

**Study on Hydraulic and Morphological
Characteristics of River Channel
with Groin Structures**

By

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2011

Abstract

In natural rivers the flow pattern and the sediment deposition/erosion process are strongly influenced by the presence of river training structures (groins structures or spur-dikes, revetments, weirs, etc.) which are usually used to provide adequate protection to the riverbank from erosion, improve the navigation conditions through the formation of deeper main channel and recently to restore the natural river scenery. From the past, conventional structure as impermeable groin was installed from single side or either side banks in various rivers around the world to reach the described functions and also due to the simplicity of design and construction. The previous studies were mainly focused on this type of structure due to the available information for its utilization in small rivers which can be found easily and with details. Due to flow separation at the impermeable groin head return currents are formed towards the groin field which often attacks the riverbank. Due to these difficulties, in some cases permeable groins are used as a solution of this problem. The flow passes through the permeable groins towards the downstream opposing the formation of return currents at the groins field, minimizing the occurrence of deeper erosion around the groins and reducing the flow velocity near the bank.

These groin structures are often extrapolated towards the larger rivers on the basis of the experience in the small rivers. Such kind of intervention creates local changes leading to changes in the entire river reach and in the long run, these local interventions would make the problem even more complex. In addition to these factors, it is already proved in some developed countries that the above conventional methods can never provide environmentally suitable solutions even though these are proved to be effective against bank erosion and to some extent stream restoration in small rivers. Considering the difficulties associated to the utilization of conventional methods in large alluvial rivers, the investigation of an alternative method for river bank protection and channel formation are necessary. In this context, the present dissertation investigates groin structures with emphasis on bandal-like structures, i.e. local low cost structures commonly applied to improve or maintain the flow depths for navigation during low flow season in alluvial rivers of Indian Sub-Continents like Bangladesh, through the laboratory experiments and numerical simulations.

Basically, this structure consists of a framework of naturally available bamboo driven into the riverbed and supported by struts, and bamboo matting is fixed to this framework at the water level which represents the upper plate. Thus bandal-like structures are cheaper compared with conventional structures such as impermeable groins made of concrete or steel. The essential characteristics of bandal-like structures are that they are positioned at an angle with the main flow (40°) and the structure has an upper half part blocked (impermeable) to divert the high

velocity flow near the water surface into the main channel direction and the lower half part with an opening (permeable) to allow the passage of flow with sediments. The reduced velocity of flow passing through the lower opening of bandal-like structures is not sufficient to transport all the sediment transported by the flow including bed load and suspended load, which has higher concentration near the bed, resulting sediment deposition at downstream near the riverbank. On the other hand, the flow diverted towards main channel can develop a deeper navigational channel. The objective is also to gain deeper insight into the physical processes of sediment deposition/erosion in movable bed channels governed by bed load and suspended load transport around the bandal-like structures comparatively with traditional structures as groins.

The initial part of this study concerns to the experimental investigations about the characteristics of flow patterns and bed deformation affected by the presence of groin structures, especially bandal-like structures, under different hydraulic conditions which means experiments under non-submerged and submerged conditions and live-bed scour condition with sediment supplied from the upstream approach flow. Afterward, the 3D (three-dimensional) morphological model to simulate the flow and sediment transport near the structures was developed. Various algorithms and parameters were implemented in the model for calculation of three-dimensional water flow and coupled sediment transport. Within the scope of the test cases, the model simulated the bed deformation in a straight channel with the previously described river training structures (bandal-like structures and groins) in the same conditions of the laboratory experiments. The sediment transport was strongly influenced by the structure type and the flow behavior varying the deposition/erosion process. The numerical simulations revealed that the calculated flow and deposition pattern can be explained by the sensitivity of the flow regarding to structures geometry and boundary conditions.

The analysis of the results shows details of the mechanism involved in the morphological processes around groin structures with emphasis on the characteristics of bandal-like structures. These showed some advantages of bandal-like structures in comparison with impermeable groins as the small local scour formed around the bandal and large deposition at downstream of the structures, especially due to the influence of suspended sediment near the structures, which contributes to the river bank protection in alluvial rivers due to the effect of flow at lower half portion of bandal. The bed degradation in the main channel can be pointed out as an important characteristic that can be useful for navigation purposes. The numerical model is an important tool for prediction of flow characteristics and sedimentation/erosion processes in rivers, moreover the present results proved the capabilities of the numerical modeling to predict the bed features around groins structures.

Keywords: *Bandal-like structures, groin structures, live-bed scour, numerical simulations.*

Acknowledgements

First of all I wish to express my sincere gratitude to my supervisor Professor Hajime Nakagawa of Kyoto University, who introduced me to the fascinating world of sediment transport study, and continuously gave me invaluable guidance, suggestions, and encouragement during the period of carrying out this study. I would like to thank him for his support and giving me the freedom to realize my own ideas and to achieve my goals. At the same time I strongly appreciate his effort in pushing me to my limits every single day. I am indebted to him, for giving me the chance to study here.

I am deeply grateful to my thesis reviewers, Professor Masaharu Fujita and Professor Tetsuya Sumi, DPRI, Kyoto University, for their valuable comments and suggestions to refine the thesis.

When I first met Prof. Hao Zhang, I was impressed by his dedication to research. He symbolized an archetype when he was working and I admired his enthusiasm. He taught me how to remain focused in my research. I would like to thank him for introducing me to the fascination of sediment transport and for encouraging me to take a Ph.D.

Then, I would like to thank Prof. Kenji Kawaike and Prof. Yasuyuki Baba, Ujigawa Open Laboratory, Kyoto University, for sharing their profound knowledge with me. They continuously supported me no matter how busy they were. A huge thanks is addressed to all my colleagues that I met and worked with since I came from my country to Japan for the Ph.D course: Dr. Ripendra Awal, Dr. Badri Baktha Shrestha, Dr. Dongkeun Lee, Mr. Ram Krishna Regmi, Mr. Hideaki Mizutani, Mr. Takaharu Utsumi, Mr. Yasunori Nambu, Mr. Hiroyasu Kawanishi, Mr. Daizaburo Touchi, Mr. Toshimasa Mataga, Mr. Yasutaka Saito, Mr. Satoshi Kouda, Mr. Atsushi Shimizu, Mr. Soshi Yoneda, Mr. Shiro Nakanishi, Ms. Hisako Ito, Ms. Natsuyo Sugimura, Dr. Mirian Maya Sakuno, Miss Lilian Miho Sakuno, Miss Lucia Megumi Kato, Dr. Cristiano Augusto Trein, Dr. Tatiana Kuroiwa, Mr. Artem Ayzvazyan, Miss Ana Carolina Bonifacio, Mr. Igor Takeshi Sanada, Miss Lucia Tomiyama, Dr. Ernesto Nomiya, Dr. Andrea Urushima, etc...., thanks for just being there when questions or doubts arise. Your advice and support have meant a lot to me and helped me to finish the thesis.

I thank all the professors and friends in the Research Center for Fluvial and Coastal Disaster, Disaster Prevention Research Institute of Kyoto University, who have made my academic experience rich and memorable. I would like to thank Mr. Fujihara, Ms. Kitagawa, Mr. Tatsumi, Mr. Nishimura, Mr. Yoshida and all the staffs in Ujigawa Open Laboratory, Disaster Prevention Research Institute of Kyoto University for their support in routine administrative process and experiment.

I am also greatly indebted to many teachers in the past, Professor Kikuo Tamada (Sao Paulo University, Brazil) for getting me interested in each and every topic of water resources

engineering and coming to Japan.

I gratefully acknowledge the financial support of the Monbukagakusho (Ministry of Education, Culture, Sports, Science and Technology, Japan).

I wish to express my grateful to my family and my wife's family for their encouragement and praying for me throughout the course of this study. All the time they gave me the feeling of doing something special. Actually, it is priceless knowing that somebody is proud of what you are doing.

Last but not least, my sincere gratitude to my darling, Emi, for her persistent love, continuous support, enormous patience, and for accepting me as I am. And Sofia to be our little princess.

“You must be the change you wish to see in the world.”

(Mahatma Gandhi)

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Chapter 1

Introduction

1.1 General

Rivers are complex and dynamic. It is often said that a river adjusts its roughness, velocity, slope, depth, width, and plan form in response to human activities and (perhaps associated) changing climatic, geologic, and hydrologic regimes. These adjustments may be rapid or slow, depending upon the source and characteristics of the forces spawning the adjustments. When a river channel is locally modified that modification may initiate changes in the channel and flow characteristics that may propagate both upstream and downstream and throughout tributary systems. These changes may occur over large distances and persist for long times.

Effective analysis of river problems requires recognition and understanding of the governing processes in the river system. There are two basic items that must always be considered in river analysis: the characteristics of the flow in the river, and the geomorphic behavior of the river channel. These two components are sometimes treated separately; however in alluvial channels (channels with movable boundaries) the flow and the shape of the boundary are interrelated. Any intervention such as construction of river training structures even to protect the river bank against the erosion has consequences to the river morphology and aquatic biota (Przedwojski et al., 1995a).

Groins are one of the widely used river training structures (spur-dikes, weirs, revetments, etc) due to the well-known characteristics of redirecting the flow to keep away from erodible banks and preserve the desired depth of a river channel for navigation (Carling et al, 1996; Schwartz and Kozerski, 2003). Diversification of the flux is also a very important goal for groin planning (see Photos 1.1, 1.2 and 1.3). Other application, since a system of groins may protect riverbanks is strictly connected with landscape formation. From this point of view the groin itself is a part of scenic environment and its appearance is very important. Due to the great number of various goals of application, different parameters have different levels of importance in choosing the structure type.

This research is focused on the investigation of the influence of bandal-like structures (Photo 1.4 and 1.5) on flow patterns and the bed deformation in a straight channel through the laboratory experiments and numerical simulations. This structure is commonly used in the Indian Sub-Continent like Bangladesh (Rahman et al., 2003a) as a local structure to maintain the

navigability of the channel in alluvial rivers. Due to the utilization of low cost materials like bamboos and wood pieces for its construction, bandal-like structures can be considered a low cost alternative structure, especially in developing countries, in which the construction of traditional structures as impermeable groins made by concrete or steel represents an undesirable cost from the economic point of view. The technical aspects of this structure were studied through few field investigations (Sharmin et al., 2007) and laboratory experiments (Rahman, et. al., 2003b, 2004, 2006). However, due to the particular characteristics of the bandals, the number of studies realized is not enough to completely understand the mechanism involved on the effect of bandal-like structures in river morphology, especially the influence on suspended sediment distribution near the riverbank. Therefore, the present investigation is important to clarify and complement the available information about the utilization of bandal-like structures as an alternative river training work.

The characteristics of this kind of structure are usually studied through laboratory experiments using experimental channels under controlled conditions which are expensive and sometimes cannot reproduce all the situations that one requires to study the flow and sediment transport in rivers which is a matter of considerable interest in the field of river engineering and sedimentation research (Graf, 1970; Ouillon and Dartus, 1997; Chang and Scotti, 2003; Schulz, 2003; Sekiguchi et al., 2004; Nagata et al., 2005).

Modeling the physical process of sediment transport, the corresponding bed changes and lateral migration of rivers is still an interesting research topic. During the last century the physical processes of interaction of water and sediment were investigated by means of field studies and laboratory experiments, but sometimes the complexity of flow patterns formed due to the interactions of water flow with the river structures cannot be represented accurately through these methods. Therefore, in the last decades due to the fast development of new computational techniques, the CFD (Computational Fluid Dynamic) models have progressively become more of a competitor to laboratory experiments. While there is a well-defined state-of-the-art for computing the hydraulics of flows in channels and natural rivers, highly sophisticated computations of sediment transport and associated morphological changes are still being researched (van Rijn, 1986; Zhang and Prosperetti, 2005; Nezu and Sanjou, 2006; Zhang et al., 2006b). Due to the need for excessive computational resources, especially for multidimensional modeling, the application and development of morphodynamic models is mainly limited to universities and research institutions. Therefore, it is of considerable importance to push progress and ensure that CFD models will be a useful tool in practical sedimentation engineering in future.



Uji river (Kyoto)



Katsura river (Kyoto)

Photo 1.1 Application of groins in rivers (Japan)

(source: <http://www.dpri.kyoto-u.ac.jp/dat/nenpo/no47/47b0/a47b0t48.pdf>)



Rhine river (Netherlands)



Waal river – tributary of Rhine river

Photo 1.2 Application of groins for improvement of navigation in rivers (Europe)

(source: <http://www.delftcluster.nl/website/nl/page393.asp> and <http://www.icpdr.org/jds/node/141>)



Mogi-Guacu river (Sao Paulo)



Capivari river (Sao Paulo)

Photo 1.3 Application of groins to bank protection in rivers (Brasil)

(source: <http://www.fcetb.br/public/cursos/phd5023/REGULARIZA.PDF>)

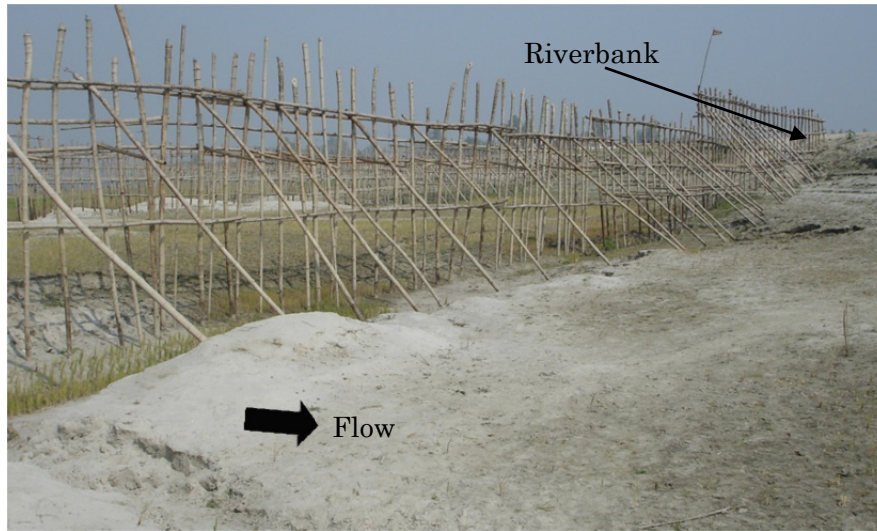


Photo 1.4 Bandal-like structures during field survey at Jamuna River, Bangladesh (January 2010)

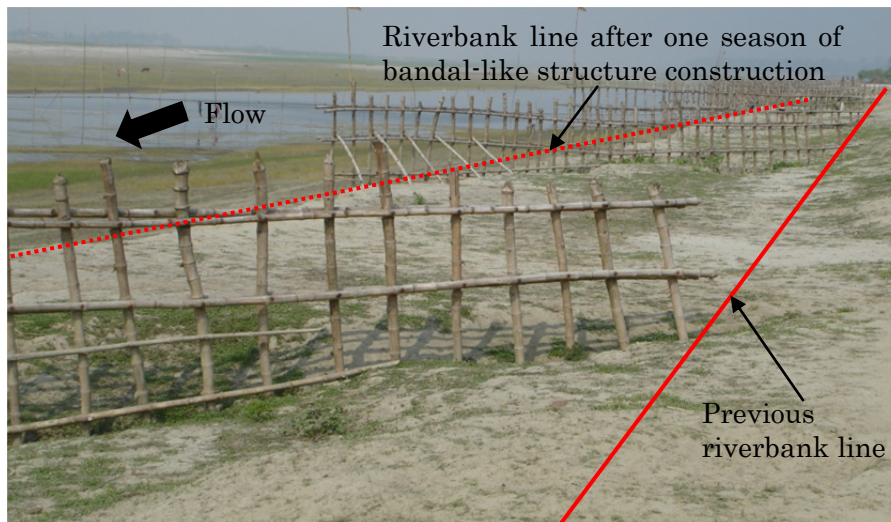


Photo 1.5 Deposition influenced by bandal-like structures at Jamuna River, Bangladesh (January 2010)

1.2 Literature review

1.2.1 Background

In Europe, Japan, USA and other countries the hydraulic structures as groins have been widely used as a measure of water training works (Przedwojski et al., 1995a). Although utilization of groins as indirect methods for bank protection is reduced as the development of effective direct methods like concrete revetment, gabion and synthetic materials (geo-bag). These are continuously installed to control the flow for navigation and improve the channel alignment. However, the required cost involved for the implementation of such direct methods becomes an obstacle for its construction in the developing countries.

River training work can be considered as the stabilization of the channel in order to maintain the desired cross section and alignment. In general, the objectives of river training may be summarized as:

- to increase the safety against flooding by accommodating the flood flow
- to improve the efficiency of the sediment transport process
- to reduce bank erosion by stabilizing the river course
- to redirect the flow to a desired river stretch

In most of the cases, the primary objective is to improve navigation by maintaining adequate channel depth (Lacey, 1930). Natural processes and human interference may disturb the equilibrium between the sediment load contributed to the channel and the sediment transport capacity of the flow. Seasonal variations in the flow, dredging of the river, construction of a reservoir, and deforestation in the catchment area are all examples of causes of disturbance. River training structures are then necessary in order to protect the channel against the changes caused by this disturbance (Grass, 1983).

Recently, river training structures attract attention again because the natural bank formed by these structures is very beneficial to river ecosystem. Hydraulic conditions such as flow velocity, water depth, bed shape, and bed material accumulated around them are so diverse to provide the ecosystem with suitable habitat. The values of these structures as a bank protection technique considering the river environment have been re-evaluated. Various types of structures have been studied through laboratory experiments or in some cases installed as a pilot project in the field. The design, location, orientation and length of these structures are very important subjects for the hydraulic engineers (Shen et al., 1966; Chee, 1982; Rajaratnam and Nwachukwu, 1983b, Lim, 1997).

The bandal-like structure is a good alternative for the new demand of river training works which can be effective for riverbank protection and improvement of navigational channel as

well as a friendly structure for the river environment. The characteristics of bandals are discussed in details in the sub-subsection 1.2.2.2.

As above mentioned, the main purposes of installation of river training structures are mainly divided into formation of navigational main channel and riverbank protection. In details, it can be changed as the goals of river training work and the characteristics of river in each country.

➤ Prevention of river bank erosion

One of the main objectives of installation of hydraulic structures in rivers is to prevent the bank erosion. In particular, a strong flow in a river causes movement of sediments, which brings out problems related to deposition/erosion process. The effects of river training structures construction depend on many factors, which are hydraulic characteristics (the water level, flow velocity, main channel discharge flow, etc.) and topographic features of river channel. Also, these effects depend on design factors, which are the length perpendicular to the bank, interval distance between two consecutive structures and arrangement of the structures to flow direction. For instance, in the case of impermeable groin as the length of structure increases the range of a bank protected extends. However, at the same time as the velocity of a main channel and at groins head changes considerably, it can causes serious local scour around structures. In addition, the installation of groins in series causes the formation of return currents at downstream of the structures, attacking the riverbank. It is very important to design a structure with proper intervals for security of riverbank against the formation of a strong reverse flow causing bank erosion.

➤ Control the flow direction

There are two main effects of flow control expected by a river training structure installation. The first effect is that an existing channel can be changed to different direction, so the direction of flow would be controlled. The second effect is the reduction of high velocity near the river bank. These effects can affect the maintenance of the required channel width and water depth for navigation purposes.

➤ Improvement of ecological environment and scenery

A river training work is a technique which can protect a bank from erosion and improve scenery in environments at the same time. In particular, as the velocity in a groins field would be reduced enough compare to a main stream, not only various habitats but also a refuge during a flood event for fishes and microorganisms can be provided, contributing to create ecological environments. Also, nature-friendly materials such as wood pieces or bamboos are used for river training works, and revetments with vegetation are used widely for the stability of riverbank.

However, these nature-friendly materials are weaker than existing materials like concrete or steel. Although mixed materials like block with vegetation can be used. These nature-friendly river techniques need to secure the stability of structure by proper protection techniques.

1.2.2 Previous related studies

During the last decades, many investigations were realized concerning to application of river training structures and its effects on flow patterns and sediment transport process in natural river channels. The main influence of these structures is related to the occurrence of riverbank erosion and the main channel degradation. The flow field differs significantly between the case of a single structure and that of a series of them. This research focuses on the study of 2 (two) structures of different types in one side of a flume to verify the complex three-dimensional characteristics of flow structures and sediment transport process around them.

1.2.2.1 Groins related studies

A number of investigations were performed to improve understanding the flow phenomena and sediment transport around groins (Brinckmann and Holtz, 1990; Przedwojski, 1995b; Mayerle et al., 1995). Most of the past researches focused on the local scouring depth and flow patterns around them. The previously described two factors as well as the stability of structures are crucial parameters for the groins application. The depth and volume of local scour caused by a hydraulic structure are difficult to estimate accurately. Many studies have been done through the measurements of the velocity distribution associated with non-submerged structures and the effects on local scour holes (Rajaratnam and Nwachukwu, 1983a; Melville, 1992). The study of Melville (1992 and 1997) summarized several studies completed since the beginning of the 1980's. A study on velocity profiles and scouring process in the vicinity of submerged groins were performed by Rahman et al. (1998), Elawady et al. (2000) and Elawady et al. (2001). A similar subject, i.e. local scouring around bridge piers and abutments was investigated by Melville (1997) and published in many papers. Experiments on geometries that are more realistically resemble groin fields are scarce and mostly restricted to field measurements (Brinke et al., 1999), other field studies of morphological patterns was investigated by Sukhodolov et al. (2004).

In addition to field measurements, the flexibility in geometry and control of flow parameters make laboratory experiments of key importance for understanding the physics behind water motion and the associated exchange process (Chen and Ikeda, 1997). Uijttewaalt et al. (2001) investigated through the experimental procedures the exchange process between groins field and the main river channel, Giri et al. (2004) realized measurements using non-submerged spur-dikes in a meandering-like laboratory channel to verify the effect of this kind of structure

on the mean flow field. Some studies were performed to describe the boundary layer motion and vortex shedding mechanism induced by structures (Gerrard, 1996).

The literature shows that in spite of the importance of conventional structures as impermeable groins (or spur dikes), less attention have been paid to study other types of river training structures as permeable groins (Mioduszeewski et al., 2003; Nasrollahi et al., 2008). In the present study, especial attention was given to the bandal-like structures, i.e. structures commonly applied to improve or maintain the flow depths for navigation during low flow season in alluvial rivers of Indian Sub-Continent (Rahman et al., 2004; Rahman et al., 2006) as an alternative method for conventional river training structures like groins adapted to local conditions and available materials. The basic function of this structure is to obstruct the flow near the water surface deviating it to the main channel direction and allow passing near the riverbed. Information available about this structure so far is from field experiences and few experimental studies, and then detailed features of flow and sediment transport around them are still unknown.

1.2.2.2 Bandal-like structures

The bandal-like structures are made by using low cost materials as bamboos or wood pieces over the conventional materials as concrete or steel. From the structure design, the bandal-like structure can be considered a structure partly similar to impermeable groin due to the blocked upper half plate, and partly similar to permeable groin, due to the permeability of lower half part that allow the flow to pass through the structure. Analyzing the available information from field experiences and few experimental studies (Rahman et al., 2004), it can be seen differences on the flow patterns around the bandal-like structure compared to the flow patterns around the conventional structures as impermeable groins. Bandal-like structures are chosen due to the importance to have an alternative long-term solution for river stabilization that will be friendly to the environment and create minimum disturbance to river courses. Experimental studies using movable bed under clear-water scour was carried out to verify the characteristics of bandal-like structures concerning to flow and sediment transport by Rahman et al. (2003a, 2003b, 2004 and 2005). They also developed a simplified analytical model to predict the main channel degradation and local scour depth around the structures, which was verified using the experimental data. The results of this verification showed reasonably agreement between the measured and calculated results. Therefore, details of flow patterns and sediment transport process under different flow conditions as submerged condition or different alignment of the bandals are still unknown. The applicability of this structure was verified in the field tests, but it is very clear the necessity of more experimental studies, field investigations and also numerical

model development to analyze based on scientific investigations the applicability of the bandal-like structure as a good solutions for the recent demand of nature friendly low cost sustainable methods used for river bank protection and channel formation.

Reviewing the available literature revealed a lack of research dealing with river structures in submerged conditions. A few studies were focused on groins under submerged conditions, such as the study of Kuhnle et al. (1999), Zaghloul (1983) and Tominaga et al. (2001). This may be due to the fact that the probability of occurrence of this situation is very rare when compared to the low flow discharge then the groins normally are projected to work on non-submerged conditions. Another reason might be the complexity and three-dimensionality of the problem, which require advanced measurement techniques and/or powerful three-dimensional computational methods.

