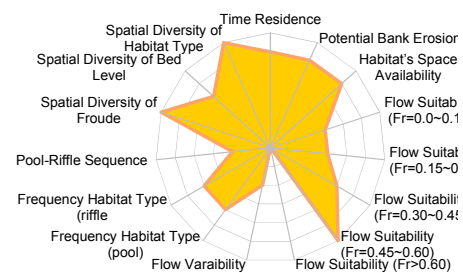
T-head (Ss/Ls=1)



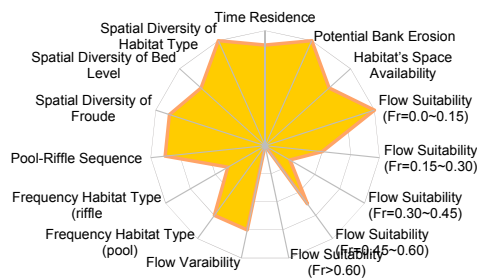
Straight (Ss/Ls=1)



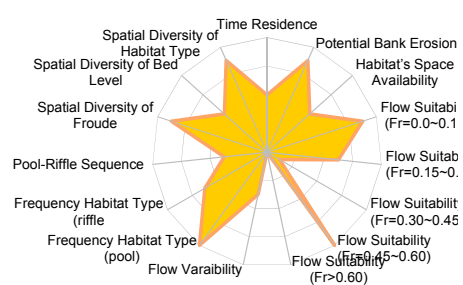
T-head (Ss/Ls=2)



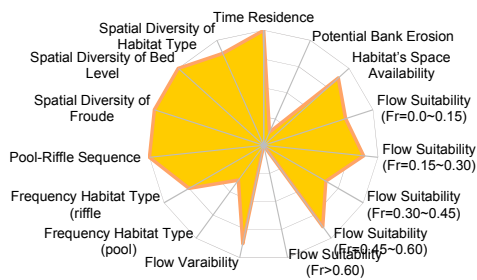
Straight (Ss/Ls=2)



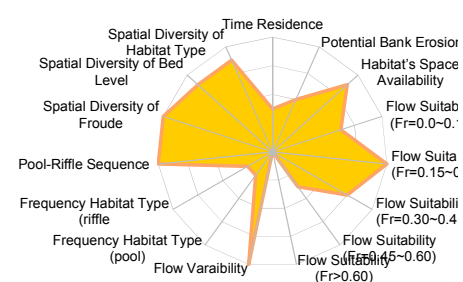
T-head (Ss/Ls=3)



Straight (Ss/Ls=3)



T-head (Ss/Ls=5)



Straight (Ss/Ls=5)

Figure 5-1. Star plots of performance of T-head and straight type spur dikes with different opening ratios (Ss/Ls)

a score was given. The maximum score (8) was given to the case with the best performance for the studied parameter and minimum score was given to the case with the worst performance for the studied parameter. It is clear that, in general, T-head spur dikes proves the better capability of them in enhancement of suitable physical habitats in streams after installation of spur dikes. The greatest effect of head shape on providing suitable physical habitats was also observed in $Ss/Ls=3$. For straight type, however, the best performance in terms of providing suitable physical habitats also observed in $Ss/Ls=2$ and 3.

5.2 Recommendations

Future researches are essential to enhance the knowledge about performance of spur dikes as an effective measure to control bank erosion, better navigation, as well as providing better habitat for fish and other stream's inhabitants. Several recommendation for further study can include:

1. Consideration of non-uniform sediment in the study can be a fascinating topic. As in all cases of current study the sediment was chosen uniform, the non-uniform sediment can turn the experiments closer to the natural situation. Study of several phenomena such as armoring, pattern of deposition of fine and coarse sediment and etc. are of great interest.
2. There is still lack of knowledge about the quality of exchange of mass and momentum in the interface between spur dike's fields and main stream. In this regard paying attention to the vertical distribution of exchange of mass and momentum is of great importance.
3. Study of suspended sediment and quality of deposition of suspended sediment in spur dikes field is also another interesting theme. Besides, considering the live bed condition will also give us exciting results about what happens in conditions close to natural river.