1.2.2.3 Numerical modeling

Peng et al. (1997) compare three-dimensional numerical results with experimental results and conclude that the flow pattern in the case of submerged groins shows strongly three-dimensional features behind groins. On the upstream face of the groin, the flow shows a downward motion because of the blockage effect. Another important aspect of the flow pattern in the case of submerged groins is the formation of a secondary flow structures. Both on top and behind the groins, there is a secondary recirculation current that is directed from the bank towards the channel axis near the surface, and the other way around near the bed (Krebs et al., 1999).

The physics of the interactions between the three-dimensional unsteady flow and the sediment transport on the bed are poorly understood and difficult to characterize (Gyr and Schmid, 1997). As a result, most scour prediction algorithm is empirically based and only predicts the maximum depth of scour (Raudkivi, 1990). Considering the submergence of these structures, as described before the difference in hydraulic characteristics and bed topography changes for both conditions of non-submerged and submerged groins is not clearly clarified yet.

Several 3D mathematical models for sediment transport are available. Olsen and Kjellesvig (1998) suggested a 3D numerical model for sediment flow in a sand trap and estimations of maximum local scour depth. Lin and Falconer (1996) constructed a 3D numerical simulation for suspended sediment in estuarine and coastal waters. Van Rijn (1987) developed a combined model in which the sediment transport is calculated with a 3D method and the flow with a depth-averaged approach in combination with the assumption of a vertical logarithmic velocity profile. Wu et al. (2000) presented a 3D numerical model for total sediment transport (suspended load and bed load rates) where the flow is calculated by solving the fully Reynolds-averaged Navier-Stokes equation in conjunction with a $k-\varepsilon$ turbulence model. McCoy

et al. (2008) investigated the flow hydrodynamics influenced by a series of groins in a straight flume using the LES method, especially the relation of flow structures in the embayment area, the mixing zone and the main channel.

Three-dimensional mathematical modeling requires an appropriate model for sediment transport (Zhang et al., 2006a). Accurate simulation of suspended sediment transport is essential for design of hydraulic structures and environmental impact assessment (Tipping et al., 1993; Itakura and Kishi, 1980). A proper sediment transport model needs to include parameters representing friction factor, sediment carrying capacity, sediment-diffusion coefficient, and sediment concentration at the riverbed. However, in a natural river it is at present not easy to express the aforementioned factors with a general and fully accurate formula. This is because each river, even each river segment, has a special self-character that depends on the complex boundary conditions and incoming flow and sediment transported from upstream. Moreover most present theories for sediment transport are based on laboratory results of equilibrium sediment transport by steady flow. The coefficients and concepts in the empirical formulas are sometimes only a scientific hypothesis, and they must eventually be verified and corrected. Many studies concerning to the effects of three-dimensional flow field around hydraulic structures on the sediment transport are accounted only for the bed load transport, but still few researches considering the interaction with suspended sediment transport which is more close to the natural river conditions.

1.3 Objectives of the research

The aim of this research is to study the morphological interaction between the bandal-like structure and the main channel of a river channel. In this context, an attempt has been made to study through laboratory experiments and numerical simulations the flow structures and bed deformation resulted from the presence of bandal-like structures and conventional structures as groins in one side of a straight channel.

The main objectives of this research are described as follows.

1. Elucidate the characteristics of flow pattern, sediment transport, and associated bed deformation around bandal-like structures under non-submerged and submerged conditions in an experimental flume.
2. Development and validation of a numerical model for simulations of river flow and bed evolution with hydraulic structures in a straight channel.

3. Analyze the advantages and disadvantages of different types of hydraulic structures as groins (impermeable and permeable) and the bandal-like structure through the comparison of following characteristics:
 - Local scour role around the structures
 - Protection of river bank against the erosion
 - Formation of deeper navigation main channel

1.4 Structure of the thesis

The present thesis consisting of five chapters is organized as follows.

Chapter 1 describes the important subjects concerning natural channel flows with efforts that are made to give a general survey of studies on the flow features of straight alluvial channel flows. Discussions are made on the functions of bandal-like structures and groins. Researches related to the utilization of hydraulic structures through experimental studies and numerical simulations are presented.

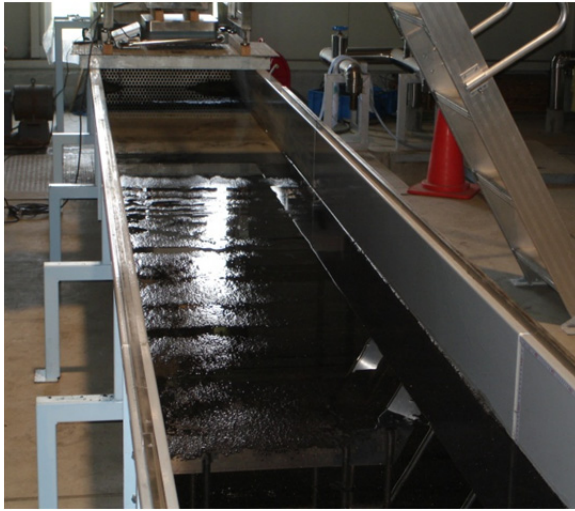
The Chapter 2 presents the experimental investigation cases and the equipments used during the measurements. From the view point of river engineering, a laboratory study is undertaken for the purposes of identifying the principal flow features associated with the interaction between main channel and these structures, and of detecting their dependency on the bed topography of main channel. Special attention is paid to the difference between simple straight alluvial channel flow and the same channel with river training structures. Many significant results are obtained from this investigation.

In Chapter 3, a 3D hydrodynamic model integrated with the sediment transport model is described. In order to simulate river flows with complicate geometries such as flows in alluvial channel with hydraulic structures, the RANS (Reynolds averaged Navier-Stokes) equations based on unstructured mesh system and a collocated orthogonal coordinate system is employed to calculate the flow field in the present model. Experimental and theoretical studies are conducted concerning the transport process of sediment in straight alluvial channels. In order to elucidate the mechanism of suspended load transport in straight alluvial channels a numerical model based on the convection-diffusion equation is described, which can be used to predict the distributions of suspended sediment concentration in the structures field.

In Chapter 4, the numerical model described in Chapter 3 is applied for the purpose of predicting the bed deformation of alluvial rivers with complex geometries as the bandal-like structures and groins (impermeable and permeable). By comparing the calculated results with the experimental measurements, it is shown that the present numerical model has the ability of simulating the bed deformation with reasonable accuracy. An analysis of the performance of

bandal-like structures as a riverbank protection and navigational channel formation structure are made in comparison with conventional structures as groins. Through these results the applicability of bandal-like structures are discussed.

Finally, in Chapter 5, the main findings and conclusions about the characteristics of bandal-like structures are summarized. Various outstanding issues are identified and recommendations for future researches are described.



Flume inlet



Flume outlet

Photo 2.1 Experimental flume

The flume slope was fixed on 0.00125 m/m for all experimental cases. The structures having a stream wise length of 0.015m was embedded in a coal (powdered anthracite with mean diameter = 0.835mm) recess with 8.50m long, 0.80m wide and 0.10m deep (0.27m deep in the test region). The coal recess was located 2.0m downstream of the flume inlet. A false wood floor at an elevation of 0.10m from the flume bottom and 1.0m long was collocated in the upstream before the movable region to reduce the water surface variation due to the increase in the flow velocity. A calibrated V-notch weir fitted at the inlet of the flume with a vernier point gauge (Photo 2.2) with an accuracy of ± 0.5 mm was used to control the inflow discharge.



Photo 2.2 Vernier point gauge

2.3 Experimental conditions

2.3.1 Hydraulic conditions

The hydraulic conditions were chosen to fulfill the sediment transport requirements. The following hydraulic parameters used for the experiments are summarized in Table 2.1. The approach flow depth (h) varies depending on the studied case. The Shields diagram was used to determine the critical shear velocity u_{*c} for the sediment (coal) particles.

- Flow depth: h (cm)
- Flow discharge: Q (l/s)
- Mean flow velocity: u (cm/s)
- Shear velocity: u_* (cm/s)
- Shear velocity ratio: u_*/u_{*c}
- Reynolds number: Re
- Froude number: Fr

Table 2.1 Details of experimental conditions

Type of structure*	I	P	BS	I	P	BS
Case	1	2	3	4	5	6
Submergence	Non-submerged			Submerged		
Flow depth, h (cm)	4.00			7.00		
Discharge, Q (l/s)	7.76			18.88		
Mean velocity, u (cm/s)	24.25			33.71		
Shear velocity, u_* (cm/s)	2.22			2.93		
Shear velocity ratio, u_*/u_{*c}	1.91			2.53		
w_s/u_*	1.745			1.319		
Reynolds number, Re	7,406			18,011		
Froude number, Fr	0.387			0.407		

* I – Impermeable groin, P – Permeable groin, BS – Bandal-like structure

The main purposes of experiments are as follows:

- to measure final equilibrium bed profile (all cases);
- to observe the influence of impermeable or permeable groins and bandal-like structures on flow patterns around these structures;
- to measure the 3D velocity field (horizontal and vertical directions);

- to capture through the video camera the movement of tracer (white PVC powder) for water surface velocity measurement by PIV technique (Particle Image Velocimetry).

2.3.2 Sediment properties

There are various materials which can be used to simulate the sediment current in suspension case. The material might be fine grinded grains of quartz, granular plastic, glass, marble, etc. Due to the necessity of a material with smaller density to satisfy the demands of threshold of motion and suspension similarities, coal (powdered anthracite) was selected as a sediment material. Coal particles are non-cohesive and light grains, which have a well-known and relatively narrow particle size distribution. This sediment has a mean diameter equal to 0.835mm and density equal to 1410 kg/m³. The grain size distribution of sediment is shown in Figure 2.2.

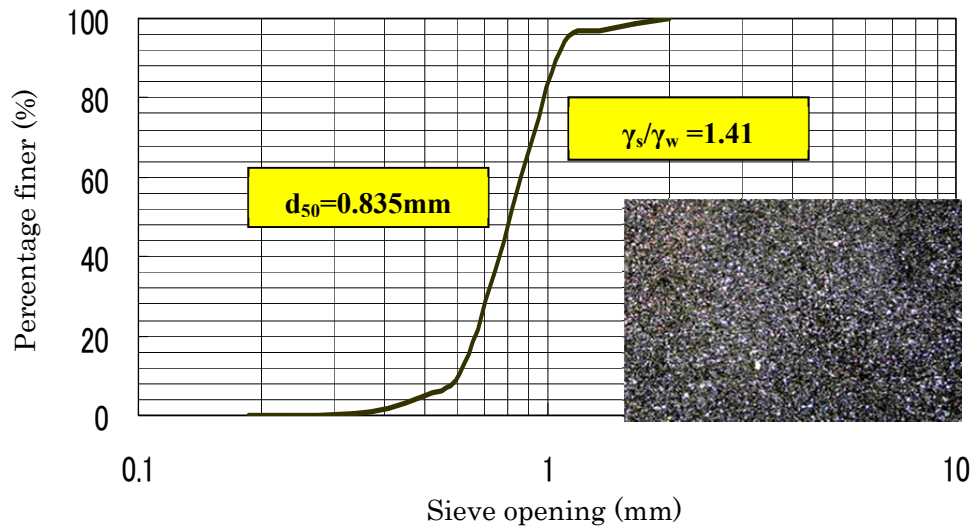


Figure 2.2 Grain size distribution of sediment (powdered anthracite – coal)

2.4 Measurement techniques

Several parameters were measured during the experimental studies, namely: 2D water surface velocities, 3D velocity fields (horizontal plan and vertical cross sections), equilibrium bed level profile, water level variation, and water discharge (see Table 2.2).

Table 2.2 Measurements and equipment used during the experiments

Measurement	Measuring equipment	Resolution	Dimension
Bed profile	Laser displacement sensor	±0.1	mm
3D velocity field	Electromagnetic current meter	±0.1	cm/s
2D Surface velocity	PIV technique	±0.1	cm/s
Water discharge	V-notch weir and point gauge	±0.5	l/s
Water level	Point gauge	±0.5	mm

2.4.1 Laser Displacement Sensor

The Laser Displacement Sensor (Keyence – LK 2500 / Photos 2.3 and 2.4) was used to measure the final equilibrium bed deformation after each experiment for all cases using impermeable groins, permeable groins and bandal-like structures. This equipment consists on a controller and a sensor head (Figure 2.3), 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 which 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 peaces 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. One example of this calibration curve can be seen in Figure 2.4. 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.

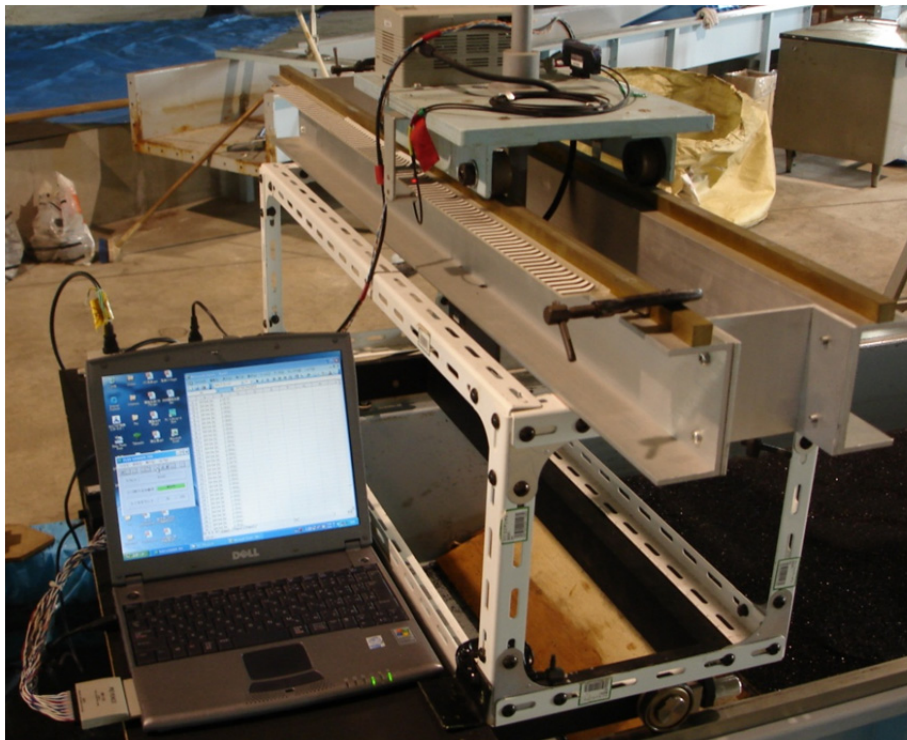


Photo 2.3 Laser Displacement Sensor (side view)

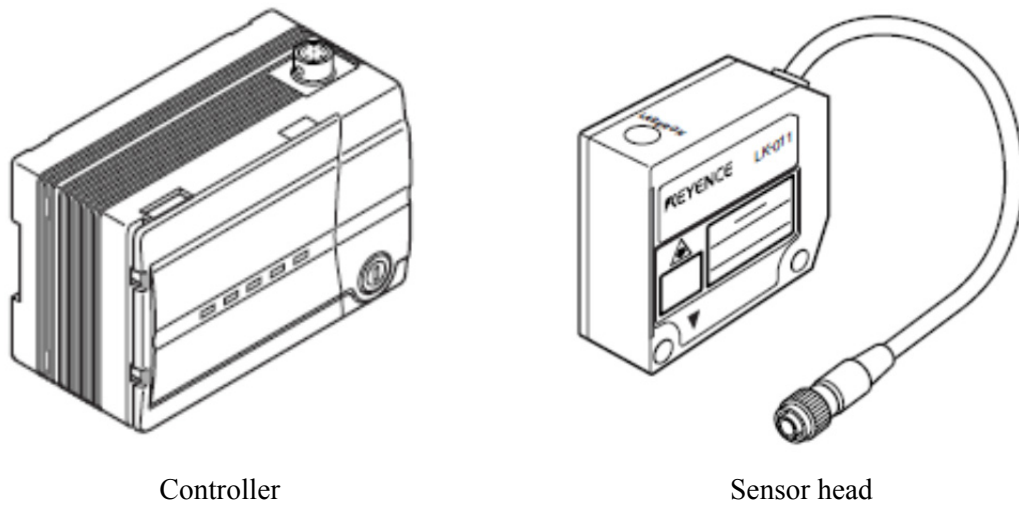


Figure 2.3 Parts of laser displacement sensor

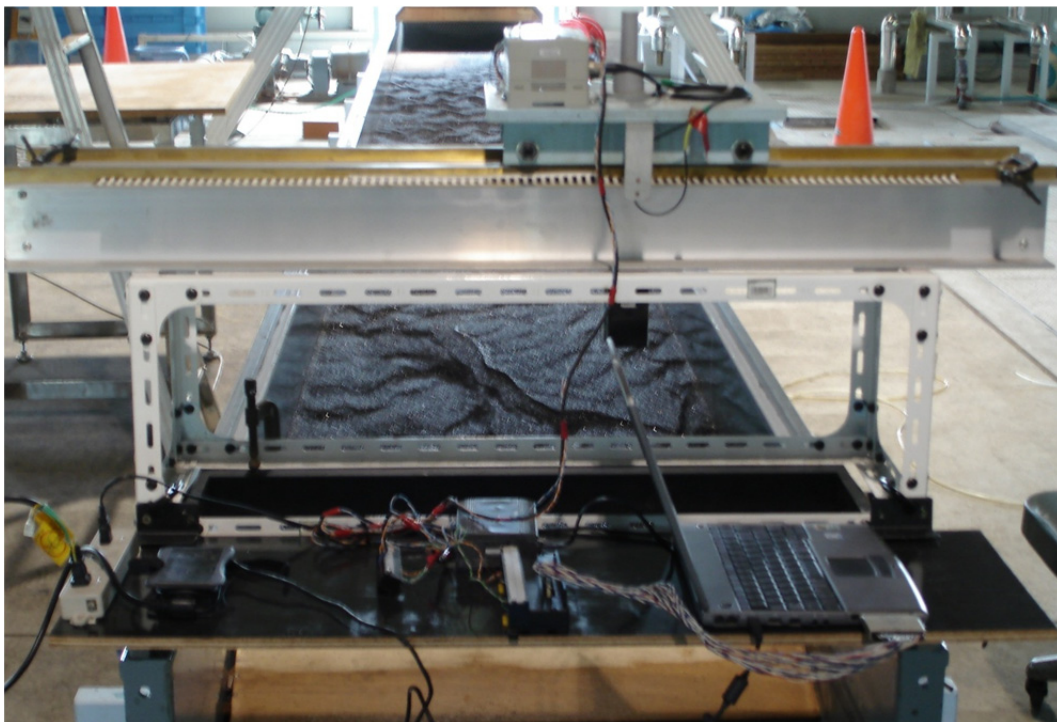


Photo 2.4 Laser Displacement Sensor (front view)

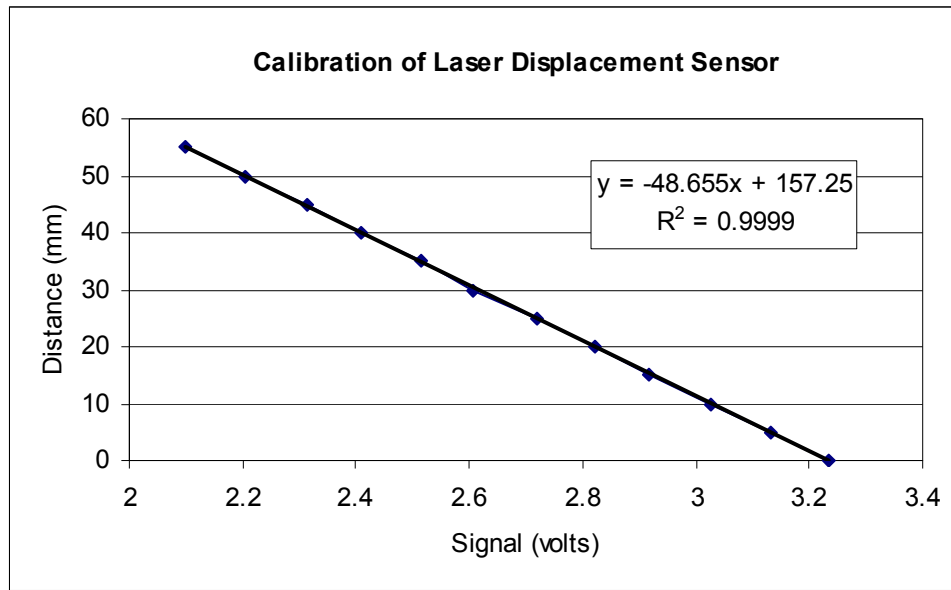


Figure 2.4 Typical calibration curve

2.4.2 Electromagnetic current meter

The three-dimensional velocity components were measured by electromagnetic current meters (Photo 2.5). Considering the axis X-longitudinal, Y-transversal and Z-vertical directions, the current meter comprised one probe (stainless steel rod) with I-shape to measure the velocity in the horizontal plane (XY) and another with L-shape to measure the velocity in vertical cross sections (planes XZ and YZ), connected to an analogical/digital data converter. The probe (I or L shapes) are positioned inside the water body and the measurement position are adjusted by a vernier point gauge, which is used for the measurements in different water depths to determine the velocity on the desired position.

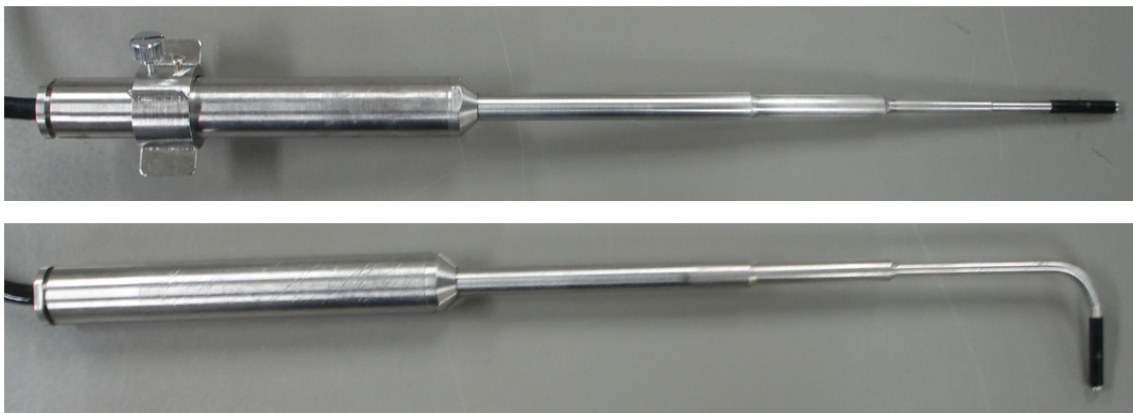
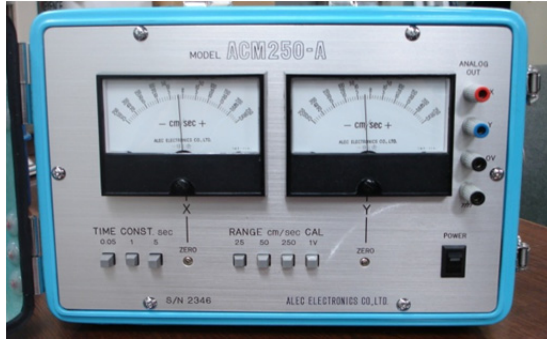


Photo 2.5 – Electromagnetic current meters (top: I-probe; bottom: L-probe)



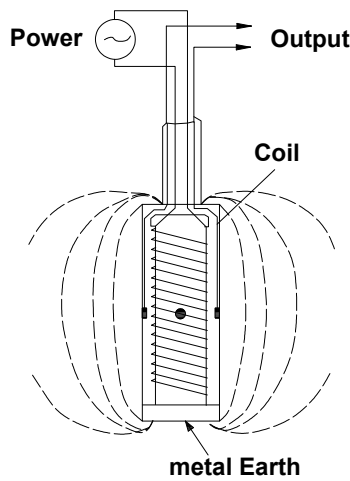
Electromagnetic current meter



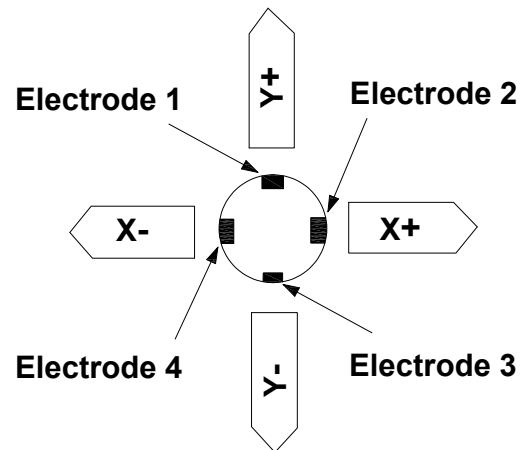
Data logger card

Photo 2.6 Analogical output converter and data logger card

The connection between the probe and the notebook PC are made by an analogical output converter that converts the signal from the probe to a corresponding output voltage and then connected to a data collection system (A/D conversion card – Keyence NR-110 and data logger software) to store the velocity data into the notebook PC (Photo 2.6). Details of electromagnetic current meter operation are explained in Figure 2.5 below.



Side view (I-probe)



Top view (I-probe)

Figure 2.5 Details of electromagnetic current meter operation

The water current carries electrical charges, which move through the magnetic field generated by the coil. The moving charges induce a voltage potential in the opposing electrode pairs (1, 3) and (2, 4), which is directly proportional to the speed of the current. The electrode pairs form orthogonal (X, Y) axes so that the current speed is given by $V = \sqrt{X^2 + Y^2}$. Together with the compass information, V can reference to this Earth coordinates.

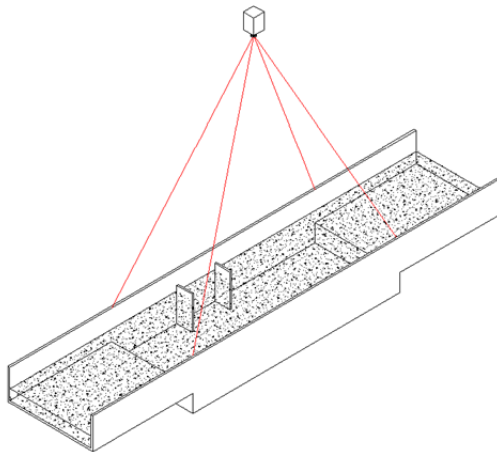
2.4.3 Particle Image Velocimetry (PIV)

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.

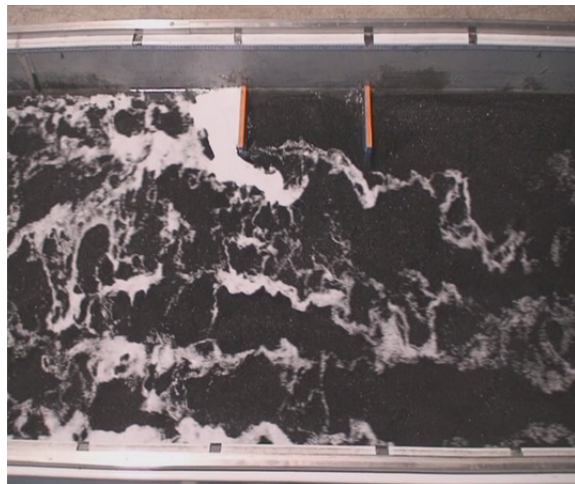
In hydraulic engineering, this technique has so far mainly been applied for surface velocity measurements of water in very uniform flow fields as well as groins experiments (Adrian, R. J., 1991; Fujita et al, 1998; Uijttewaal et al., 2001).

A digital video camera was used to record the images. The video camera was fixed above the flume covering an area of 2.0m (flow direction) by 1.0m (transverse direction), where the structures are located. The recorded images were systematically transformed to remove perspective distortion from the objective lens and then processed using PIV software (Fujita, I., and Tsubaki, R., 2004). Seeding was obtained by means of white PVC (polyvinyl chloride) particles and reasonable light as shown in Figure 2.6. The PVC particles had an average diameter of 0.06mm and a specific weight of 400kg/m^3 .

The dispersed light allowed recording their positions at two successive instants by means of a video camera.



Position of video camera for PIV measurements



Flow with tracers (PVC powder)

Figure 2.6 Details of surface velocity measurements using PIV

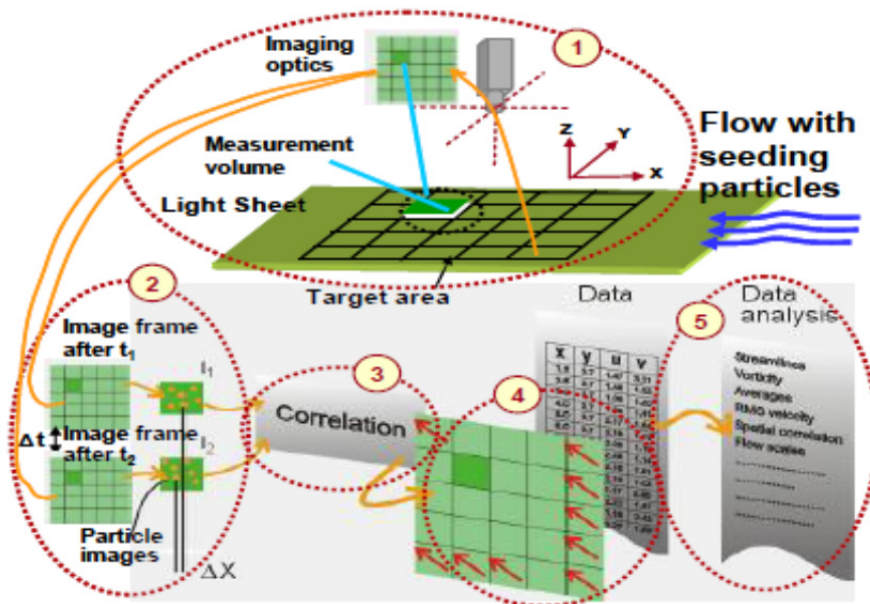


Figure 2.7 Basic principle scheme of PIV operation

(source: <http://www.dantcdynamics.com/>)

The PIV technique determines the velocity of water flow indirectly by measuring the velocity of tracer particles within the flow. Rather than finding the displacement of a single seed particle, the PIV technique tracks the movement of a group of particles within a designated area, the so-called target area. Figure 2.7 shows a typical setup for PIV measurement with the sequence of steps necessary, which are briefly explained in the following.

A difficult part of the experimental set-up is the choice of proper tracer particles. In this case for surface velocity measurements the tracer particles have to float at the water surface so that the material has to be somewhat lighter than water. Particles which are too light can be affected by air flow above the water surface. The flow is seeded with powdered particles (PVC – Polyvinyl Chloride powder) with mean diameter equal to 50 μ m. The dispersed light allows their positions to be recorded at successive instants by video camera during the required time to process the images.

- ⊕ - The plan view (target area) is divided into several small sub-areas, known as measurement volume.
- ⊙ - In each measurement volume, the cross-correlation algorithm is applied in order to calculate the shift of the particles (ΔX) in the time between two images (ΔT).
- ⊕ and ⊙ - A raw vector map is formed from the group of vectors calculated in each measurement volume, showing the velocity field of the measured plane view. This is done for every area, giving a 2D map of the instantaneous velocity field at the time of the recording.
- ⊙ - From the velocity values given by the raw vector map, it is possible to calculate other types of data, such as streamlines, vorticity and vector statistics.

2.4.4 Water discharge measurements

The inflow discharge was imposed by a water pump monitored by a V-notch weir during the experiments which allowed checking the stability of the approach flow. The measurement apparatus are showed in Photo 2.7. During each experiment the location of the water surface at the flume channel were measured by means of point gauge. This allowed verification that the boundary conditions were constant during the experiments.

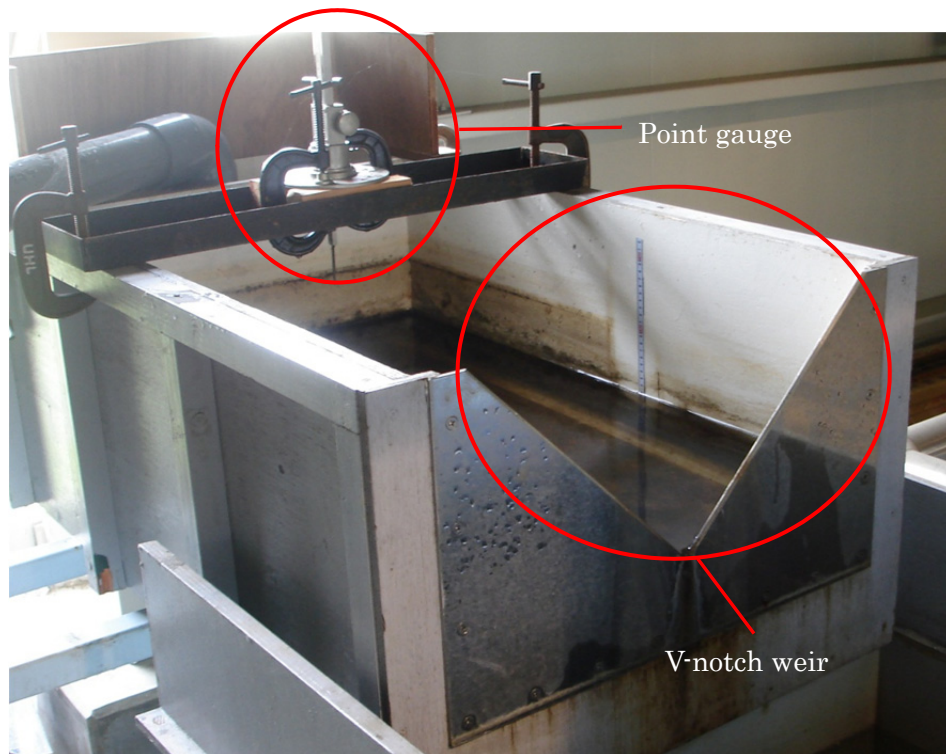


Photo 2.7 V-notch weir and point gauge for water discharge control

2.5 Experimental Procedure

Basically the experimental procedure followed the same steps for all cases as described in the next paragraphs. The flume was prepared with sediment (coal) in the area described as movable bed in Figure 2.1, where the sediment height corresponding to 10.0cm above the flume bottom, except in the test region, in which the sediment depth has 27.0cm, predicting the magnitude of erosion around the structures.

The experiments are conducted under uniform flow conditions. The hydraulic parameters adopted for these experiments are given in Table 2.1. 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 experiment was run under live-bed scour condition. Uniform flow condition is established by adjusting the height of tailgate at the end of the flume to desired position. Constant rate of sediment is supplied continuously from the upstream boundary of the flume to maintain the dynamic equilibrium state. The dry sediment is mixed with water before it is supplied in order to avoid the dispersion effects. The sediment transport rate is evaluated with the bed load transport formula proposed by Ashida and Michiue (1972), but the amount of supplied sediment is finally adjusted after some trial experiments. For each experimental run, 6 (six) hours are found to be the sufficient time for the attainment of dynamic equilibrium condition according to the test experiments. Then the flow discharge was slowly reduced to zero. After carefully draining out the water from the experimental flume and after verify this condition, the scour depths at different cross-sections were measured by a laser displacement meter described in item 2.4.1. In order to determine the flow velocity around the structures, electromagnetic current meters described in item 2.4.2 were used. However, the measurement using the current meters is an intrusive method which causes undesirable bed changes. Due to this problem, a cement powder was spread uniformly over the scoured bed to fix it. After the sediment was sufficiently impregnated with the cement powder it was left to set for a period of 24 hours. Having dried further up to 24 hours, the scoured bed profile became rockhard, facilitating the flow velocity measurements.

2.5.1 Impermeable Groins

The characteristics of flow and sediment transport around river training structures were studied using different types of structures. One of them is a widely used impermeable groin which is considered a conventional structure (Alvarez, 1990). The main hydraulic disadvantage of this type of structure is the effect of flow separation at the groin head, caused by the blockage of the flow and formation of complex three-dimensional flow around it (Figure 2.8) (Dey and Barbhuiya, 2006). Therefore, special attention must be given to the toe protection at the head of

the groins, where severe scouring usually occurs.

In the present experiments, this type of groin is made by a wood plate with 1.5cm thickness, 15.0cm length perpendicular to flow direction and 5.0cm height above the initial flat bed level (Photo 2.8). The non-submerged condition is usually studied and many researches related to this type of groin can be found in the literature (Ahmad, 1953; Uijttewaalt et al., 2005). Regarding the field works, this condition are used to project the groins design (Klaasen et al., 2002). The water level in the present experiments was fixed on 4.0cm from the initial flat bed level.

Another condition studied is the submerged condition, which represents, for example the occurrence of a flood event and few studies can be found related to this condition (Uijttewaalt and Berg, 2002; Kawanishi, 2008). The submerged case is used to verify the effects of overtopping flow patterns around the groins and the bed deformation resulted from in compared with the non-submerged case.

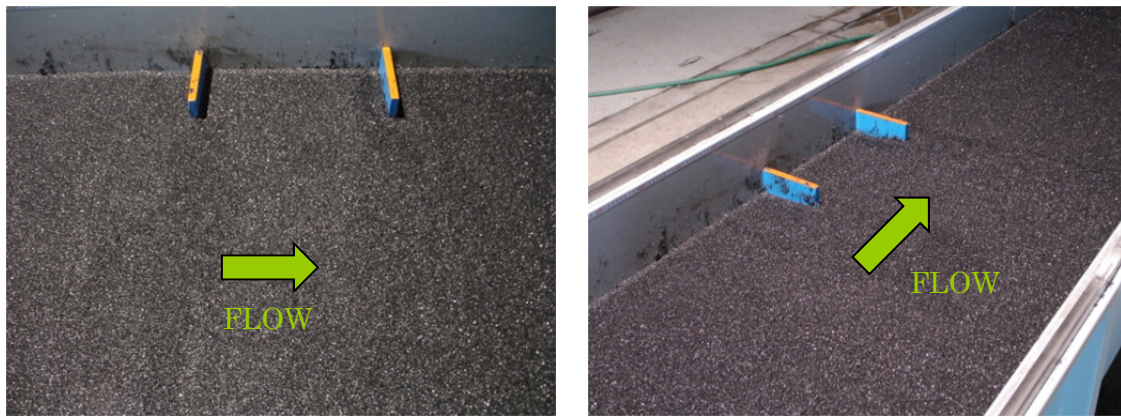


Photo 2.8 Impermeable groins used in the experiments

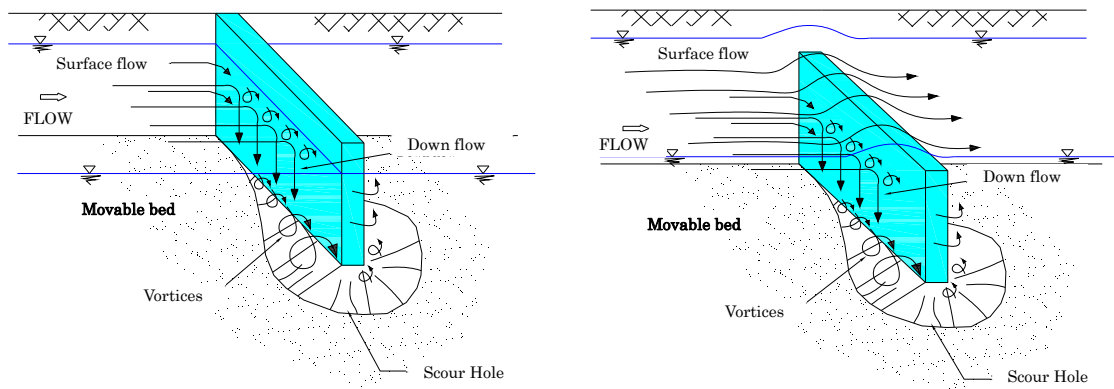


Figure 2.8 Flow patterns around an impermeable groin (left: non-submerged; right: submerged)

2.5.2 Permeable Groins

This type of structure are studied due to the recent demand of river restoration projects considering the possibility of reduction of the near bank flow velocities creating a rapid deposition in that area, in particular in alluvial rivers with considerable sediment load and high sediment concentration near the bed (Figure 2.9). To prevent flow separation and to achieve a gradual deceleration of the flow velocities towards the river bank the maximum permeability, e.g. percentage of opening area through the groin divided by the total area of groin, chosen should be about 80% at the groin head decreasing to 40% at the groin root.

Permeable groins may be built of steel piles, reinforced concrete piles, natural materials as wood or bamboo, which are driven into the riverbed and the flood plain, and they may consist of a single pile row or several rows. In addition to current and wave attack, horizontal loads caused by floating debris must be considered in the design. The advantages of permeable groins are evident when applied in so-called groin fields.

Usually, single groins protect the bank against erosion only over restricted area in the vicinity of the structure and need to be rather long to be effective. Moreover, due to their sensitivity to changing directions of flow attack, single groins are not recommended for general application and in particular not in braided river reach. Instead, groins should preferably be used in series, if a certain reach of the river bank is to be protected.

In the present experiments, it was used permeable groins on single pile row with 50% of permeability, e.g. the distance of two consecutive piles is equal to one pile diameter. The number of piles of one permeable groin are 12 (twelve) with a diameter of 0.60cm. Under the non-submerged condition was verified the influence of permeable groins (Photo 2.9) on flow and bed deformation.



Photo 2.9 Permeable groins used in the experiments

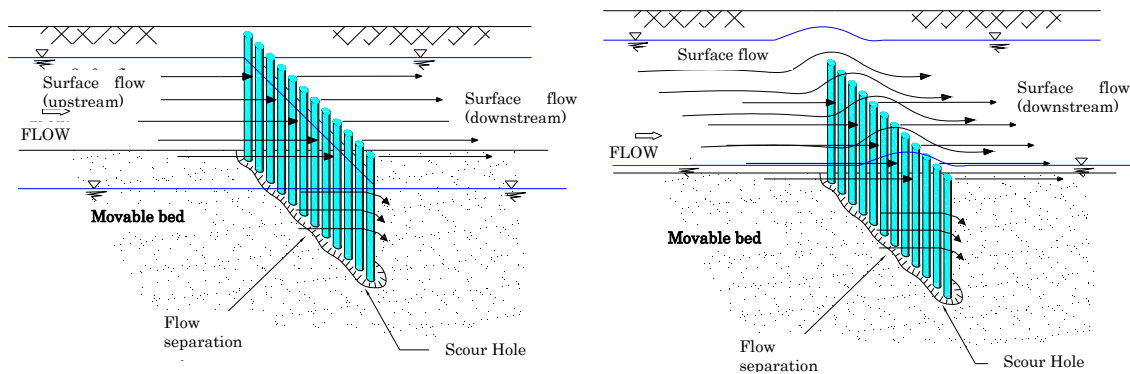


Figure 2.9 Flow patterns around an permeable groin (left: non-submerged; right: submerged)

Similar to the impermeable groins case, this condition was studied by some researchers (Mioduszewski et al., 2003; Nasrollahi et al., 2008) with different purposes as to optimize the distance between the groins, to verify the influence of a series of groins or to study the influence of permeability of groin on flow patterns.

Comparison of the results with impermeable groins and discussion about the applicability of each type of groin was investigated through experiments including other condition as the submerged condition with 2.0cm of submergence (water depth equal to 7.0cm).

2.5.3 Bandal-like Structures

The bandal-like structure can be considered as an alternative method for river training structure developed in Indian Sub-Continent countries like Bangladesh. It is usually used for the maintenance of navigation channels during low flow period (Hanna, 2001). This structure is a temporary structure built for one season period and being damaged or washed away during flood period. The function of this structure is to obstruct flow near the water surface and allow it to pass near the riverbed. They are made by available natural materials as wooden log or bamboos that are regarded as low cost materials when compared to the conventional structures made by concrete or steel.

The available information about bandal-like structures so far is from few field experiences or laboratory studies and features of flow structures and sediment transport process around them are still unknown. Thus detailed study about the mechanism which affects the complex 3D flow structures and bed deformation around bandals need to be investigated.

The working principles of bandal-like structures for the control of water flow and sediment transport are shown schematically in Figures 2.10 and 2.11 (Rahman et al., 2003a, 2003b). Within the lower half of the flow depth, major portion of the sediment flow is concentrated, while, the reverse is true for the water flow discharges. The essential characteristics of these structures are that they are positioned at an angle with main flow direction. As a thumb rule, the

blockage of the flow section at upper part should be about 50% in order to maintain the flow acceleration. The surface flow is being forced to the upstream face creating significant pressure difference between the upstream and downstream side of the structure. The bottom flow directed perpendicular to bandal structure results near bed sediment transport along the same direction. Therefore, much sediment is supplied towards the one side of channel and relatively much water is transported to the other side. The reduced flows passing through the opening of structures are not sufficient to transport all the sediment coming towards this direction, resulting sedimentation over the bank side. On the other hand, more water flows with little sediment moves towards the main channel that develop deeper navigational channel over there.

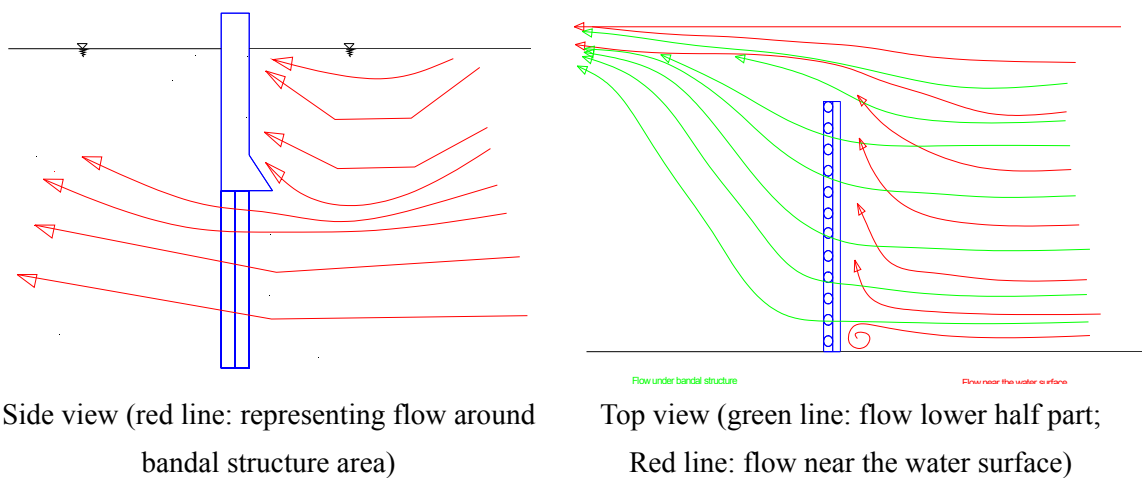


Figure 2.10 Flow around Bandal-like structures (streamlines)

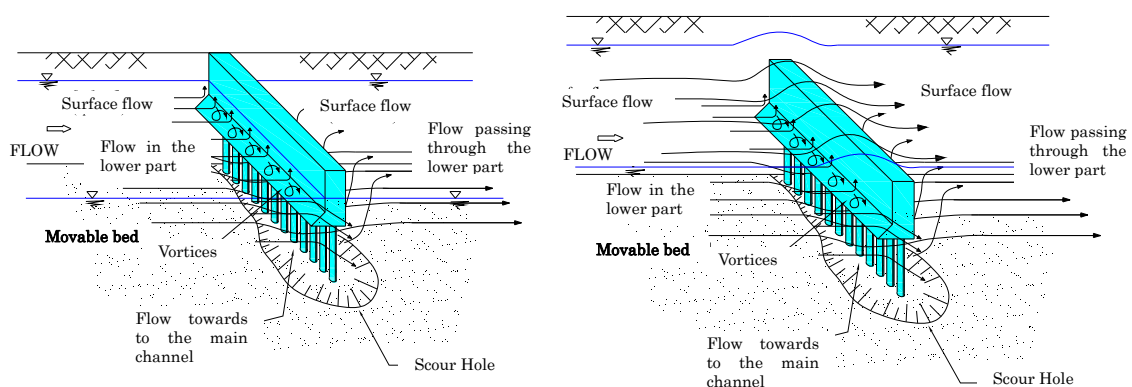


Figure 2.11 Flow patterns around an Bandal-like structure (left: non-submerged; right: submerged)

The design of bandal-like structure is very similar to a permeable groin due to the lower half part of this structure is constituted by a piles and an impermeable groin due to the upper half

part is made by an impermeable plate (Figure 2.12), but the function is different of these two conventional types of groins. The characteristics of flow can be resumed as the deviation of high velocity flow near the water surface to the main channel direction at the upper part and at the lower part, the passage of lower velocity flow with high concentration of sediment (bed load and suspended sediment) than that the concentration near the water surface. In the experiments, the bandal-like structures are formed by a bended plate in your upper part, i.e. the upper plate have an angle of 30° with the vertical axis according to Figure 2.12 and Photo 2.10 to minimize the effect of downward flow formed due to the blockage of flow in the bed, and a lower part with cylindrical piles representing the permeable part of this structure. The non-submerged condition is the same adopted in the groins cases and the submerged condition with 2.0cm submergence (water depth equal to 7.0cm) was adopted for comparison with the groins cases.