4. The investigation about the ecological implication of installing spur dikes would not be complete if the effects on biotic parameters in case of presence of spur dikes are not considered.
5. This type of topic for study, especially when the focus of study is about ecological aspect of spur dikes will be further comprehensive and complete, in case field study is carried out as well. Experimental analysis and/or numerical and habitat modeling of ecological implication of spur dike can be completed by carrying out similar study in field site. Field survey can give more precise and practical image of the effect of spur dikes on stream ecology.

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List of Figures

FIGURE 1-1. A COMPOUND (PARTLY PERMEABLE AND PARTLY IMPERMEABLE) SPUR DIKE IN ARKANSAS IN US (YASI 2009)	3
FIGURE 1-2. A SERIES OF SPUR DIKES IN RIVER ELBE, GERMANY WITH DIFFERENT ORIENTATION (WEITBRECHT 2004)	4
FIGURE 1-3. LEFT: DIFFERENT KINDS OF SPUR DIKES IN PLAN VIEW; RIGHT: A T-HEAD SPUR DIKE CONSTRUCTED IN RIVER ALLARO, ITALY (VIA MACCAFERRI.COM)	5
FIGURE 1-4. AN SPUR DIKE WITH TRAPEZOIDAL SHAPE CROSS SECTION AT SARAKHS RIVER, IRAN (YASI 2009)	8
FIGURE 1-5. SPUR DIKES FOR PROTECTING BANKS IN ZANJANROOD RIVER, IRAN (IMAGE COURTESY OF GOOGLE)	10
FIGURE 1-6. SPUR DIKES FOR LANDSCAPE IMPROVEMENT AND PROTECTING BANKS IN TOKACHI RIVER, JAPAN (INSTALLATION -LEFT- AND IMMEDIATELY AFTER FLOOD -RIGHT-) (HONG KOO 2007)	11
FIGURE 1-7. SPATIAL DISTRIBUTION OF SURFACE RADIANT TEMPERATURES USING TIR IMAGERY IN ODER RIVER, GERMANY (TONOLLA, WOLTER ET AL. 2012).....	12
FIGURE 1-8. SCHEMATIC OF WORKFLOW OF CURRENT DISSERTATION BASED UPON THE REQUIRED PARAMETERS FOR STUDY ON DIFFERENT ASPECTS OF INSTALLATION OF SPUR DIKES	15
FIGURE 2-1. (RIGHT) SHEAR STRESS AMPLIFICATION CONTOURS FOR A SINGLE T-HEAD SPUR DIKES WITH DIFFERENT WING’S LENGTH(SAFARZADEH, NEYSHABOURI ET AL. 2010); (LEFT) BED CHANGES DUE TO PRESENCE OF T-HEAD SPUR DIKE IN 90-DEGREE CHANNEL BEND(GHODSIAN AND VAGHEFI 2009)	23
FIGURE 2-2. TIME-AVERAGED VELOCITY VECTORS ON HORIZONTAL PLANE NEAR THE MIDDLE OF WATER DEPTH IN A BOX WITH L-HEAD AND STRAIGHT TYPE SPUR DIKES (CAI AND TOMINAGA 2012)	32