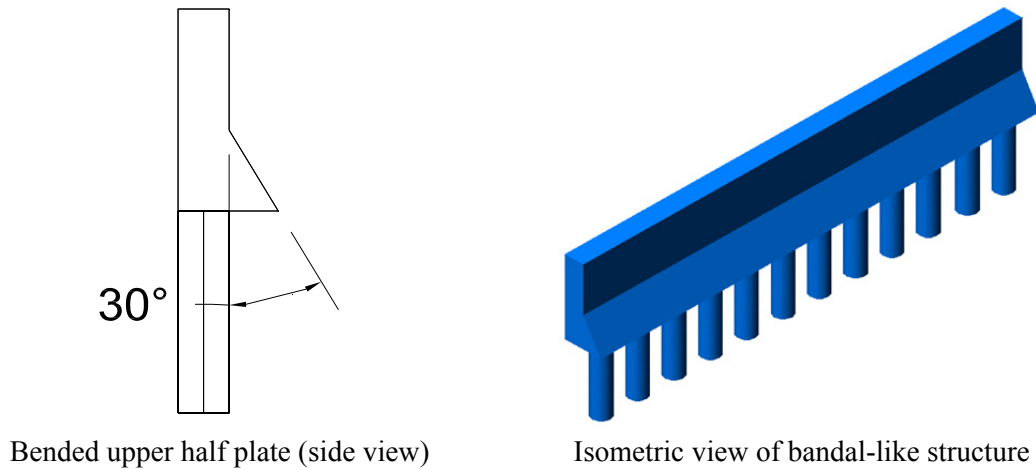


Figure 2.12 Bandal-like structure design

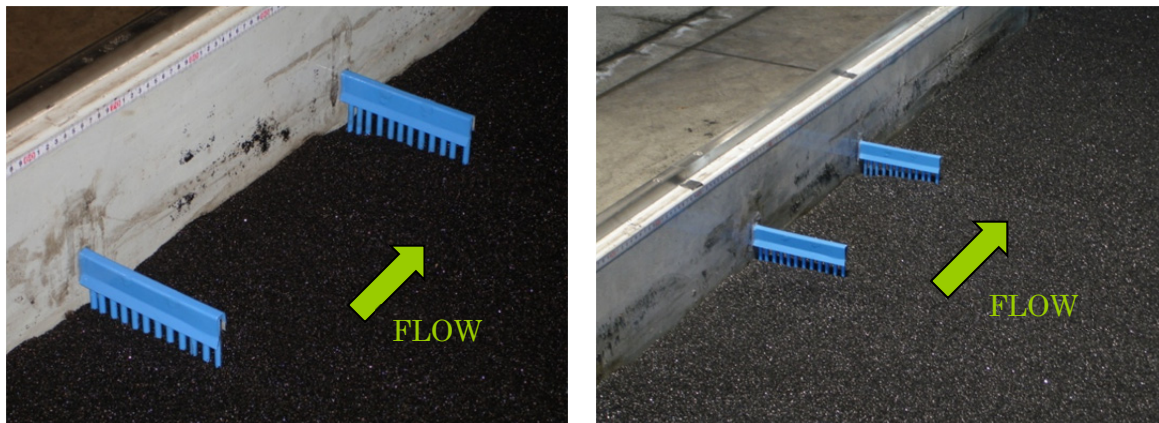


Photo 2.10 Bandal-like structures used in the experiments

2.6 Results and discussions

Experimental studies have an important meaning to provide reliable data about the characteristics of flow in a channel and the development of scour hole around the hydraulic structures. In this section, experimental observations and results are presented and discussed. The effects of each type of structure on the flow field and the deposition or/and erosion process are investigated.

2.6.1 Velocity distribution

2.6.1.1 Impermeable Groins

One of the primary objectives of these experiments is to examine the effect of variation in the type of structure on flow patterns. Moreover, the ability of the numerical model to simulate the experimental results is checked comparatively in the Chapter 4.

The flow structures in the impermeable groins field on the water surface are shown in Photos 2.11 and 2.12. It can be seen the flow separation at upstream groin (Groin A) toe which causes diversion of flow towards the main channel and the formation of mixing area between the main channel and the embayment area, especially in Case 1 under non-submerged condition.

In submerged condition (Case 4), the phenomenon of flow separation occurs but due to the passage of overtopping flow is difficult to visualize from the water surface (Photos 2.12), only the tendency of flow towards the main channel direction can be visualized.

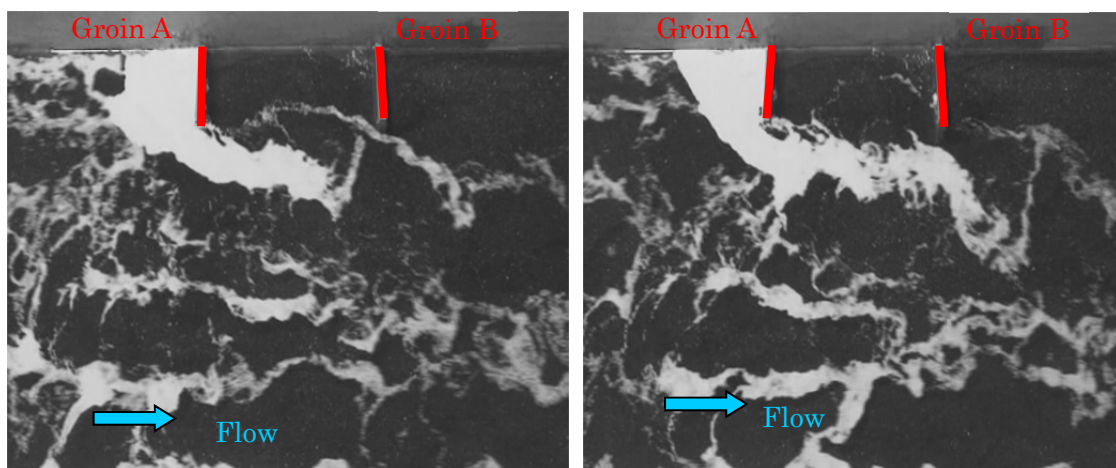


Photo 2.11 Surface flow visualization of the impermeable groins – Case 1

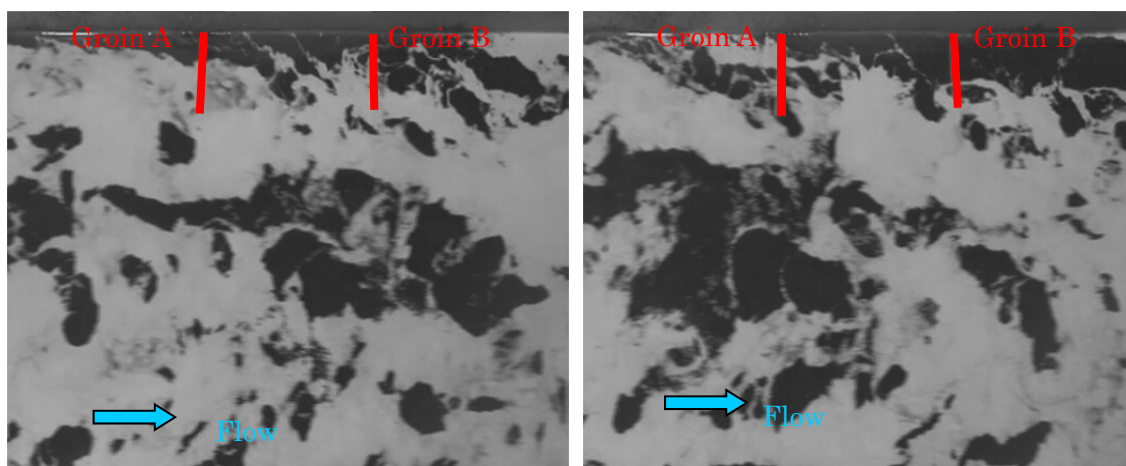


Photo 2.12 Surface flow visualization of the impermeable groins – Case 4

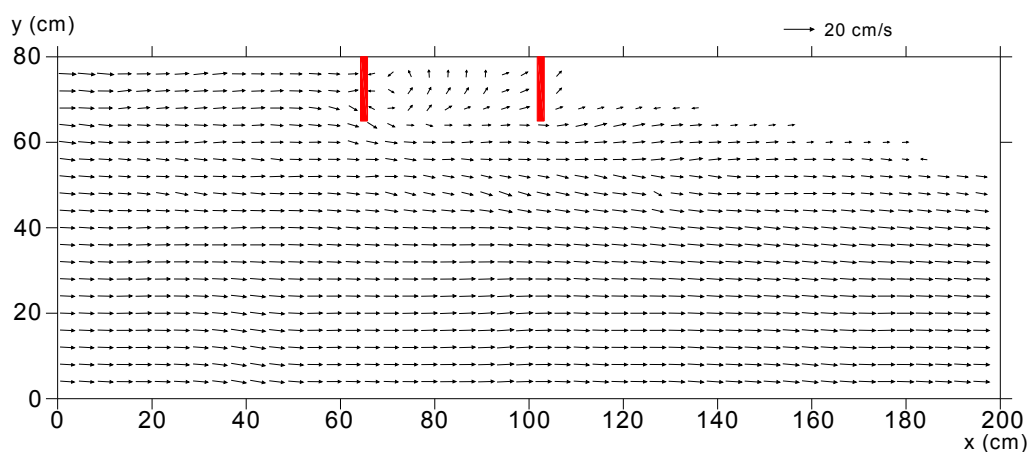


Figure 2.13 Velocity field around impermeable groins in plane XY at $z=2.0\text{cm}$ – Case 1

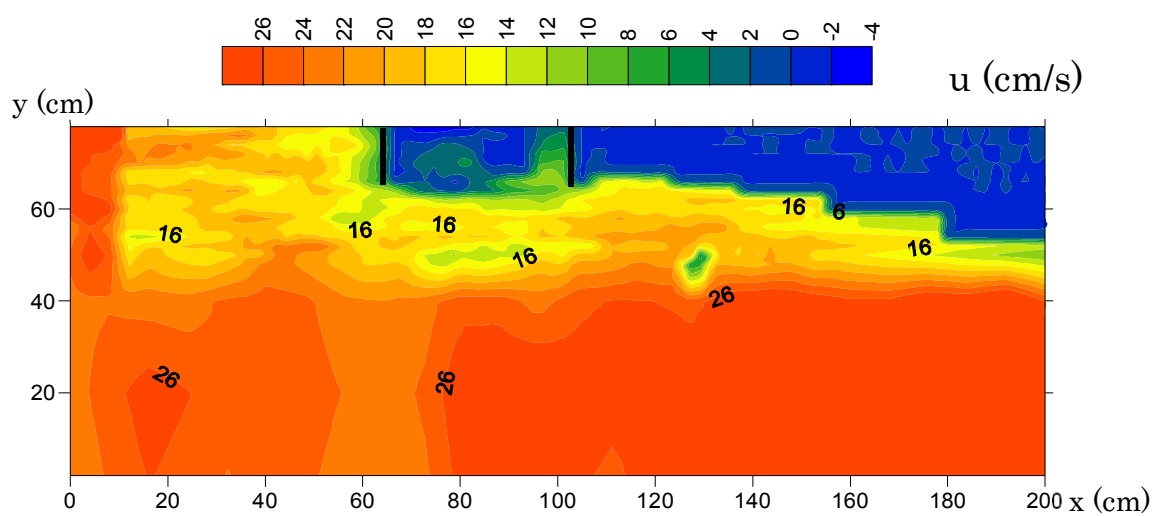


Figure 2.14 Longitudinal velocity contour (u) around impermeable groins in plane XY at $z=2.0\text{cm}$ – Case 1

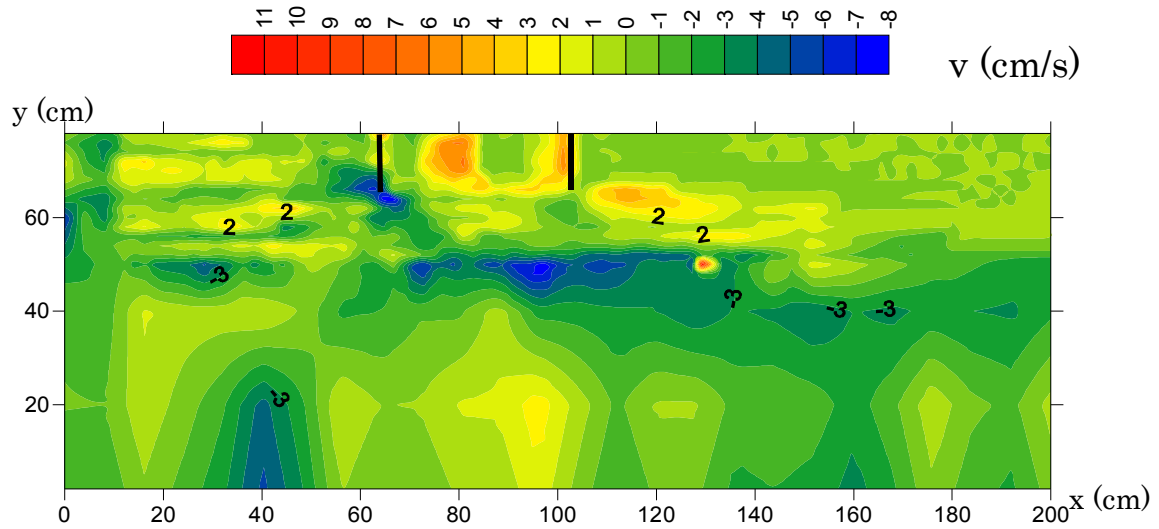


Figure 2.15 Transversal velocity contour (v) around impermeable groins in plane XY at $z=2.0\text{cm}$ – Case 1

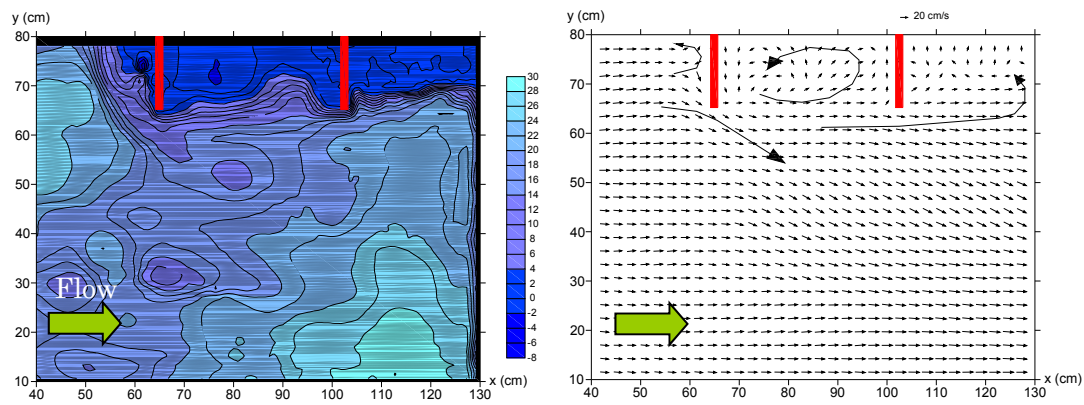


Figure 2.16 Surface velocity field around impermeable groins in plane XY – Case 1

The Figures 2.13, 2.14 and 2.15 show the two dimensional (x,y) horizontal velocity vectors (u,v) at the depth of $z=2.0\text{cm}$ and the Figure 2.16 the velocity at water surface (the level $z=0.0\text{cm}$ corresponds to the initial flat bed level) in Case 1, respectively. In these figures, the upstream approach flow field shows a tendency of diversion towards to the main channel direction due to the blockage of flow by the structure. The flow deviation to the main channel direction can be seen clearly at groin toe and the formation of recirculation currents in the area between the two groins (embayment) and at downstream of both groins.

From the velocity contour showed in the Figures 2.14 (longitudinal direction) and 2.15 (transverse direction), the formation of return currents (anticlockwise) is observed in the embayment area near the side wall. These currents can attack the sidewall (riverbank) and cause

some erosion even with reduced flow velocity. In the main channel, the flow velocity shows high values showing the tendency to increase in magnitude due to the reduction of transverse cross-sectional area caused by the presence of groins. The flow diverted from the upstream groin becomes parallel to the flume direction at downstream of groins field. The velocity vectors within scour hole around the upstream groin show almost perpendicular diversion towards main channel and return currents in a sharp angle to the bank side wall. In the impermeable groins field, strong vortex, reverse flow and sharp return currents as horse-shoe vortex is also seen due to the effect of the structure. The flow field around the structures is unsteady due to the influence of the structures, even with a steady discharge in this case.

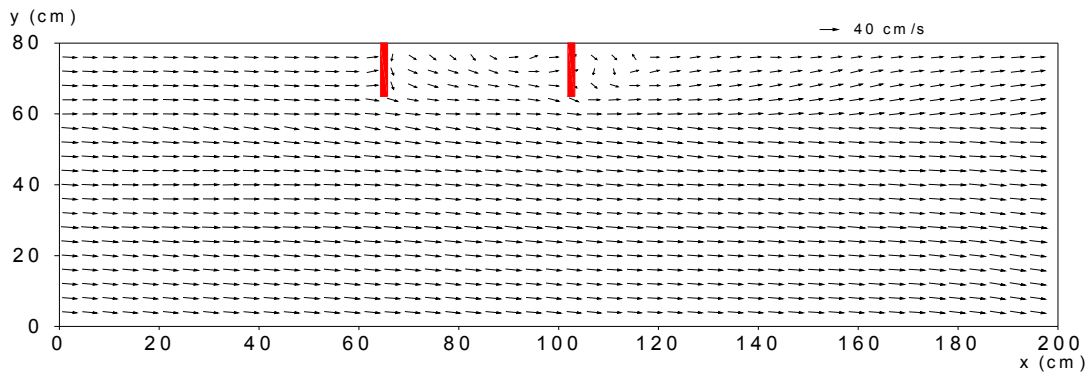


Figure 2.17 Velocity field around impermeable groins in plane XY at $z=3.50\text{cm}$ – Case 4

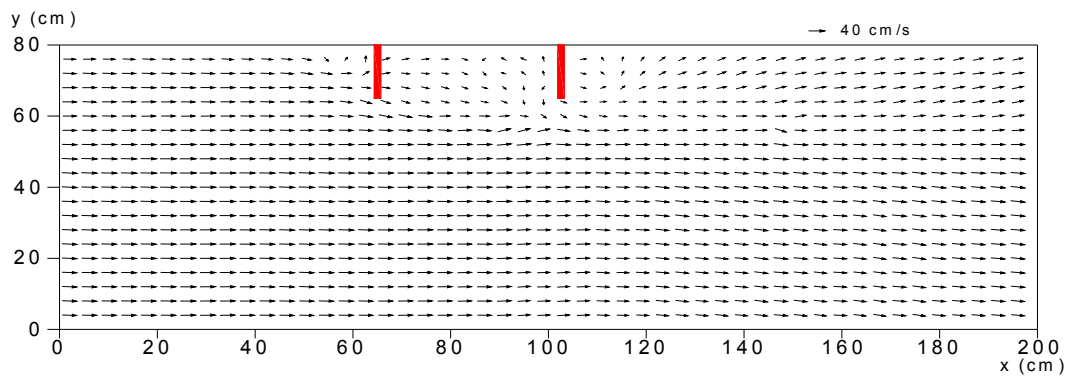


Figure 2.18 Velocity field around impermeable groins in plane XY at $z=5.50\text{cm}$ – Case 4

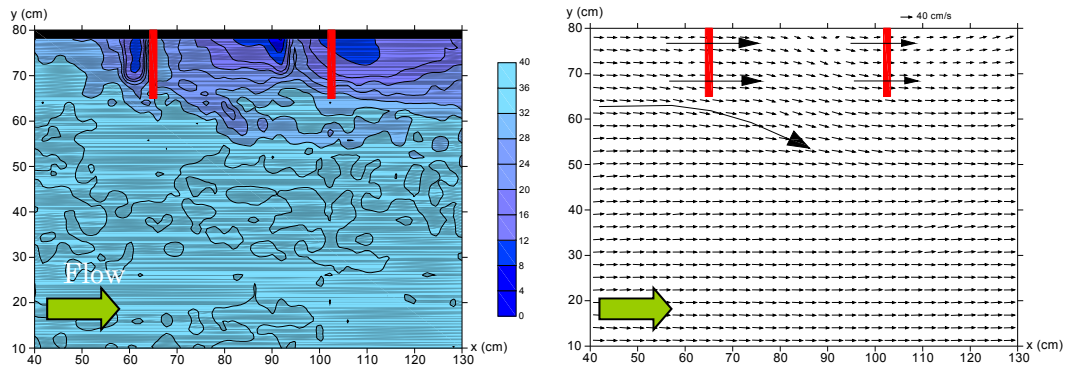


Figure 2.19 Surface velocity field around impermeable groins in plane XY – Case 4

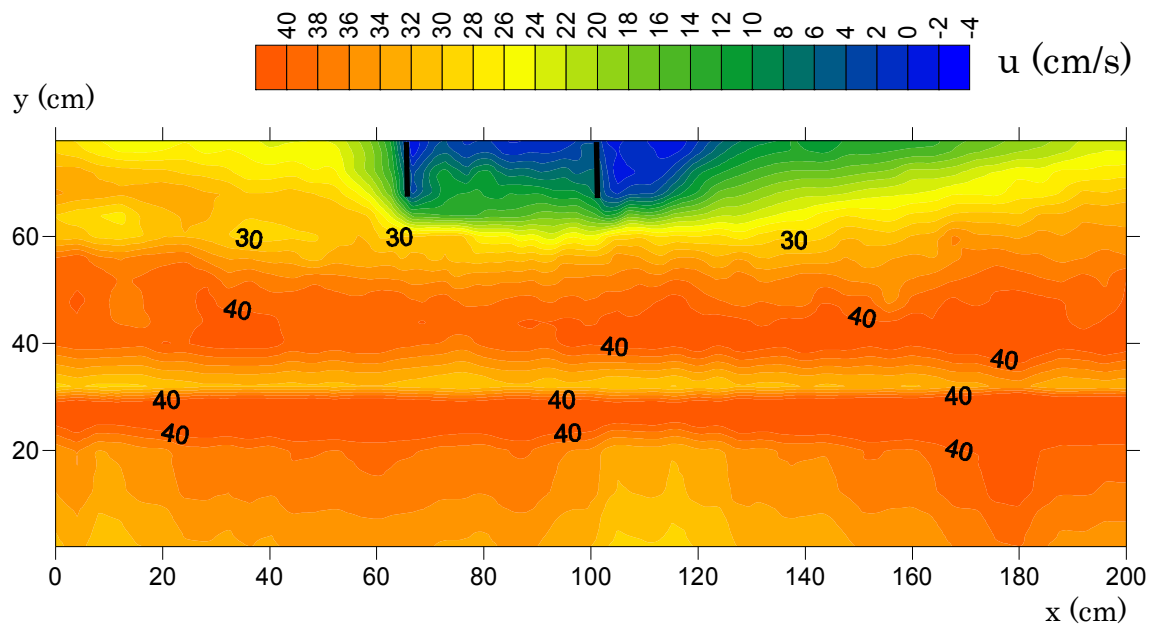


Figure 2.20 Longitudinal velocity contour (u) around impermeable groins in plane XY at $z=3.50\text{cm}$ – Case 4

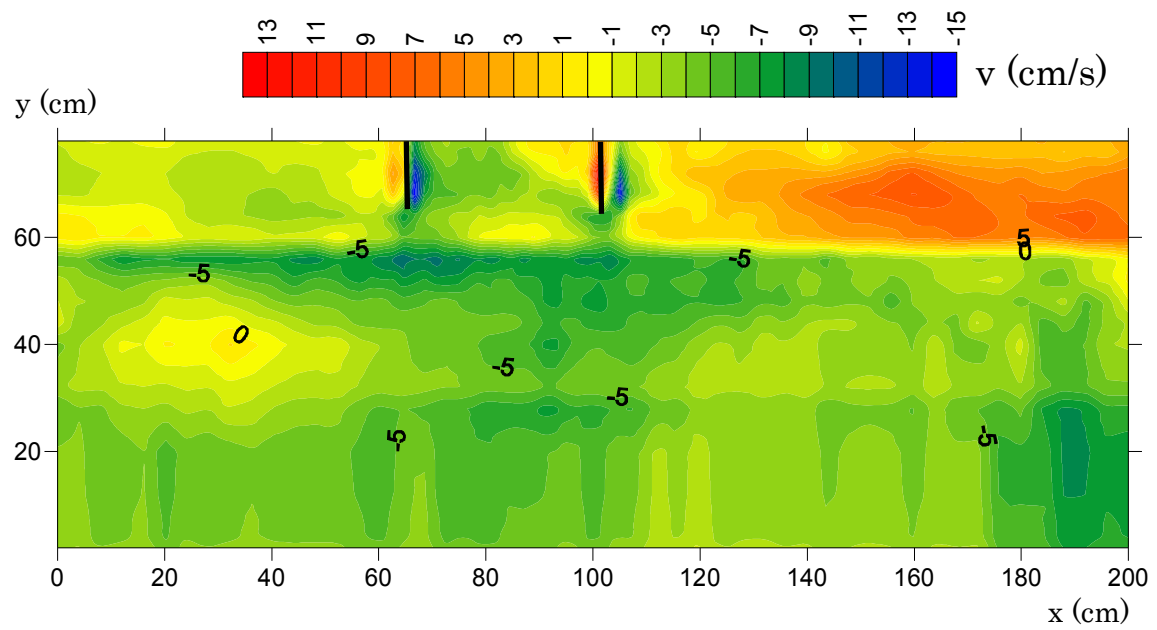


Figure 2.21 Transversal velocity contour (v) around impermeable groins in plane XY at $z=3.50\text{cm}$ – Case 4

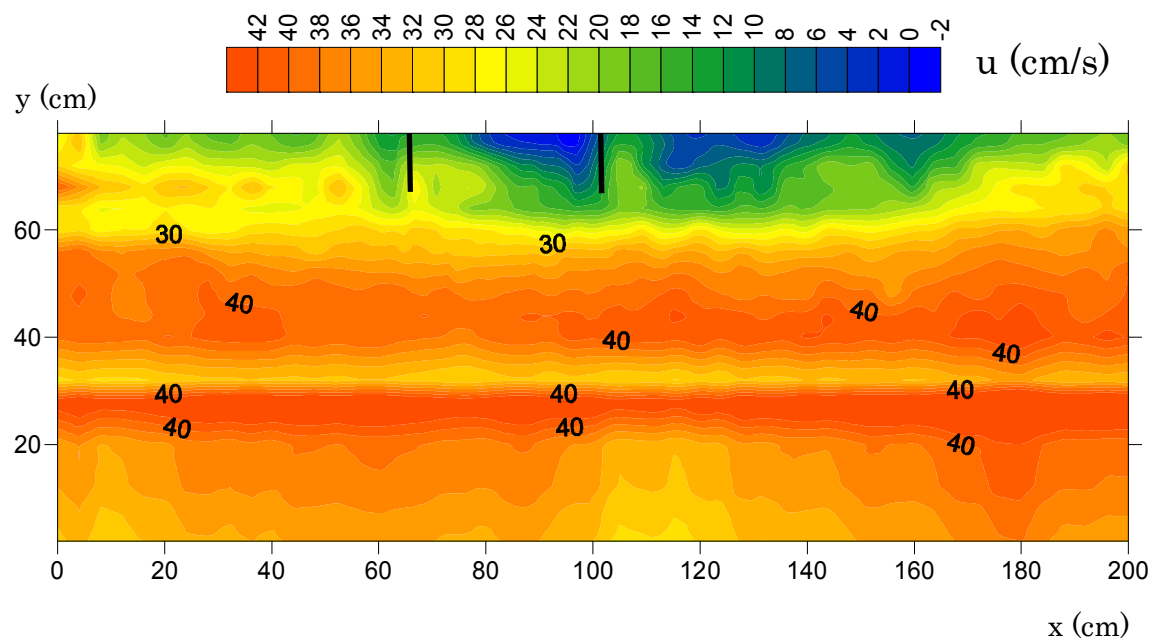


Figure 2.22 Longitudinal velocity contour (u) around impermeable groins in plane XY at $z=5.50\text{cm}$ – Case 4

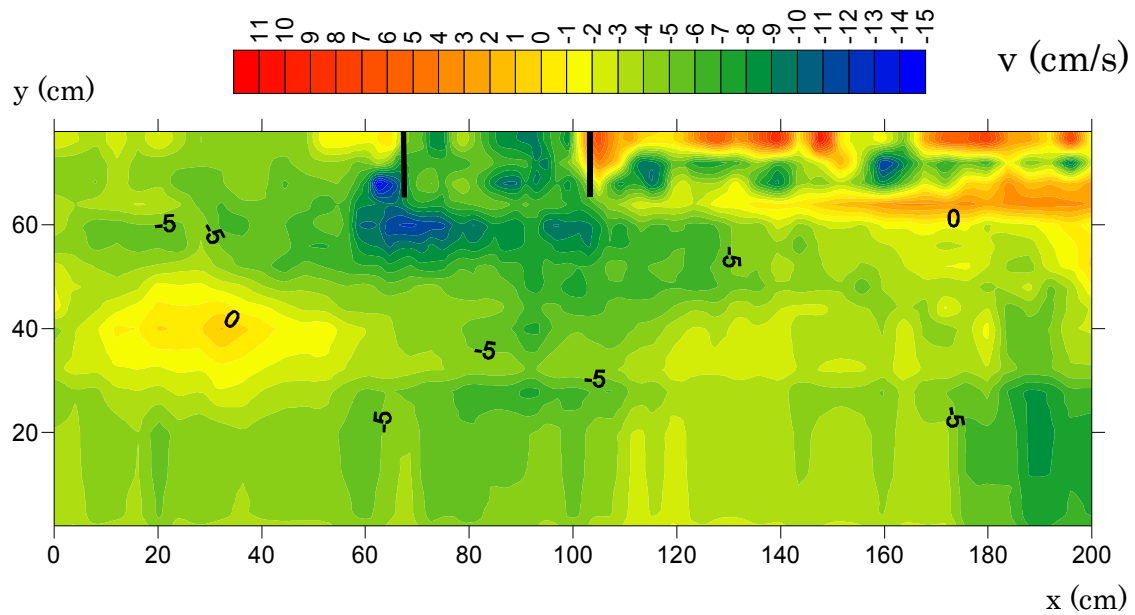


Figure 2.23 Transversal velocity contour (v) around impermeable groins in plane XY at $z=5.50\text{cm}$ – Case 4

In the submerged case, the Figures 2.17, 2.18, 2.19, 2.20, 2.21, 2.22 and 2.23 show similar characteristics of flow patterns that it was observed in the non-submerged condition, the strong deviation flow from the upstream groin (Groin A) and a tendency to the formation of recirculation currents in the groins field due to the flow separation at head of groin A can be seen, however the overtopping flow decreases the occurrence of this recirculation which becomes weak, especially close to the water surface. The velocity reduction due to the presence of groin can be seen on Photo 2.12 through the appearance of very small waves in the water surface and the velocity vectors (Figure 2.19). From the velocity contour showed in the Figures 2.20, 2.21, 2.22 and 2.23 for Case 4, the effects of submergence can be seen especially near the water surface in which the reduction of magnitude in the transversal component (v) of velocity occurs in the groins field.

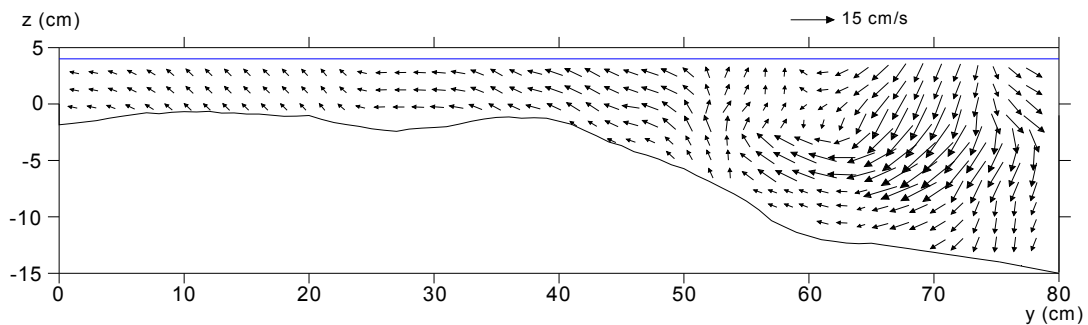


Figure 2.24 Velocity field around impermeable groins in plane YZ at $z=62.0\text{cm}$ – Case 1

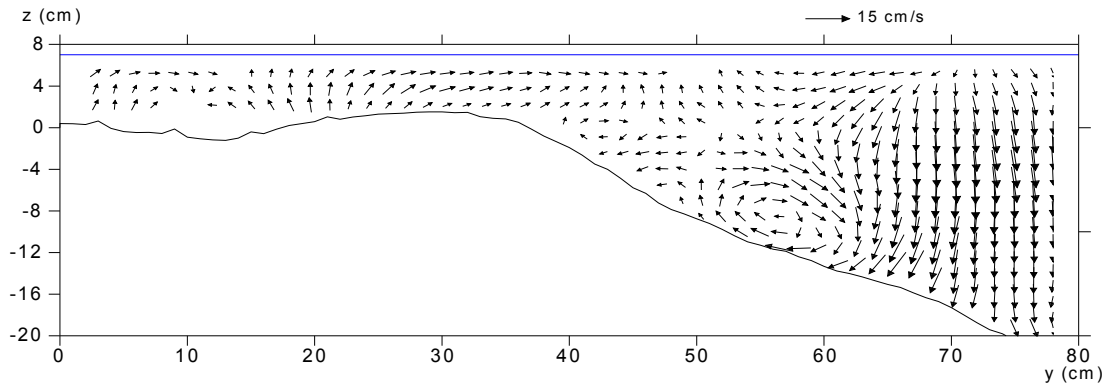


Figure 2.25 Velocity field around impermeable groins in plane YZ at $x=62.0\text{cm}$ – Case 4

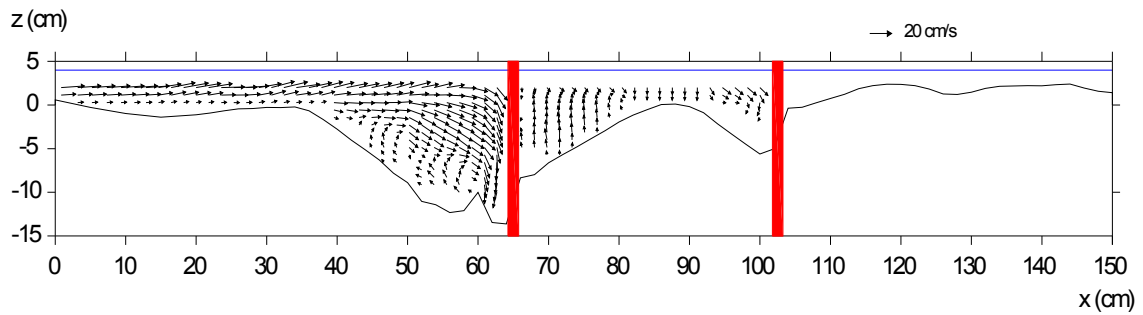


Figure 2.26 Velocity field around impermeable groins in plane XZ at $y = 72.0\text{cm}$ – Case 1

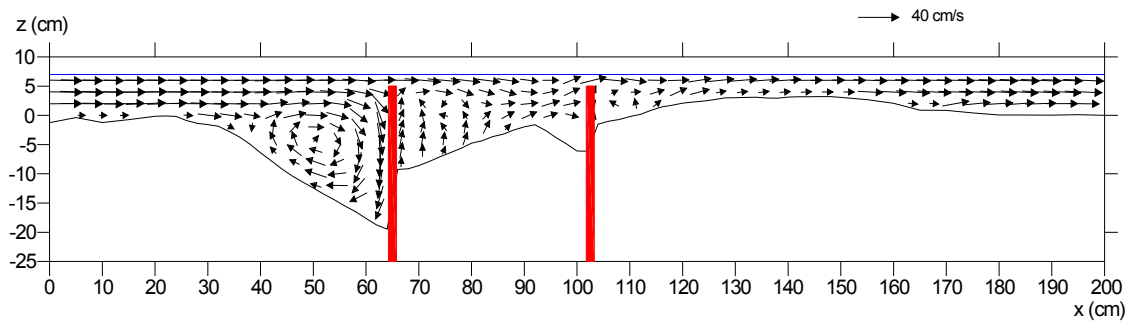


Figure 2.27 Velocity field around impermeable groins in plane XZ at $y = 72.0\text{cm}$ – Case 4

The three-dimensional flow resulting from the interaction between the flow and the impermeable groins field causes formation of downward flux, especially at the upstream region of groin A. These flow can be seen in Figures 2.24 and 2.25 (transverse cross-section) and

Figures 2.26 and 2.27 (longitudinal section). The transverse cross-section refers to position $x = 62.0\text{cm}$ (2.5cm upstream of groin A) and the longitudinal section to the position $y = 72.0\text{cm}$ (8.0cm from the left side wall). In Figure 2.24 under non-submerged condition, the flow separation from the head of groin A is strong due to the magnitude of velocity vectors. This diverted flow is seen to be moving towards the main channel, especially close to the bottom layers. Near the bank side wall is possible to observe the inward flow direction due to the concentrated flow at upstream of the groin. From the middle line of groins ($y = 72.0\text{cm}$), the vectors are directed towards the main channel and also vertical re-circulation currents with considerable magnitude. In the submerged condition, the Figure 2.25 shows a similar velocity patterns with differences in the magnitude. Case 4 shows very clearly the flow deviation due to the presence of impermeable groin and due to the higher flow velocity can be observed the formation of vertical vortex near the groin head ($y=60.0\text{cm}$), and in the main channel the inward and outward velocity vectors.

The velocity vectors (u,w) in the longitudinal section (x,z) show for the non-submerged condition (Figure 2.26) a very high downward direction vectors at upstream of the groin A, the magnitude of this velocity is higher near the water surface and gradually decreases near the bed. These downward vectors explain the reason for groin field erosion observed during the experiments. In the submerged case, the magnitude of velocity vectors is higher due to the higher flow discharge, and the flow passing over the groin increases the velocity magnitude and contribute to the formation of upward flow in groins field, where is possible to see the formation of vertical vortex in groins field and at downstream of groin B.

The uv velocity vectors clearly show that the separated flow from the impermeable groin heads are returning to the groins field. Near the scour holes, the return current has a sharp return angle towards the bank. We can observe that the velocity contours are regularly penetrating deep inside the groins field. From these figures the recirculation towards the groins field are clearly understood. This strong recirculation ensures very active mass exchange between the main channel and the groin fields.

Impermeable groins cause constriction of river channels and change the approach flow pattern. Introduction of such groins induces high concentration of velocity, bed shear stress, vortices, downward flows and turbulence at the upstream of groin head. At the upstream of groins field energy loss occurs in the velocity at groin head and the potential head increases in the form of water level rise, causing shear stress increment. In the main channel, there are two effects; one is the contraction effect and another is the flow diversion by the groins. Around the groins two effects are working, i.e. the contraction effect and the protrusion effect of the groins, where there is more concentrated at groins head.

2.6.1.2 Permeable Groins

In the permeable groins cases, through the flow visualization is possible to observe differences comparing to the impermeable groins case. Firstly, the flow separation from the groins heads is visible but the intensity is very weak. Also, the turbulence effects of this structure have small intensity with very weak disturbance on flow patterns. In Case 2 (Photo 2.13) under non-submerged condition, the influence of this structure on flow due to the permeability of groin (50%) has significant effects on the flow passing through the structure which avoids the formation of vortices and the recirculation currents in between the groins. Another effect is the reduction of the velocity magnitude of flow passing through the piles. A weak separation of the flow was observed on toe of groin A that causes the deviation of flow direction towards the main channel. In the submerged case (Case 5), the Photo 2.14 shows very similar flow pattern on the water surface, the effect of groins can be seen through the formation of small waves on the water surface and a weak deviation of flow in the main channel direction.

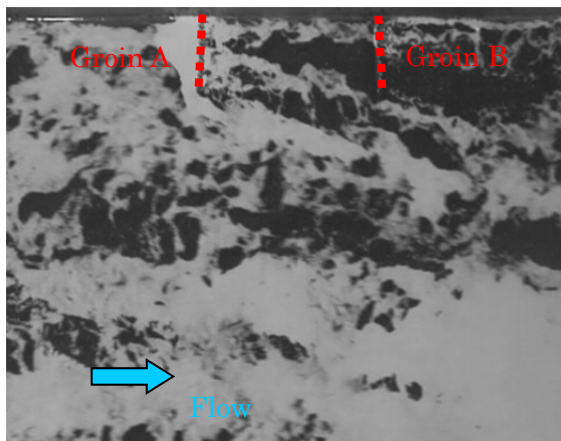


Photo 2.13 Surface flow visualization of the permeable groins – Case 2

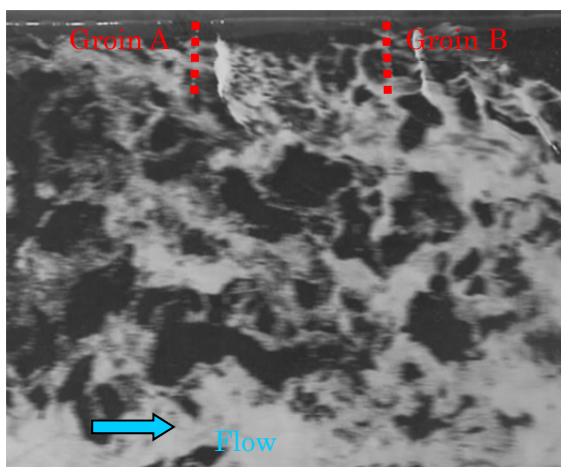
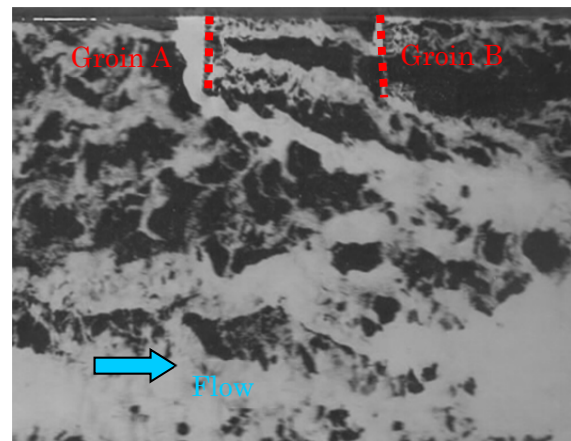


Photo 2.14 Surface flow visualization of the permeable groins – Case 5

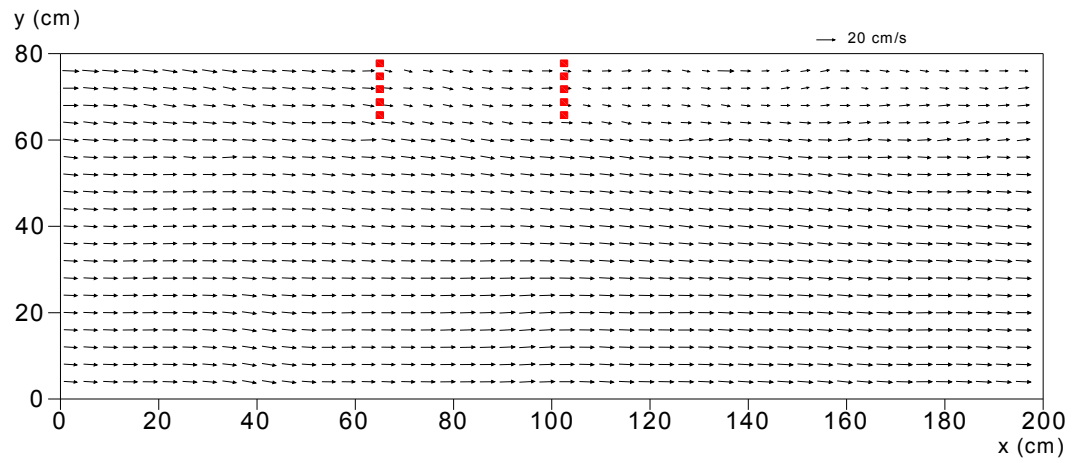


Figure 2.28 Velocity field around permeable groins in plane XY at $z=2.0\text{cm}$ – Case 2

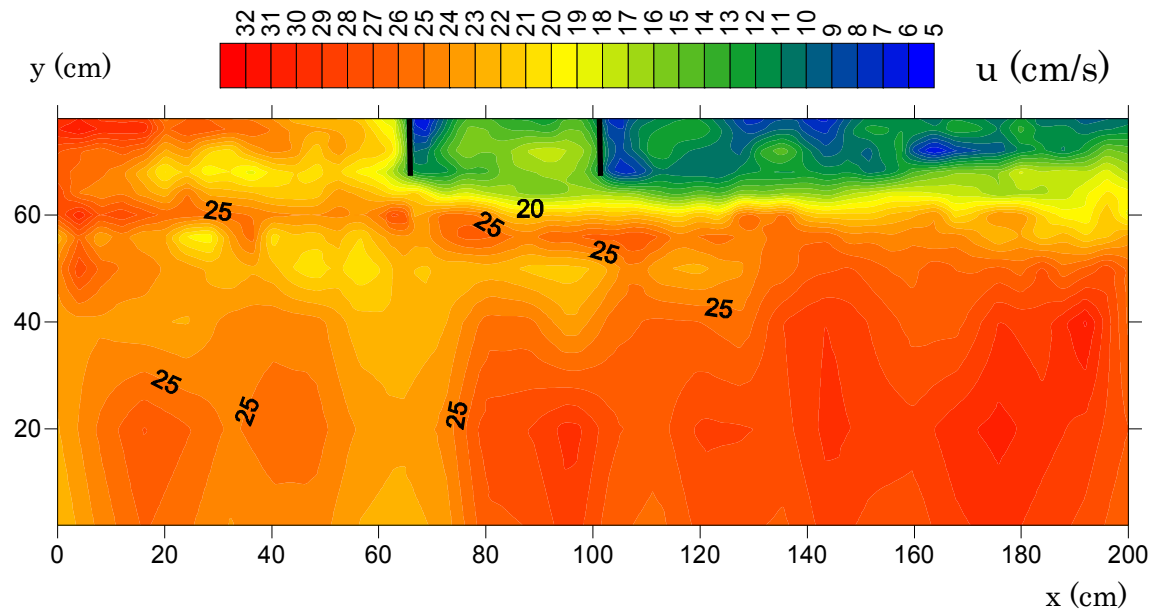


Figure 2.29 Longitudinal velocity contour (u) around permeable groins in plane XY at $z=2.0\text{cm}$ – Case 2