FIGURE 2-3. DISTRIBUTION PATTERN OF TWO NON-INDIGENOUS AQUATIC MACROINVERTEBRATES AND TWO INDIGENOUS AQUATIC MACROINVERTEBRATE TAXA WITHIN A SPUR DIKE'S FIELD IN ELBE RIVER, GERMANY (EGGERS, KLEINWÄCHTER ET AL. 2003).	34
FIGURE 3-1. A VIEW OF CHANNEL USED FOR FIXED BED EXPERIMENTS	40
FIGURE 3-2. SCHEMATIC VIEW OF FLUME AND SPUR DIKES.....	40
FIGURE 3-3. T-HEAD SPUR DIKES USED IN THE FIXED BED EXPERIMENTS	41
FIGURE 3-4. (LEFT) THE CAMERA USED FOR RECORDING THE CONTINUES IMAGES; (RIGHT) WHITE PVC TRACER PARTICLES	43
FIGURE 3-5. (LEFT) A VIEW BRIDGE CONSTRUCTED OVER THE FLUME TO MOUNT THE CAMERA; (RIGHT) SCALED SHEET USED FOR CALIBRATION OF RECORDED IMAGES.	43
FIGURE 3-6. AN EXAMPLE OF OUTPUT OF THE PIVLAB SOFTWARE	44
FIGURE 3-7. FLOW VELOCITY VECTORS ON THE WATER SURFACE FOR T-HEAD SPUR DIKES (A) $S_s/L_s=2$, (B) $S_s/L_s=3$, AND (C) $S_s/L_s=6$	46
FIGURE 3-8. FLOW VELOCITY VECTORS ON THE WATER SURFACE FOR STRAIGHT SPUR DIKES (A) $S_s/L_s=2$, (B) $S_s/L_s=3$, AND (C) $S_s/L_s=6$	47
FIGURE 3-9. FLOW VELOCITY VECTORS ON THE WATER SURFACE FOR T-HEAD SPUR DIKES ($S_s/L_s=2$) AT DIFFERENT SUBMERGENCE RATIO (A) $H_w/H_s < 1$, (B) $H_w/H_s=1.2$ AND (C) $H_w/H_s=2$	48
FIGURE 3-10. FLOW VELOCITY VECTORS ON THE WATER SURFACE FOR T-HEAD SPUR DIKES ($S_s/L_s=3$) AT DIFFERENT SUBMERGENCE RATIO (A) $H_w/H_s < 1$, (B) $H_w/H_s=1.2$ AND (C) $H_w/H_s=2$	49
FIGURE 3-11. FLOW VELOCITY VECTORS ON THE WATER SURFACE FOR T-HEAD SPUR DIKES ($S_s/L_s=6$) AT (A) $H_w/H_s < 1$, (B) $H_w/H_s=1.2$ AND (C) $H_w/H_s=2$	50
FIGURE 3-12. FLOW STREAMLINES ON THE WATER SURFACE FOR T-HEAD AND STRAIGHT SPUR DIKES (A) $S_s/L_s=2$, (B) $S_s/L_s=3$, AND (C) $S_s/L_s=6$	50
FIGURE 3-13. MEASURED MEAN RESIDENCE TIME IN SPUR DIKES' FIELD FOR DIFFERENT OPENING RATIOS.....	52
FIGURE 3-14. THE ACCUMULATION OF ALL FUNCTIONAL GROUPS OF PLANKTON IN SIDE-ARMS OF DANUBE AFTER A FLOOD PULSE (HEIN, BARANYI ET AL. 2003, HEIN, RECKENDORFER ET AL. 2005).	53
FIGURE 3-15. MASS EXCHANGE COEFFICIENT IN SPUR DIKES' FIELD FOR DIFFERENT OPENING RATIOS	55