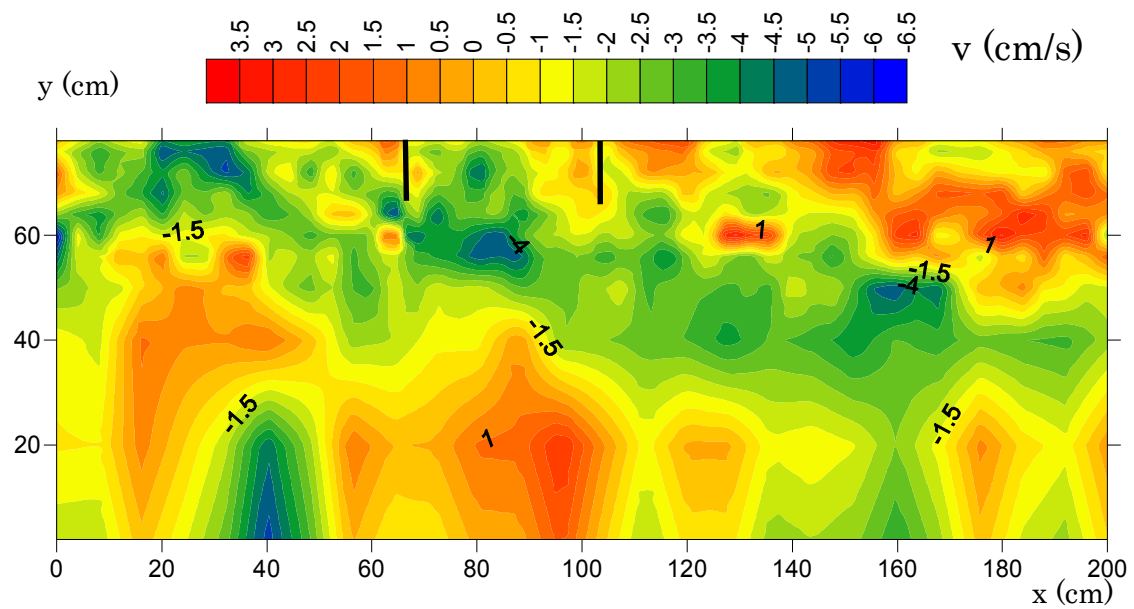


Figure 2.30 Transversal velocity contour (v) around permeable grains in plane XY at $z=2.0\text{cm}$
– Case 2

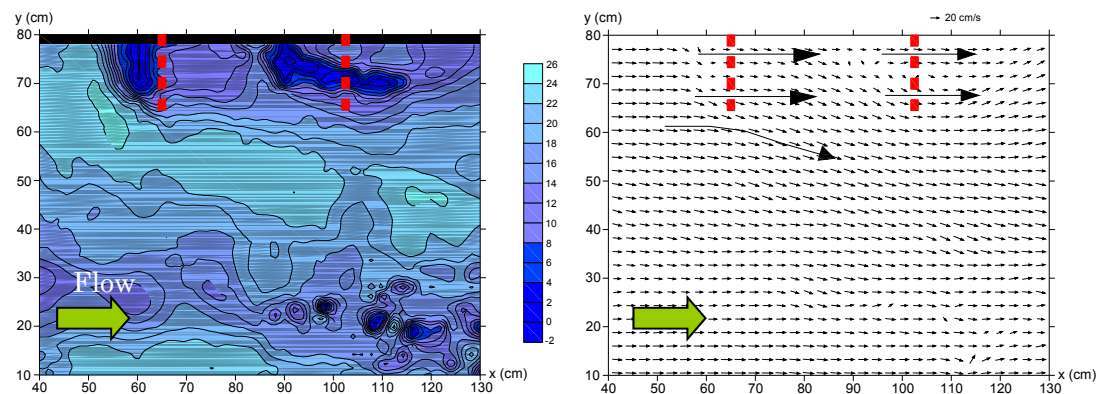


Figure 2.31 Surface velocity field around permeable grains in plane XY – Case 2

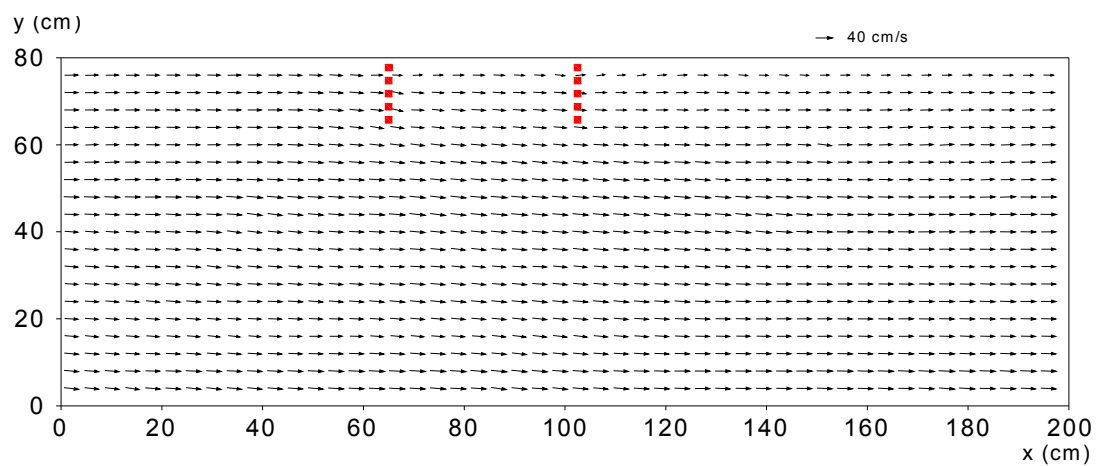


Figure 2.32 Velocity field around permeable groins in plane XY at $z=3.50\text{cm}$ – Case 5

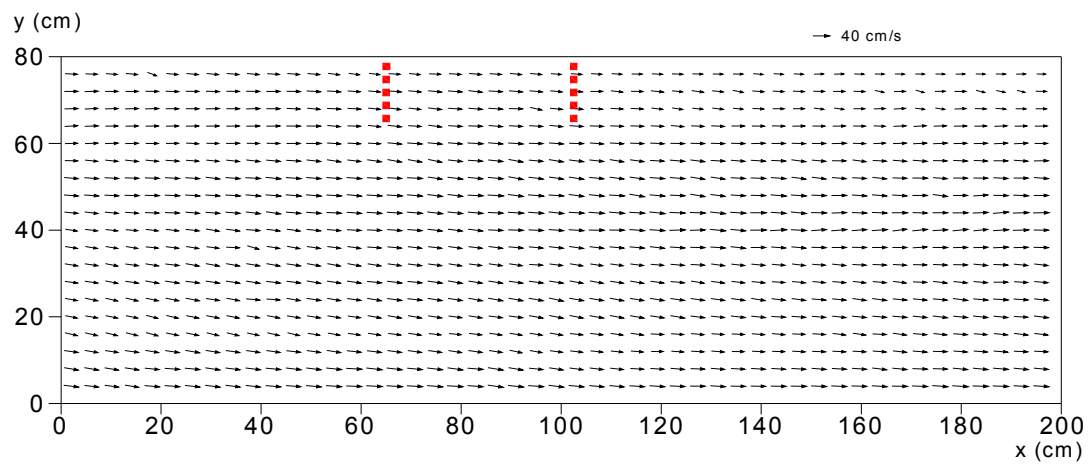


Figure 2.33 Velocity field around permeable groins in plane XY at $z=5.50\text{cm}$ – Case 5

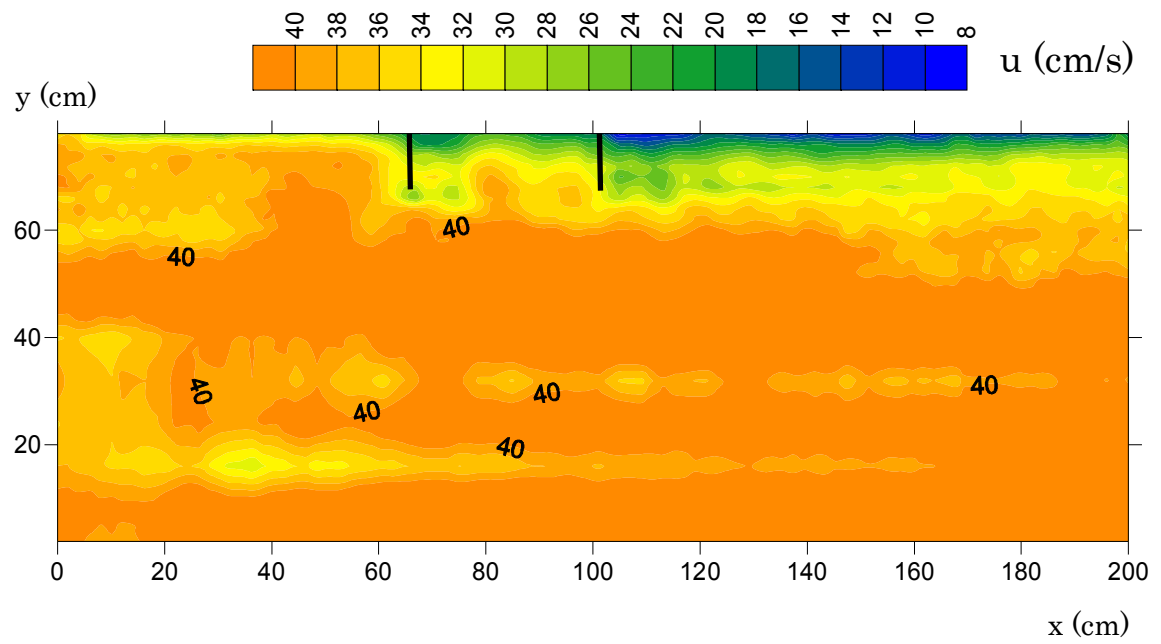


Figure 2.34 Longitudinal velocity contour (u) around permeable grains in plane XY at $z=3.50\text{cm}$ – Case 5

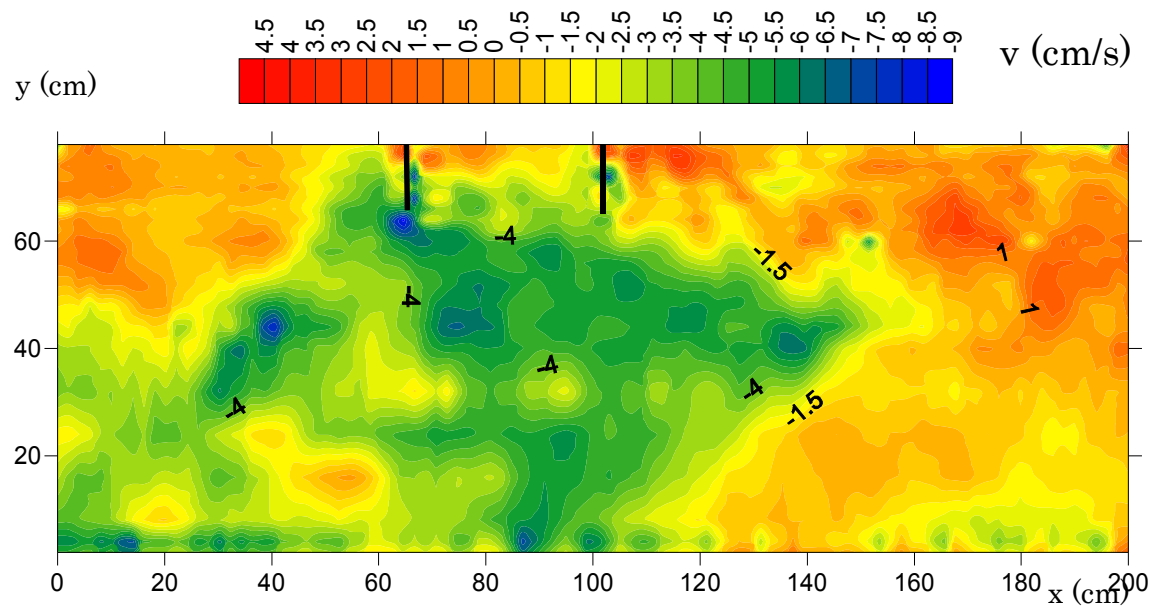


Figure 2.35 Transversal velocity contour (v) around permeable grains in plane XY at $z=3.50\text{cm}$ – Case 5

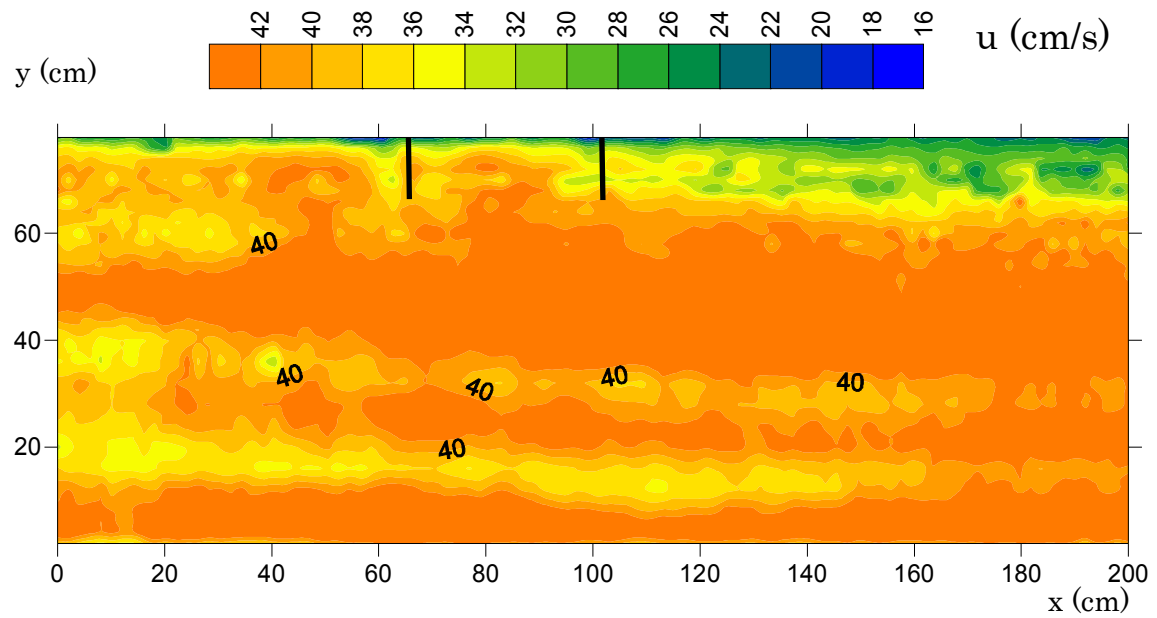


Figure 2.36 Longitudinal velocity contour (u) around permeable grains in plane XY at $z=5.50\text{cm}$ – Case 5

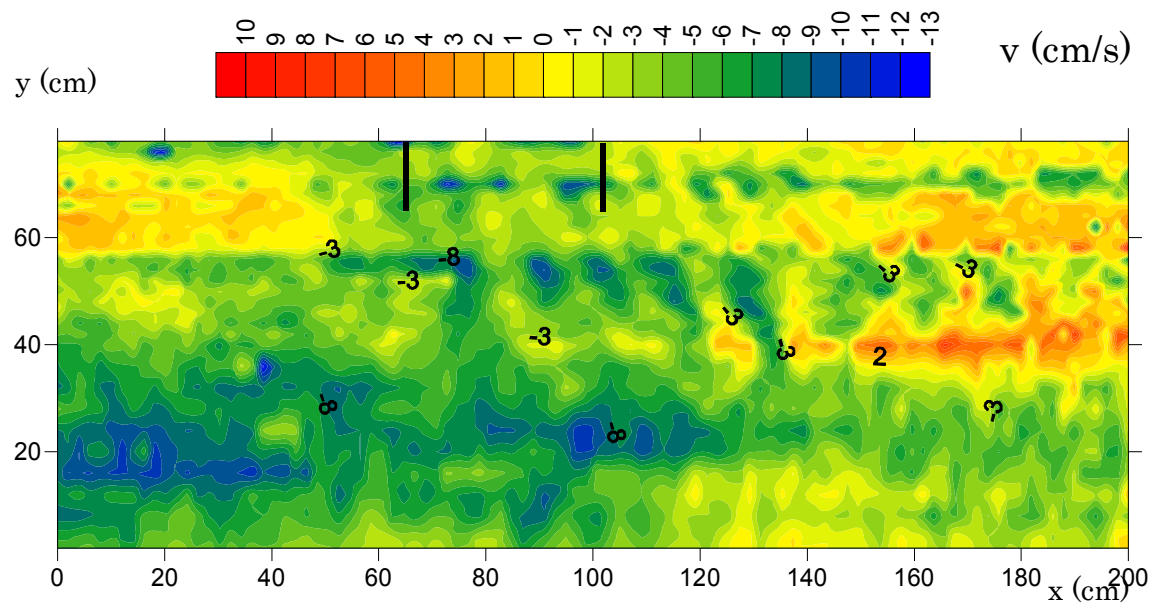


Figure 2.37 Transversal velocity contour (v) around permeable grains in plane XY at $z=5.50\text{cm}$ – Case 5

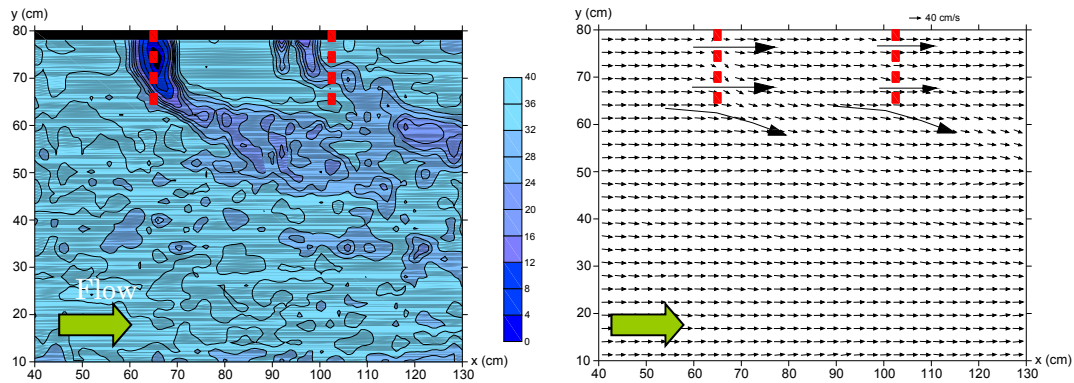


Figure 2.38 Surface velocity field around permeable groins in plane XY – Case 5

The two-dimensional (x,y) velocity vectors (u,v) are shown in Figures 2.28, 2.29, 2.32, 2.33 and 2.34, for Cases 2 and 5. In Case 2 at $z = 2.0\text{cm}$ (Figure 2.28) and at water surface (Figure 2.29), the upstream approach velocity vectors show a tendency of diversion towards the main channel, the surface flow separation at the groin heads is very weak. No recirculation currents are observed in the groins field, because the momentum transfer by the water flowing through the piles is sufficient to balance the momentum transfer through the mixing layer. From the head of groin A, the velocity vectors are deflected and it continues up to the opposite bank. In Figures 2.30 to 2.31 and Figures 2.35 to 2.38, for Cases 2 and 5, respectively, it is observed that the main channel flow velocity is increased in magnitude and becomes quite faster than in the groins field velocity, and it has a tendency to increase in magnitude at downstream direction. Relatively stronger flow separation is seen at the head of groin A compared to downstream groin. The associated high velocity gradient gives rise the formation of deviation flow towards the main channel direction.

The transversal cross-section velocity vectors (v,w) and the longitudinal section velocity vectors (u,w) do not show any remarkable difference at upstream and inside the groins field area. And then these results not are shown in this work. The XY velocity vectors clearly show that the weak separated flow from the groin heads does not return to the groins field, rather those are straightened up and follows almost a bank parallel direction. From these figures the absence of recirculation towards the groins field is confirmed. There is no direct mass exchange between the main channel and the groins field because of the non-existence of recirculation flow. However, the transition of the low velocity vectors still found in a narrow band just downstream of the groin tip.

Construction of groins causes contraction of river channels and influences the approach flow pattern. Permeable groins act as a kind of roughness element and causes reduction of flow velocity. In addition to these effects the weak flow separation and flow diversion by the groin

pile induce increase in main channel velocity. As a consequence, the bed shear stress and turbulence increase in the main channel. Combination of these factors causes the formation of small scour holes around the permeable groins and the small degradation of main channel bed.

2.6.1.3 Bandal-like Structures

The bandal-like structures as commented before have design characteristics similar to an impermeable groin (upper half plate) and a permeable groin (lower half part). During these experiments this structure was used perpendicular to the flow direction and with upper half plate modified (an angle of 30° with the vertical direction) as shown in Figure 2.12. The bandal-like structure usually is used under non-submerged condition during lower flow season, because it is made by materials like wooden log or bamboo, and being damaged or washed away during the flood period. In the experiments were tested two conditions, non-submerged and submerged conditions to evaluate different behaviors in both conditions.

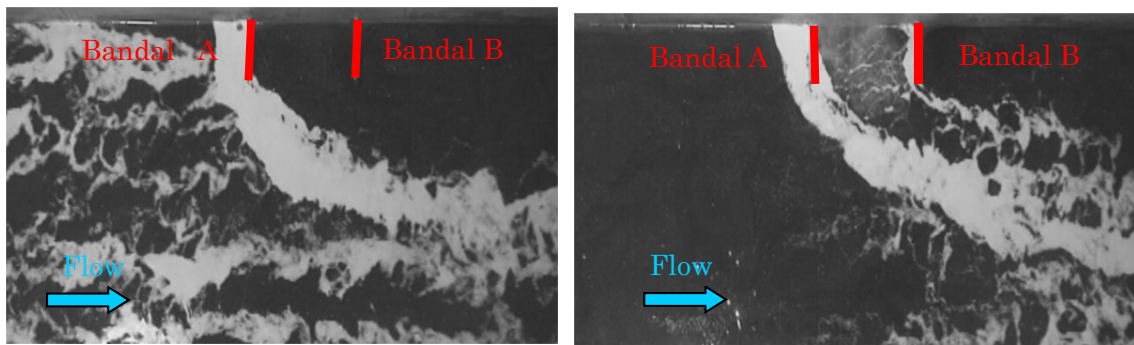


Photo 2.15 Surface flow visualization of the bandal-like structures – Case 3

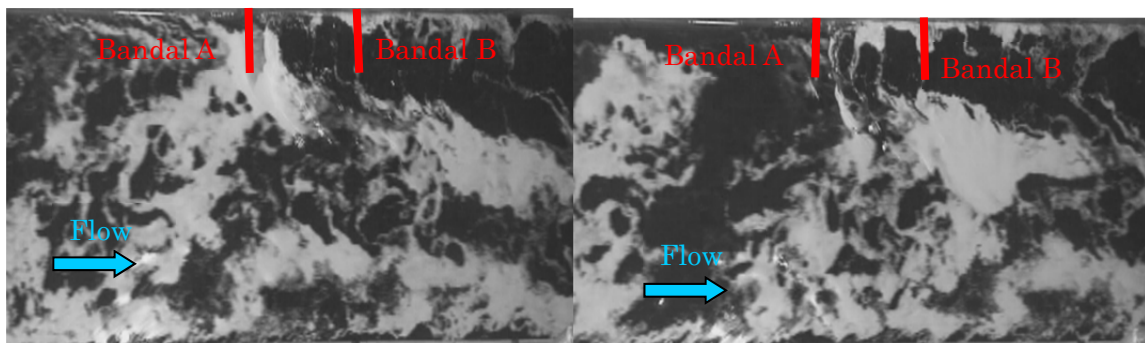


Photo 2.16 Surface flow visualization of the bandal-like structures – Case 6

From the surface flow visualization (Photos 2.15 and 2.16), is possible to verify the flow deviation after passing the upstream bandal-like structure (bandal A) and the appearance of flow passing through the lower part of bandal in the area between the bandals, especially in Case 5,

avoiding the formation of recirculation currents due to the flow separation at bandal A in the bandals field and at downstream of bandal B.

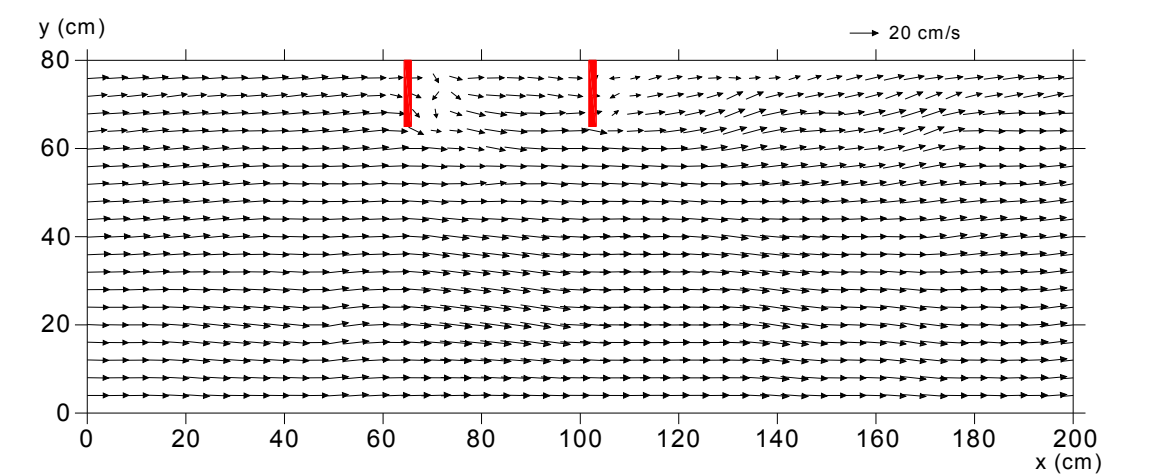


Figure 2.39 Velocity field around bandal-like structures in plane XY at $z=2.0\text{cm}$ – Case 3

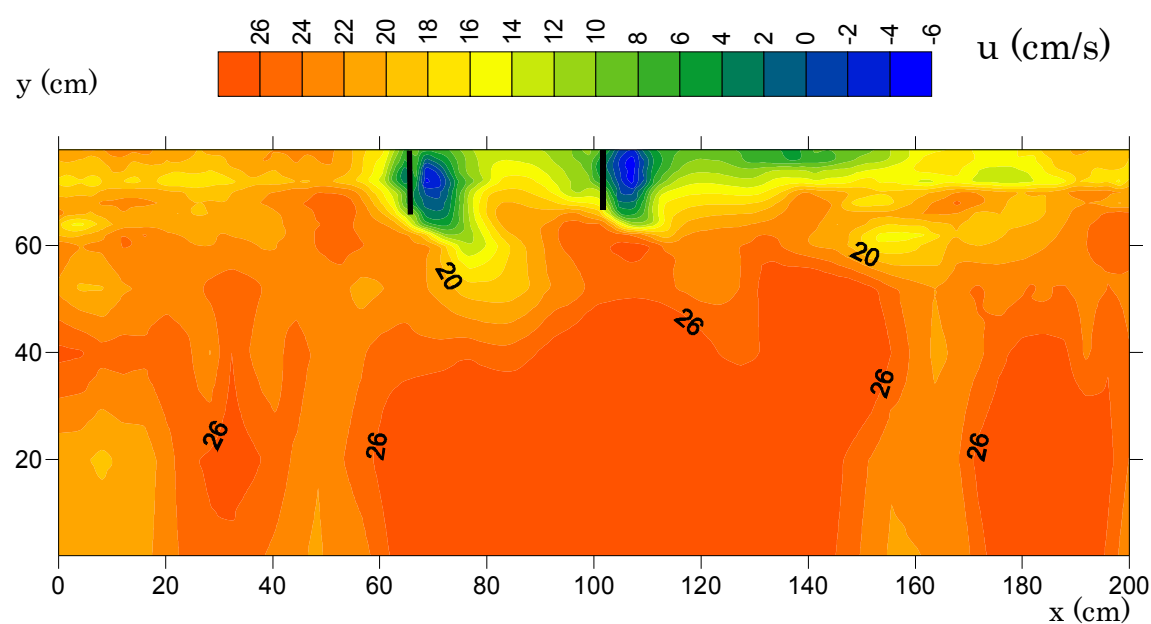


Figure 2.40 Longitudinal velocity contour (u) around bandal-like structures in plane XY at $z=2.0\text{cm}$ – Case 3

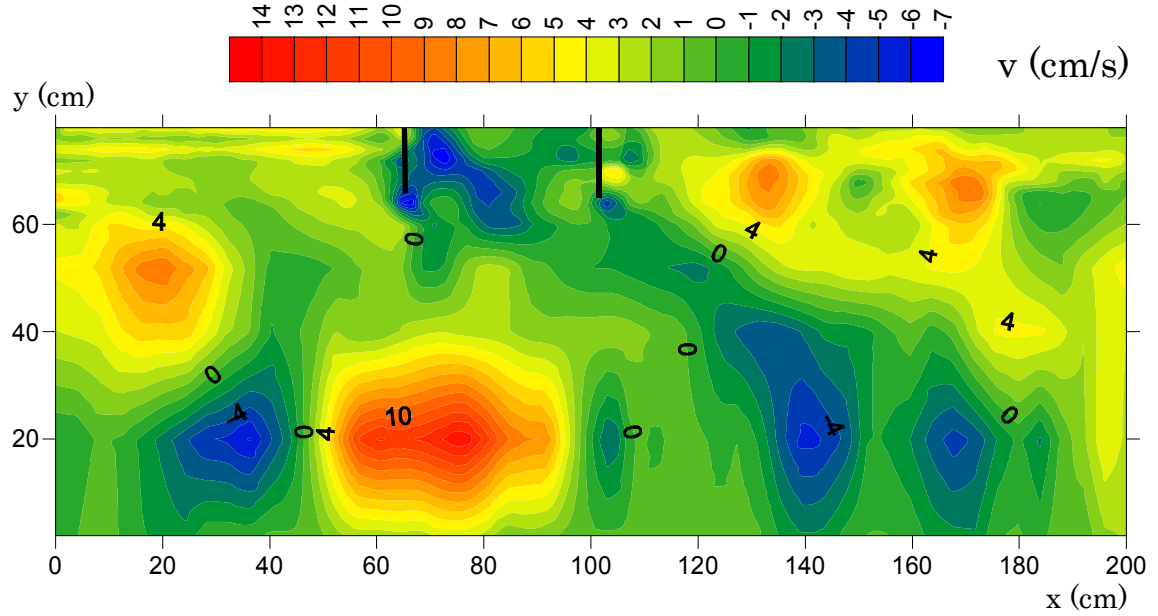


Figure 2.41 Transversal velocity contour (v) around bandal-like structures in plane XY at $z=2.0\text{cm}$ – Case 3

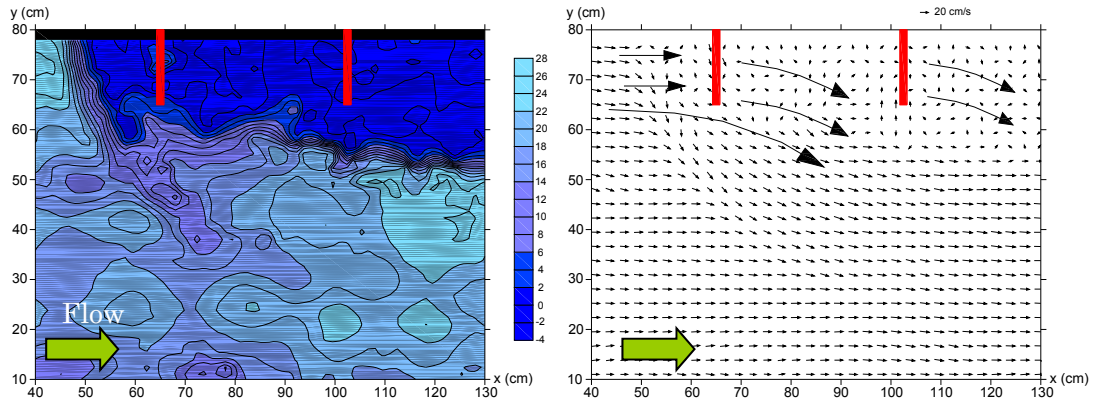


Figure 2.42 Surface velocity field around bandal-like structures in plane XY – Case 3

The results of flow field measurements in the XY direction for Cases 3 and 6 (Figures 2.39, 2.42, 2.43, 2.44 and 2.49) show that the flow diversion towards the main channel is similar to the impermeable groins case, but the intensity is lower due to partly of the obstructed flow near the bed is passing through the opening on the lower part and forming the bubbling flow at the downstream of the bandal-like structures, especially in Case 3. From this bubbling flow, the components moving along the back-side alignment of the blockage plate towards the main channel. The diverted flow from the back-side is preventing the recirculation currents in this region. The bandal-like structures field velocity has been reduced after passing the bandal B and in the main channel direction the velocity vectors increases in magnitude (Figures 2.40, 2.41, 2.45, 2.46, 2.47 and 2.48).

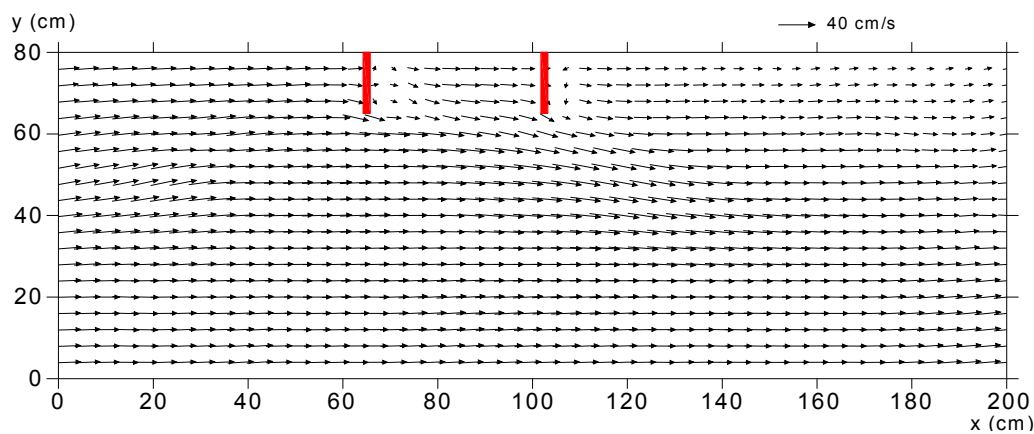


Figure 2.43 Velocity field around bandal-like structures in plane XY at $z=3.50\text{cm}$ – Case 6

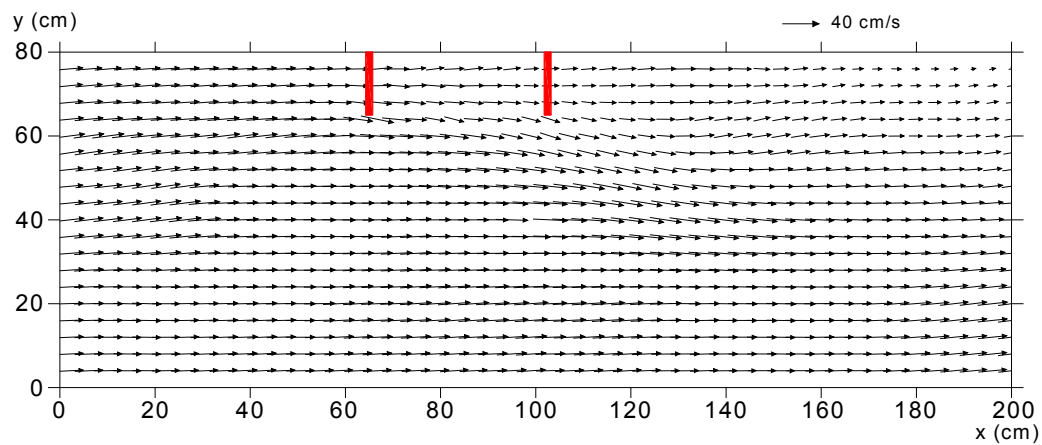


Figure 2.44 Velocity field around bandal-like structures in plane XY at $z=5.50\text{cm}$ – Case 6

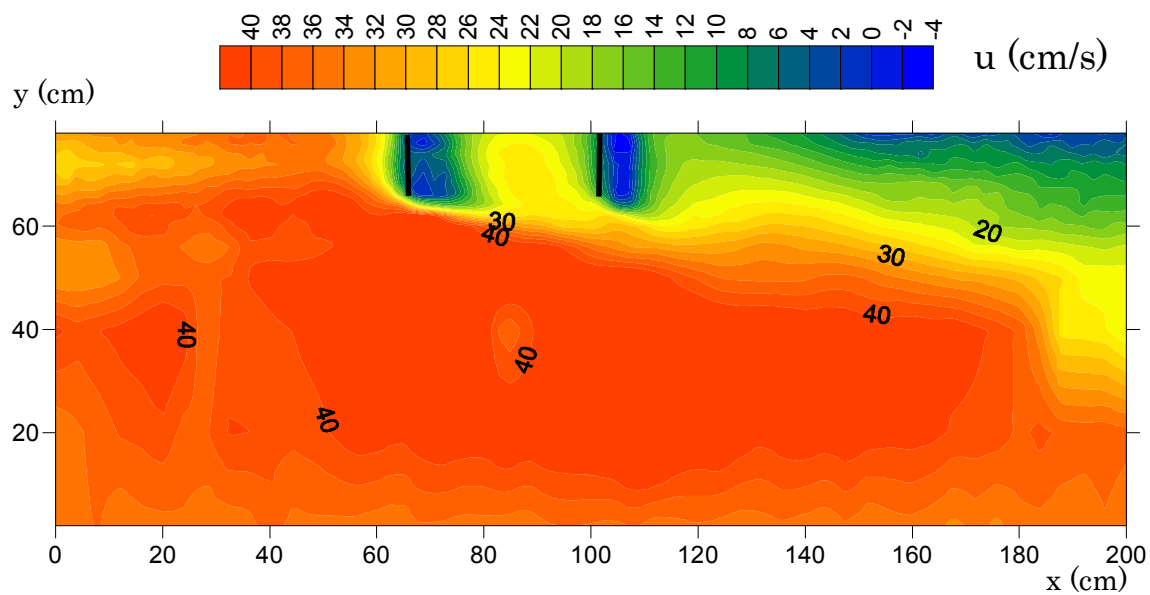


Figure 2.45 Longitudinal velocity contour (u) around bandal-like structures in plane XY at $z=3.50\text{cm}$ – Case 6

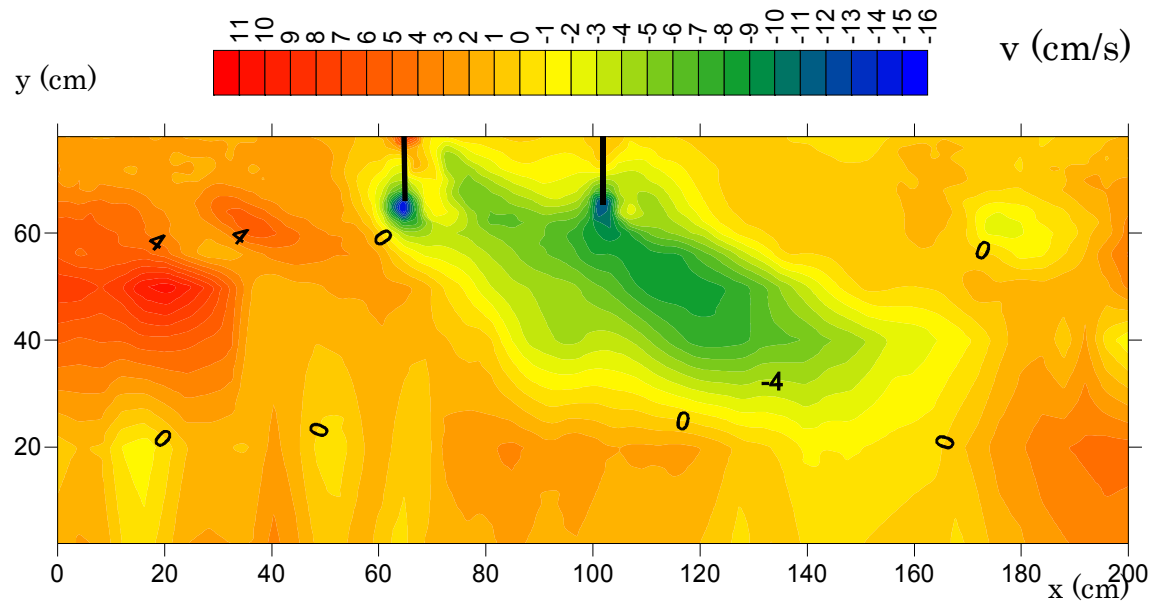


Figure 2.46 Transversal velocity contour (v) around bandal-like structures in plane XY at $z=3.50\text{cm}$ – Case 6

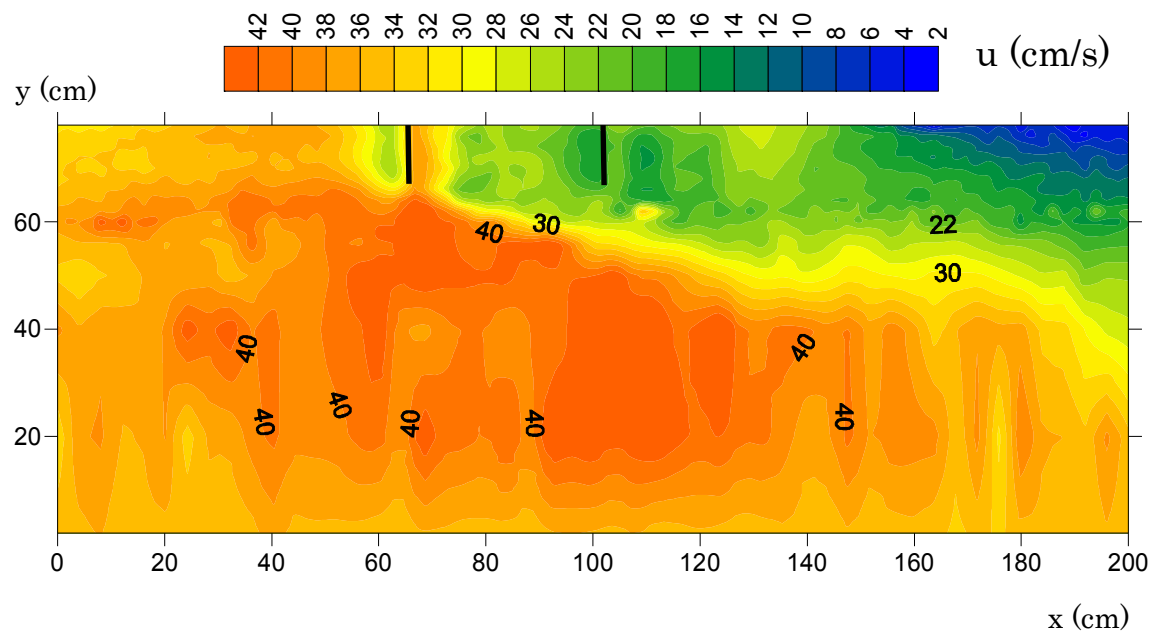


Figure 2.47 Longitudinal velocity contour (u) around bandal-like structures in plane XY at $z=5.50\text{cm}$ – Case 6

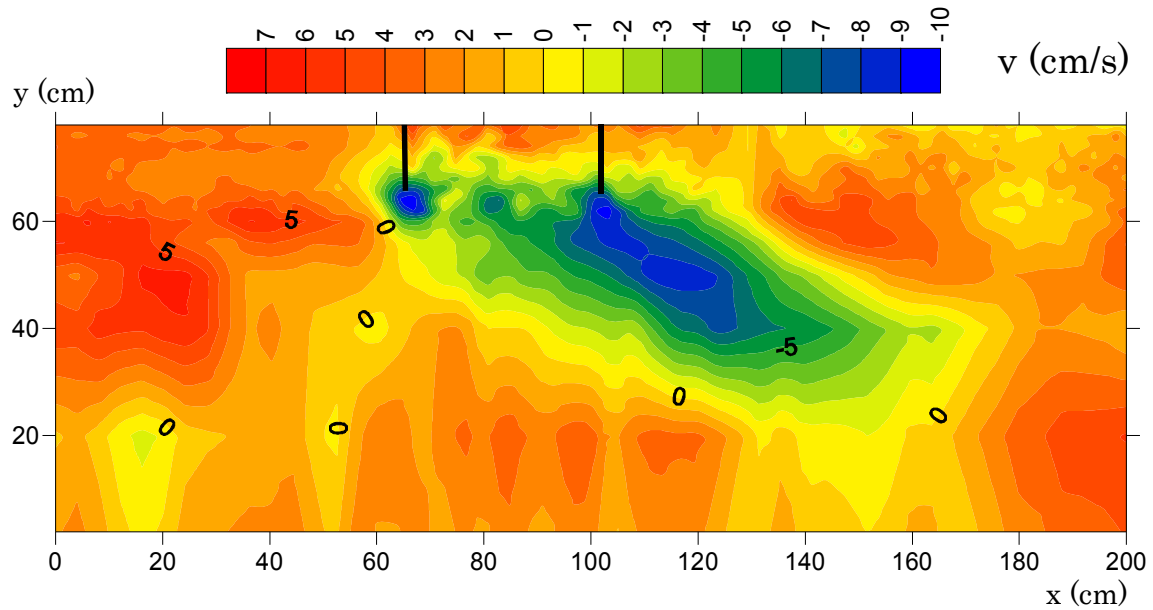


Figure 2.48 Transversal velocity contour (v) around bandal-like structures in plane XY at $z=5.50\text{cm}$ – Case 6

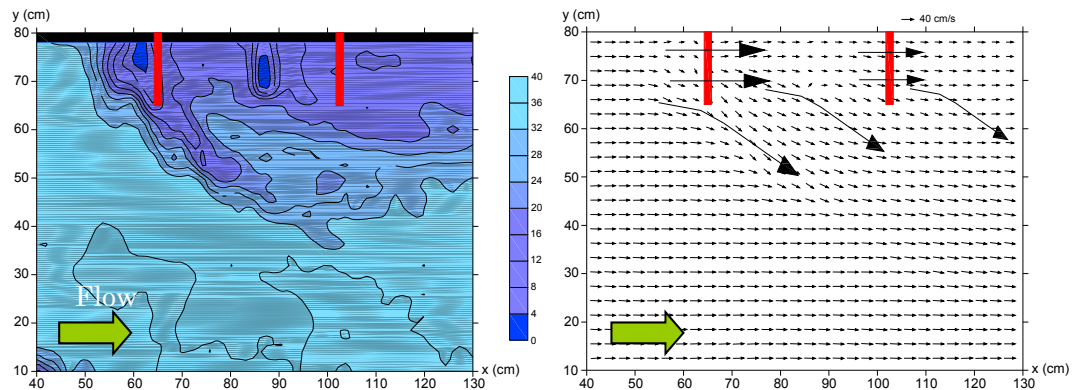


Figure 2.49 Surface velocity field around bandal-like structures in plane XY – Case 6

The YZ velocity vectors at transversal cross section $x = 62.0\text{cm}$ are shown in Figures 2.50 and 2.52. At the upstream region of the bandal-like structure A almost vertically downward vectors of high magnitude are seen and the flow diversion from the bandal front side is less than expected. The total amount of the downward flow discharge can be assumed to be diverted towards the main channel within the lateral control section considered at the groin top. At $y = 64.0\text{cm}$ to 57.0cm , a vertical circulation flow near the head of bandal A is seen. In the main channel area, strong downward vectors are seen up to $y = 40.0\text{cm}$, which causes bed degradation. The XZ velocity vectors along longitudinal section at $y = 72.0\text{cm}$ are shown in Figures 2.51 and 2.53. The velocity vectors show much higher downward magnitude around the bandal-like structures. Near the bandal heads, upward component is seen indicating the flow passing under

the blockage plates are coming up near the bandal heads. At downstream of bandal B the magnitude of the velocity vectors are reduced and become almost flume parallel in direction. The active flow diversion around the bandal area and from the bandals field towards the main channel as explained in the above figures will impart mass exchange between the bandals field and the main channel. Moreover the free passage under the blockage plates gives a kind of mass exchange in the longitudinal groin field direction.