FIGURE 3-16. THE WAY OF CALCULATION THE VALUE OF U IN WEST (W) SIDE OF CENTER CELL (P) USING SOU SCHEME	59
FIGURE 3-17. A VIEW OF THE GRID USED FOR SIMULATION OF CASES.....	61
FIGURE 3-18. VERIFICATION OF NUMERICAL SIMULATION WITH EXPERIMENTAL DATA (VELOCITY MAGNITUDE AT WATER SURFACE) ○ EXPERIMENTAL DATA — NUMERICAL RESULTS	61
FIGURE 3-19. STREAMLINE AND CONTOUR OF MAGNITUDE OF VELOCITY IN WATER SURFACE PLANE FOR EXPERIMENTAL DATA (ABOVE) AND NUMERICAL RESULTS (BELOW)	62
FIGURE 3-20. SCHEMATIC VIEW OF THE POSITION OF THE STUDIED PLANES.....	64
FIGURE 3-21. PATH OF THE STREAMLINES OF FLOW IN THE PLANE NEAR THE WATER SURFACE (ABOVE) AND THE PLANE CLOSE TO THE BED (BELOW) IN STRAIGHT SPUR DIKES ($S_s/L_s=2$)	65
FIGURE 3-22. PATH OF THE STREAMLINES OF FLOW IN THE PLANE NEAR THE WATER SURFACE (ABOVE) AND THE PLANE CLOSE TO THE BED (BELOW) IN T-HEAD SPUR DIKES ($S_s/L_s=2$).....	65
FIGURE 3-23. CONTOUR OF VELOCITY MAGNITUDE IN THE PLANE NEAR THE WATER SURFACE (ABOVE) AND THE PLANE CLOSE TO THE BED (BELOW)	66
FIGURE 3-24. CONTOUR OF VERTICAL COMPONENT OF VELOCITY IN THE PLANE CLOSE TO THE BED	67
FIGURE 3-25. PATHS OF THE STREAMLINES FOR SERIES OF STRAIGHT TYPE SPUR DIKES (LEFT) AND T-HEAD SPUR DIKES (RIGHT) IN THREE LONGITUDINAL SECTIONS: ABOVE: $Y/L=0.1$; MIDDLE: $Y/L=0.5$; BELOW: $Y/L=1$	69
FIGURE 3-26. THE PATH OF STREAMLINE AND THE CONTOUR OF TURBULENCE KINETIC ENERGY (TKE) IN THREE DIFFERENT CROSS SECTIONS AROUND SPUR DIKES' FIELD (LEFT: STRAIGHT TYPE SPUR DIKES ; RIGHT: T-HEAD SPUR DIKES) I: THE PLANE 1D; II: THE PLANE 2D; III: THE PLANE 3D.....	69
FIGURE 4-1. EXPERIMENTAL FLUME; (LEFT) FLUME INLET ;(RIGHT) FLUME OUTLET.....	72
FIGURE 4-2. SCHEMATIC VIEW OF EXPERIMENTAL SETUP; SIDE VIEW (TOP) AND TOP VIEW (BOTTOM) (NOT SCALED).....	73
FIGURE 4-3. (LEFT) STRAIGHT SPUR DIKE, AND (RIGHT) T-HEAD SPUR DIKES USED IN THE EXPERIMENTAL SETUP	75
FIGURE 4-4. GRAIN SIZE DISTRIBUTION OF SEDIMENT USED IN THE EXPERIMENT CHANNEL	77
FIGURE 4-5. V-NOTCH WEIR AND VERNIER POINT GAUGE FOR CONTROLLING WATER DISCHARGE	78
FIGURE 4-6. TIME EVOLUTION OF THE MAXIMUM SCOUR DEPTH IN THE SCOUR HOLE OF THE FIRST SPUR DIKE OF SERIES FOR THE CONTROL TEST CASE	79

FIGURE 4-7. THE VERNIER POINT GAUGE USED FOR MEASURING THE WATER LEVEL IN DIFFERENT CROSS SECTIONS ALONG THE CHANNEL.....	80
FIGURE 4-8. SET OF LASER DISPLACEMENT SENSOR USED FOR MEASURING THE FINAL BED DEFORMATION.....	81
FIGURE 4-9 . REPRESENTATION OF MEASURING POINTS FOR A CASE OF T-HEAD SPUR DIKES WITH OPENING RATIOS OF 2.0, CAPTURED BY LASER BED PROFILER	82
FIGURE 4-10. THE SCAFFOLD MOUNTED FOR HOLDING THE DIGITAL CAMERAS (RIGHT PHOTO) WHICH WERE USED FOR MONITORING BED FORM MIGRATION	83
FIGURE 4-11. EQUILIBRIUM BED LEVELS IN A SERIES OF T-HEAD SPUR DIKES (A) $S_s/L_s = 1$ (B) $S_s/L_s = 2$ (C) $S_s/L_s = 3$ (D) $S_s/L_s = 5$ ALL CASES ARE EMERGED ($H_w/H_s < 1$)	84
FIGURE 4-12. EQUILIBRIUM BED LEVELS IN A SERIES OF STRAIGHT SPUR DIKES (A) $S_s/L_s = 1$ (B) $S_s/L_s = 2$ (C) $S_s/L_s = 3$ (D) $S_s/L_s = 5$ ALL CASES ARE EMERGED ($H_w/H_s < 1$)	85
FIGURE 4-13. EQUILIBRIUM BED LEVELS IN A SERIES OF T-HEAD SPUR DIKES WITH DIFFERENT SUBMERGENCE RATIOS (A) $H_w/H_s < 1$ (B) $H_w/H_s = 1.2$ (C) $H_w/H_s = 1.7$ (D) $H_w/H_s = 3.4$	88
FIGURE 4-14. LONGITUDINAL AND TRANSVERSAL ANGLES ON A SLOPING BED CELL.....	93
FIGURE 4-15. THE COMPARISON BETWEEN EXPERIMENTAL DATA (ABOVE) AND NUMERICAL RESULT (BELOW) FOR CASES WITH $S_s/L_s = 1$. (POW,LANE (1955)'S FORMULA WERE USED)	95
FIGURE 4-16. THE COMPARISON BETWEEN EXPERIMENTAL DATA (ABOVE) AND NUMERICAL RESULTS (BELOW) FOR CASES WITH $S_s/L_s = 3$ (LEFT) AND $S_s/L_s = 5$ (RIGHT). (POW,LANE (1955)'S FORMULA WERE USED)	96
FIGURE 4-17. THE COMPARISON BETWEEN EXPERIMENTAL DATA AND NUMERICAL RESULTS FOR CASES WITH $S_s/L_s = 1$ (LEFT) AND $S_s/L_s = 3$ (RIGHT); DIFFERENT NUMERICAL APPROACHED WERE USED.....	97
FIGURE 4-18. THE OLD (LEFT) AND NEW FINE MESH (RIGHT) DEPLOYED FOR THE AREA BETWEEN FIRST AND SECOND SPUR DIKES.....	98
FIGURE 4-19. THE COMPARISON BETWEEN EXPERIMENTAL DATA AND NUMERICAL RESULTS FOR CASE WITH $S_s/L_s = 3$ MODELED IN FINE MESH	99
FIGURE 4-20. FINAL NUMERICAL RESULTS FOR CASE WITH $S_s/L_s = 1$ (ABOVE), $S_s/L_s = 3$ (MIDDLE) AND $S_s/L_s = 5$ (BELOW) (RIGHT COLUMN: EXPERIMENTAL DATA; LEFT COLUMN: NUMERICAL RESULTS)	100

FIGURE 4-21. NUMERICAL RESULTS FOR CASE WITH $S_s/L_s=3$ MODELED IN A FINER MESH PRODUCED BY DOUBLING THE NUMBER OF TRANSVERSE CELLS	100
FIGURE 4-22. THE POTENTIAL BANK EROSION FOR T-HEAD AND STRAIGHT TYPE SPUR DIKES WITH DIFFERENT OPENING RATIOS (ALL CASES ARE EMERGED), CALCULATED BASED ON EXPERIMENTAL DATA	103
FIGURE 4-23. THE POTENTIAL BANK EROSION FOR T-HEAD SPUR DIKES WITH DIFFERENT SUBMERGENCE RATIOS, CALCULATED BASED ON EXPERIMENTAL DATA	104
FIGURE 4-24. THE VOLUME OF SCOUR BELOW LEVEL “-1” CM IN T-HEAD AND STRAIGHT TYPE SPUR DIKES WITH DIFFERENT OPENING RATIOS (S_s/L_s), CALCULATED BASED ON EXPERIMENTAL DATA	108
FIGURE 4-25. THE PLANAR AREA OF SCOUR ZONES BELOW LEVEL “-1” CM IN T-HEAD AND STRAIGHT TYPE SPUR DIKES WITH DIFFERENT OPENING RATIOS (S_s/L_s), BASED ON EXPERIMENTAL DATA.....	109
FIGURE 4-26. THE SURFACE AREA OF SCOUR ZONES BELOW LEVEL “-1” CM IN T-HEAD AND STRAIGHT TYPE SPUR DIKES WITH DIFFERENT OPENING RATIOS (S_s/L_s), BASED ON EXPERIMENTAL DATA.....	109
FIGURE 4-27. (A) THE VOLUME, (B) PLANAR EXTENSION, AND (C) SURFACE AREA OF POOLS FOR T-HEAD SPUR DIKE’S WITH DIFFERENT HEIGHTS (H_w/H_s), BASED ON EXPERIMENTAL DATA.....	111
FIGURE 4-28. CLASSIFICATION OF POOL, RUN, AND RIFFLE HABITATS BY VELOCITY /DEPTH RATIOS (V/D) OF 1.24 AND 3.20 AND FROUDE NUMBERS (Fr) OF 0.18 AND 0.41; ILLUSTRATING THE SEPARATION OF POOL (TRIANGLES) AND RIFFLE (SQUARES) HABITAT (A) AND THE RANGE OF VELOCITIES AND DEPTHS CLASSED AS RUN (CIRCLES) HABITAT (B) (JOWETT 1993).....	114
FIGURE 4-29. HISTOGRAMS OF FROUDE NUMBER AT DIFFERENT TYPES OF SPUR DIKES, CALCULATED BASED ON RESULTS OF NUMERICAL MODELING.....	116
FIGURE 4-30. THE SCATTERPLOT OF VELOCITY AND DEPTH DATA AROUND SPUR DIKES WITH DIFFERENT HEAD SHAPES AND OPENING RATIOS (RIGHT: T-HEAD, LEFT: STIAIGHT TYPE; (A,E) $S_s/L_s=1$, (B,F) $S_s/L_s=2$, (C,G) $S_s/L_s=3$, (D,H) $S_s/L_s=5$), CALCULATED BASED ON RESULTS OF NUMERICAL MODELING	118
FIGURE 4-31. HISTOGRAMS OF HABITAT TYPES AT SPUR DIKES WITH DIFFERENT HEAD SHAPES (ABOVE) AND OPENING RATIOS (BELOW), CALCULATED BASED ON RESULTS OF NUMERICAL MODELING	119
FIGURE 4-32. HISTOGRAMS OF FROUDE NUMBER AT SPUR DIKES WITH DIFFERENT OPENING RATIOS (ABOVE: T-HEAD SPUR DIKES; BELOW: STRAIGHT TYPE SPUR DIKES), CALCULATED BASED ON RESULTS OF NUMERICAL MODELING...	120

FIGURE 4-33. THE LONGITUDINAL BED PROFILE ALONG THE INTERFACE BETWEEN SPUR DIKES' FIELDS AND MAIN CHANNEL, CALCULATED BASED ON DATA OF EXPERIMENTAL RESULTS	123
FIGURE 4-34. THE EFFECT OF DIFFERENT OPENING RATIOS ON THE FORMATION OF CHANNEL MORPHOLOGY IN (A) T-HEAD AND (B) STRAIGHT SPUR DIKES, CALCULATED BASED ON DATA OF EXPERIMENTAL RESULTS.....	124
FIGURE 4-35. EXAMPLE OF DIFFERENT GRAIN SIZE DISTRIBUTIONS AROUND AN INDIVIDUAL STRAIGHT SPUR DIKES (THE BOLD LINE: SPUR DIKE; RED AND YELLOW DOTS: SAMPLING POINTS WITH TWO DIFFERENT MEAN DIAMETER; BACKGROUND: THE SCHEMATIC BED CHANGES AROUND SPUR DIKE)	128
FIGURE 4-36. VALUES OF DIVERSITY INDEX ACCORDING TO SHANNON'S DIVERSITY INDEX	129
FIGURE 4-37. THE SPATIAL DIVERSITY OF (A) FROUDE NUMBERS (BASED ON DATA OF NUMERICAL MODELING), (B) BED LEVELS (BASED ON DATA OF EXPERIMENTAL WORK) AND (C) HABITAT TYPES (POOL AND RIFFLE) (BASED ON DATA OF NUMERICAL MODELING) IN T-HEAD SPUR DIKES AND STRAIGHT SPUR DIKES FOR DIFFERENT OPENING RATIOS.....	132
FIGURE 4-38. TEMPORAL CHANGES OF BED LEVEL DUE TO THE SERIES OF T-HEAD SPUR DIKES (THE BEGINNING TIME IN ABOVE IMAGES IS SET TO 12:00:00)	135
FIGURE 5-1. STAR PLOTS OF PERFORMANCE OF T-HEAD AND STRAIGHT TYPE SPUR DIKES WITH DIFFERENT OPENING RATIOS (S_s/L_s)	142

List of Tables

TABLE 2-1. THE RESEARCHES ON “SINGLE STRAIGHT” SPUR DIKE	19
TABLE 2-2. THE PREVIOUS RESEARCHES ABOUT “SINGLE” T-HEAD AND L-HEAD SPUR DIKE	21
TABLE 2-3. THE PREVIOUS RESEARCHES ABOUT “SERIES OF” “STRAIGHT” SPUR DIKE	25
TABLE 2-4. THE PREVIOUS RESEARCHES ABOUT “SERIES OF” “T-HEAD AND L-HEAD” SPUR DIKE	31
TABLE 3-1. DETAILS OF EXPERIMENTAL HYDRAULIC CONDITIONS IN FIXED-BED CHANNEL	41
TABLE 3-2. SUMMARY OF MEASUREMENTS AND MEASURING TECHNIQUES IN FIXED-BED CHANNEL.....	42
TABLE 3-3. FIXED-BED CHANNEL EXPERIMENTAL CASES (EMERGED CONDITION)	44
TABLE 3-4. FIXED-BED CHANNEL EXPERIMENTAL CASES (SUBMERGED CONDITION).....	45
TABLE 3-5. FIXED COEFFIENTS FOR STANDARD K-E TURBULENCE MODEL	57
TABLE 4-1. MOVABLE BED CHANNEL EXPERIMENTAL CASES (EMERGED CONDITION)	74
TABLE 4-2. MOVABLE BED CHANNEL EXPERIMENTAL CASES (SUBMERGED CONDITION)	75
TABLE 4-3. DETAILS OF EXPERIMENTAL CONDITIONS IN MOVABLE BED EXPERIMENTS	76
TABLE 4-4. SUMMARY OF MEASUREMENTS AND MEASURING TECHNIQUES IN MOVABLE BED EXPERIMENTS	79
TABLE 4-5. POTENTIAL BANK EROSION FOR EXPERIMENTAL CASES (EMERGED CONDITION)	102
TABLE 4-6. THE RECOMMENDED RANGES OF FLOW PARAMETERS BY PREVIOUS RESEARCHERS.....	114
TABLE 4-7. TWO SAMPLES OF DATASET WITH DIFFERENT DIVERSITY	126

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