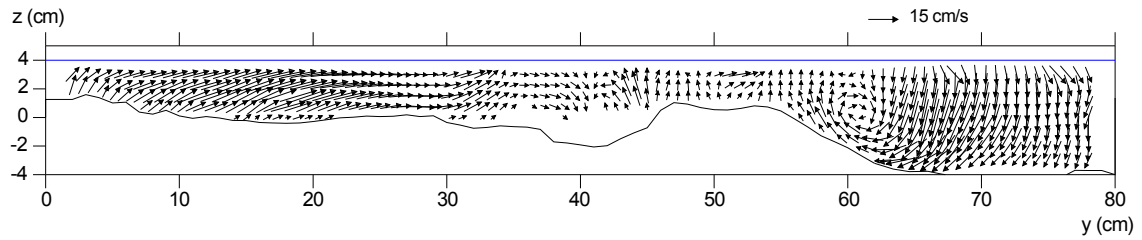


Figure 2.50 Velocity field around bandal-like structures in plane YZ at $z=62.0\text{cm}$ – Case 3

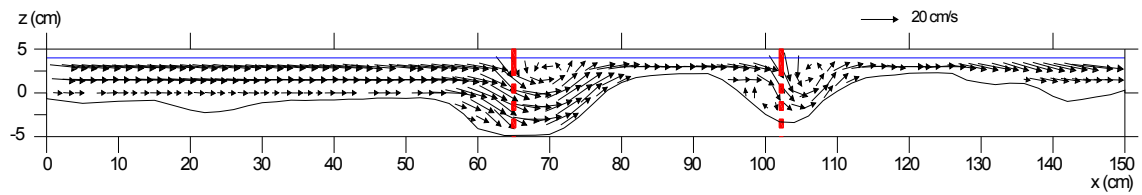


Figure 2.51 Velocity field around bandal structures in plane XZ at $y=72.0\text{cm}$ – Case 3

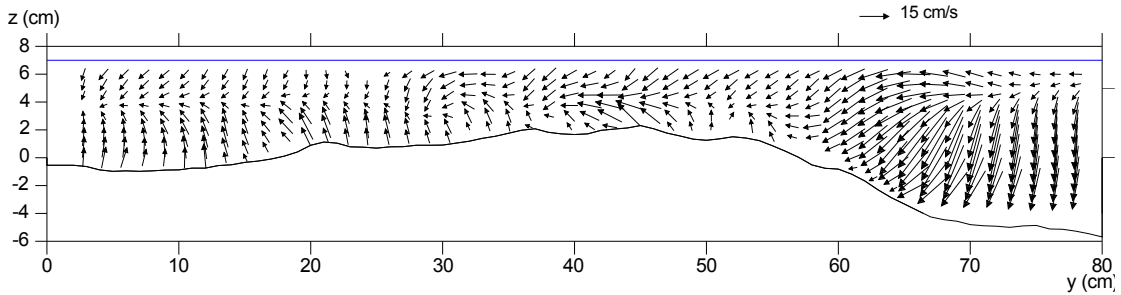


Figure 2.52 Velocity field around bandal structures in plane YZ at $x=62.0\text{cm}$ – Case 6

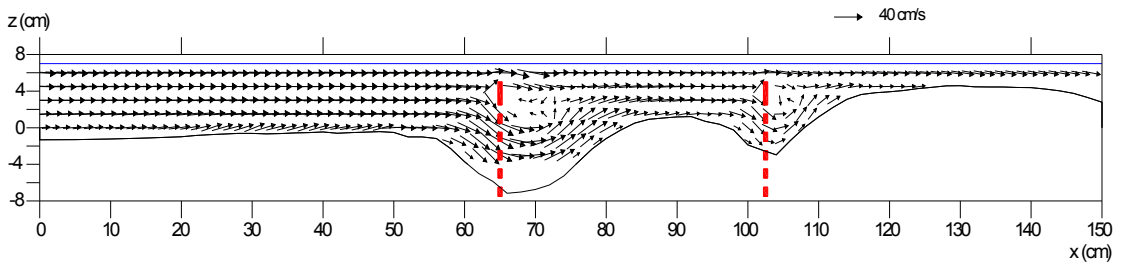


Figure 2.53 Velocity field around bandal structures in plane XZ at $y=72.0\text{cm}$ – Case 6

2.6.2 Bed deformation

2.6.2.1 Impermeable Groins

The final equilibrium scour contours is presented in Figures 2.54 and 2.55 for impermeable groins cases described in Table 2.1. The scour hole is deepest near the edge of the upstream-sidewall and the headwall (Tsuchiya and Ishizaki, 1966). Generally speaking scour hole has similar shape like a cone (Rahman and Haque, 2002), and in the permeable groins cases are smaller than the other cases. Also one can see in the figures of bed deformation the range of scouring is smaller. Bed material washed out near the groin is deposited in the area sheltered by the groins, especially downstream region of the downstream groin.

The separated flow from the upstream groin intensified the downward flux component which created deep scour holes in front of the groins heads (Gill, 1972). The scour hole formation in front of the downstream groin were quite slow and flatter in shape. During the experiment, as the time passed the scour hole around the groin A becomes bigger and deeper. After 6 hours, these scour holes became very big. The concentrated flow at downstream area of groins field eroded sediment from the main channel. The vortex motion had eroded huge amount of sediment from the groins field, especially around the upstream structure (groin A).

The maximum scour around groin A for Cases 1 and 4 is about 14.77cm and 23.37cm, respectively. For the structural safety of the groins, toe protection is needed. In the groins field, very small area is seen to be above or at the initial bed level and prominent erosion is seen in the groins field region. The bed form height in the main channel is relatively small.

The longitudinal bed profiles at $Y=40.0\text{cm}$, 60.0cm , 70.0cm and 75.0cm are shown in Figures 2.56 to 2.59. From these figures the comparatively scour in the groins field area is observed for Cases 1 and 2. At section $Y=75.0\text{cm}$ and $Y=70.0\text{cm}$ scouring is most severe. These figures show large scour in front of the groins heads and, strong bed degradation in the main channel after passing the upstream groin and a deposition area near the bank, especially at downstream of groin B.

From XY velocity vectors in the non-submerged condition (Figures 2.13 and 2.14) the flow concentration at the upstream area of groin A and separation from the groin head is seen. Inside the scour hole strong reverse flow, vortex, almost perpendicular diversion to main channel and sharp return current to bank side is observed. In the submerged case, the effects of recirculation currents are minimized through the flow passing over the groins (Figures 2.17 to 2.19). Combination of these factors are causing massive scour around the groins. From XZ velocity vectors (Figures 2.26 and 2.27) higher magnitude vertical downward flow is observed just at the upstream of groin A. So these figures show that the flow obstruction causes rapid sediment removal from the upstream bed. From YZ velocity vectors at groin head in the Figure 2.24, very

strong flow separation having downward direction is observed, which influenced sediment removal from the groin head area. From all these figures, the recirculation flow returning towards the groins field, very close to the wall is clearly observed. The XY velocity vectors prove the existence of vortex cell just downstream of the groin, which removes the bed material and deposits in the downstream of groins field area. These entire complex phenomenon produce big scour holes around the groins. The deepest scour hole is seen at the upstream of groin area.

Due to constriction of the channel by impermeable groins, the main channel velocity is increased thus amplifying the shear stress. From YZ velocity vectors at near the head of groin A (Figures 2.24 and 2.25), very strong downward velocity components are observed from the separated flow. This phenomenon injects discharge into the main channel at the bottom layers. A vertical circulation between $Y=50.0\text{cm}$ and 65.0cm lines are observed. This causes sediment dislodgement from the bed, which can be easily transported to the downstream direction by the increased velocity. Such phenomenon shows the interaction between the scour holes and the main channel and influences the general morphological change of the channel bed.

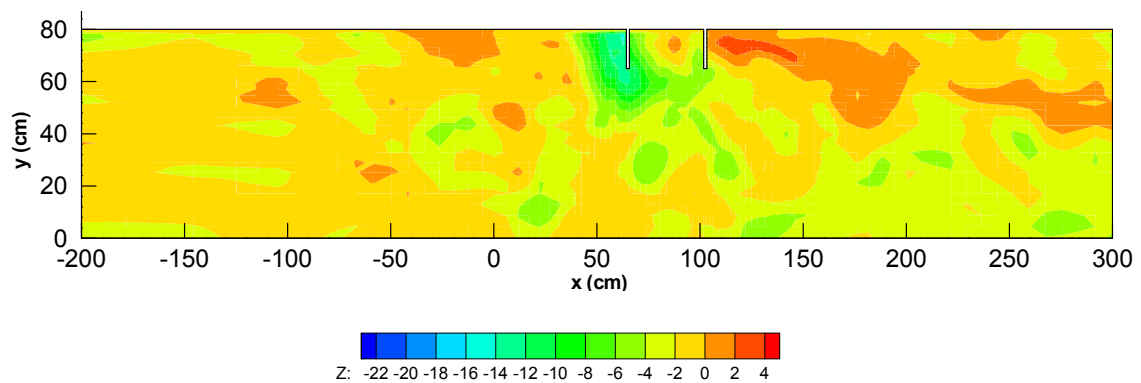


Figure 2.54 Bed contours at equilibrium condition – Case 1 (impermeable groins)

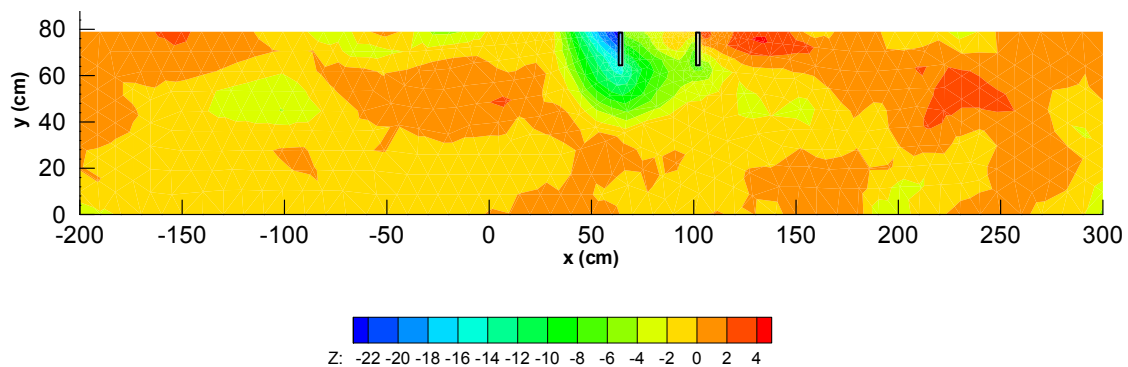


Figure 2.55 Bed contours at equilibrium condition – Case 4 (impermeable groins)

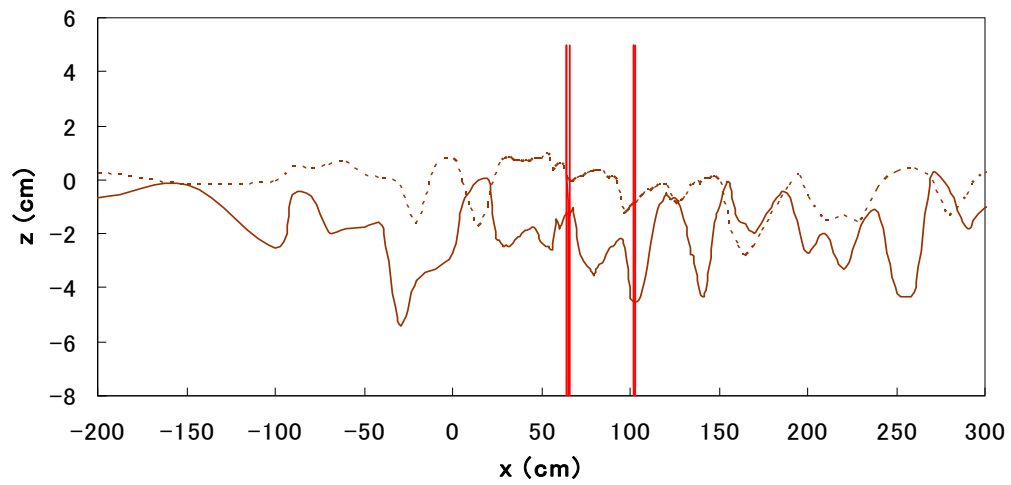


Figure 2.56 Longitudinal bed profile in plane XZ at $y=40.0\text{cm}$ – Case 1 (straight line) and Case 2 (dashed line)

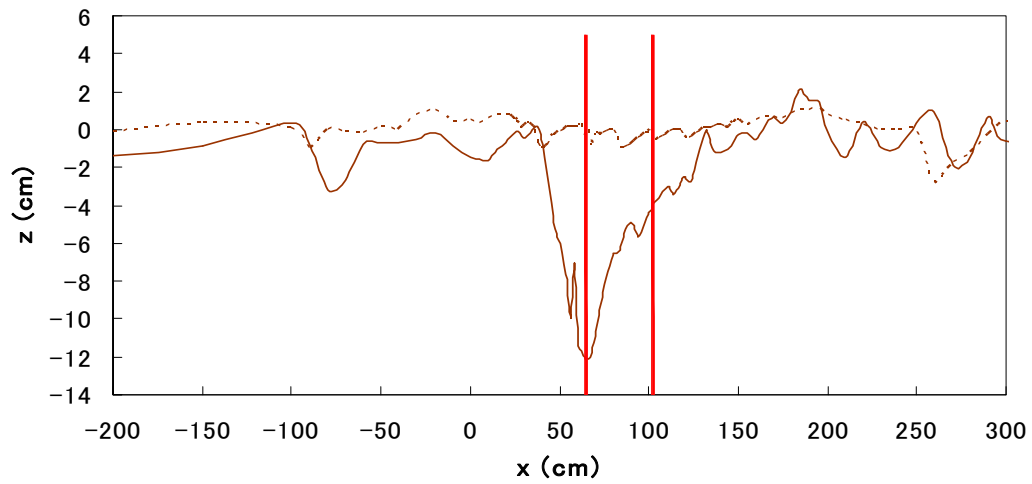


Figure 2.57 Longitudinal bed profile in plane XZ at $y=60.0\text{cm}$ – Case 1 (straight line) and Case 2 (dashed line)

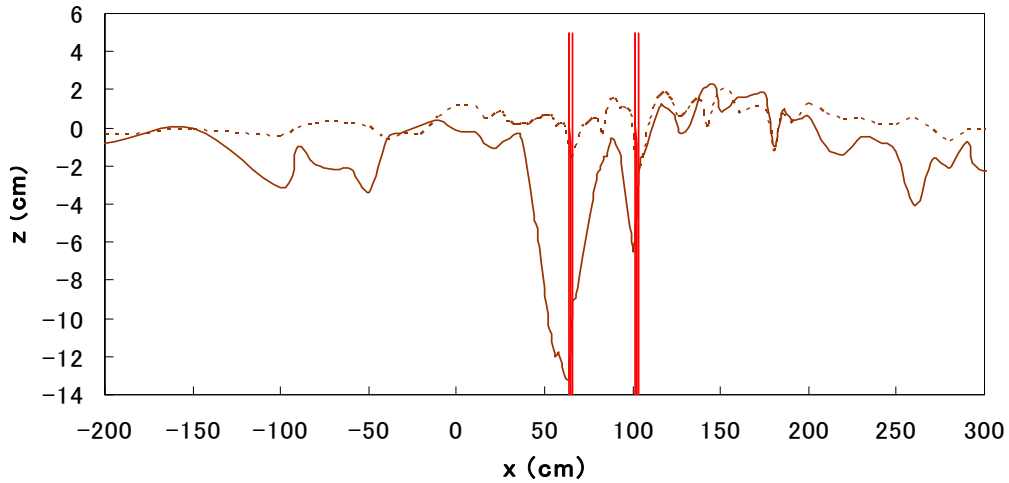


Figure 2.58 Longitudinal bed profile in plane XZ at $y=70.0\text{cm}$ – Case 1 (straight line) and Case 2 (dashed line)

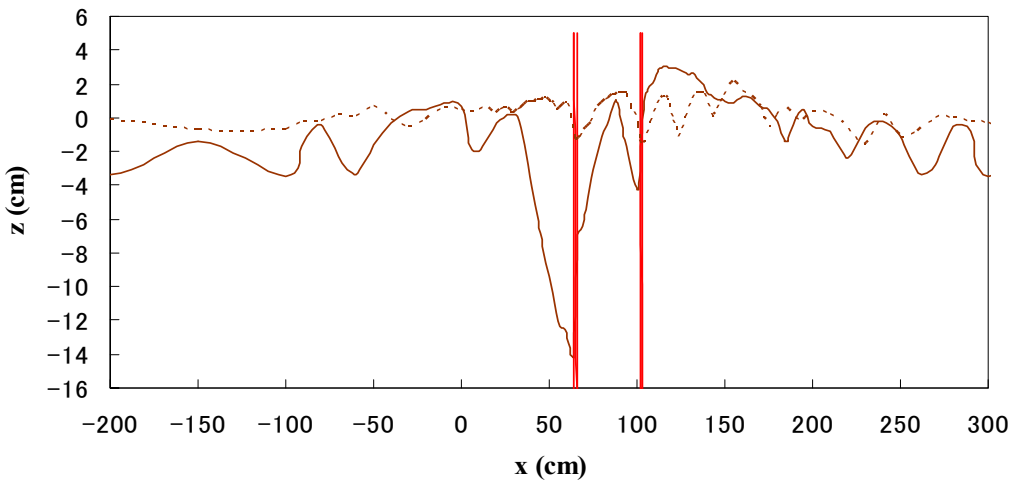


Figure 2.59 Longitudinal bed profile in plane XZ at $y=75.0\text{cm}$ – Case 1 (straight line) and Case 2 (dashed line)

2.6.2.2 Permeable Groins

In the permeable cases, the final equilibrium scour contour is presented in Figures 2.60 and 2.61. The scour hole is smaller than the other types of structures. The scour process was accelerated due to the separated flow from the groins head. The flow was retarded in the groins field, resulting in an increase on main channel velocity. During the experiments, the scour hole increased in size, maintaining an angle with the groin head, having a tendency of sediment movement towards the groins field. The vortex motion in the scour hole; induced another scour-hole like bed form downstream of the first one. This process continued and a series of big scour-hole like bed forms reached the opposite bank. These bed forms continued along the other side flume wall line with much sediment movement. Each of these bed forms had induced

smaller secondary bed forms towards the groins field side and continued to move further into the groins field. The development of scour hole in front of groin B was much slower and smaller in size than the groin A. The inward sediment movement seemed to have retarded the scour hole formation in the groins head.

From XY velocity vectors (Figs 2.28, 2.29, and 2.32 to 2.34) the flow concentration and separation from the groin heads are seen to be very weak. After passing through the piles openings the flow velocity is reduced in both cases. It results in very small downward component at the upstream of groins field. As a result the local scour is much less in magnitude. Due to uniform roughness effect of permeable groin piles and reduced groin field velocity, the main channel velocity is increased thus amplifying the shear stress. This phenomenon shows the interaction between the groins field and the main channel, and influences in the morphological changes of the channel bed. The longitudinal bed profiles at $Y = 40.0\text{cm}$, 60.0cm , 70.0cm and 75.0cm sections are shown in the Figures 2.62 to 2.65, comparing Cases 4 and 5. From these figures it is seen that, the main channel area has an average degradation and near the bank there exist a wide deposition area. The velocity in these lateral sections is found to have a closely uniform distribution in the main channel region.

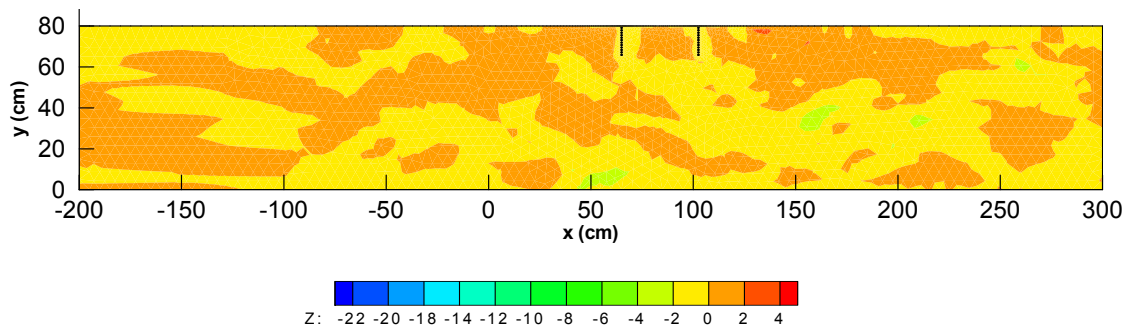


Figure 2.60 Bed contours at equilibrium condition – Case 2 (permeable groins)

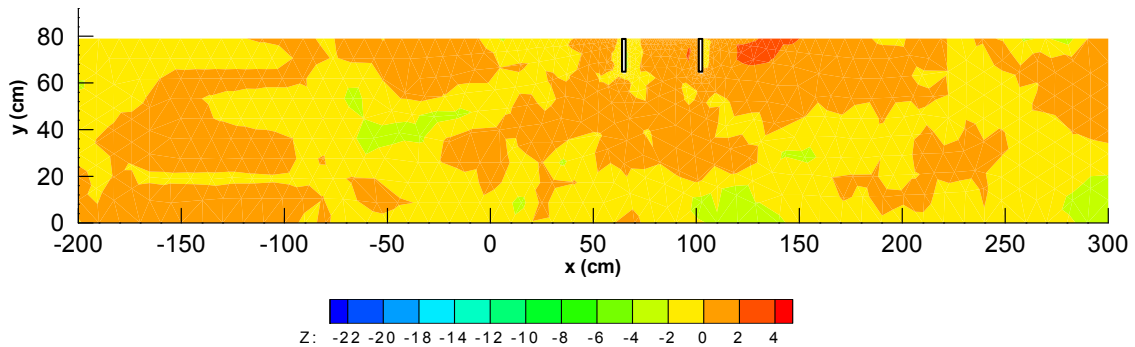


Figure 2.61 Bed contours at equilibrium condition – Case 5 (permeable groins)

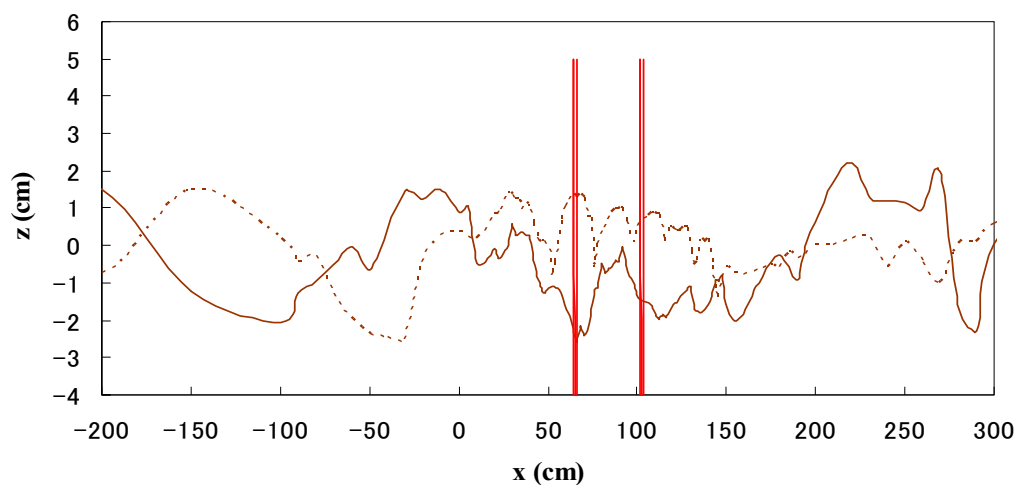


Figure 2.62 Longitudinal bed profile in plane XZ at $y=40.0\text{cm}$ – Case 4 (straight line) and Case 5 (dashed line)

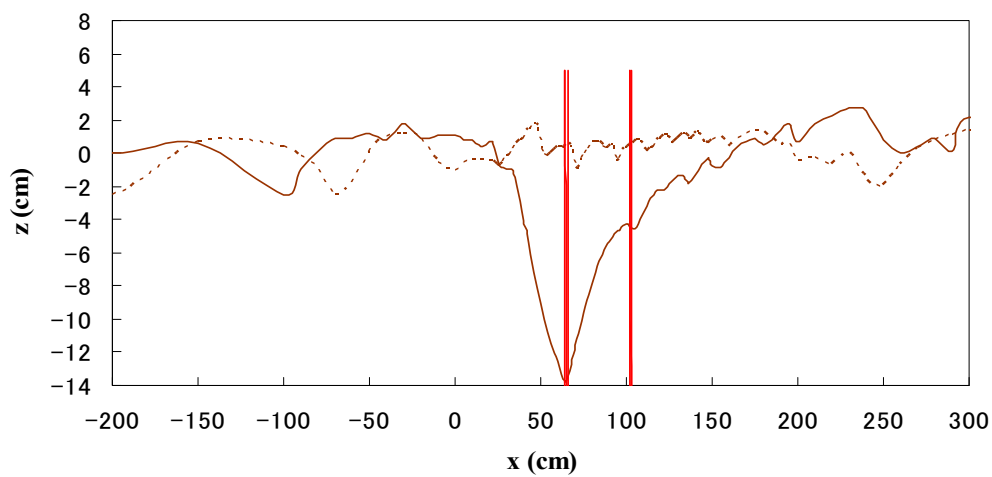


Figure 2.63 Longitudinal bed profile in plane XZ at $y=60.0\text{cm}$ – Case 4 (straight line) and Case 5 (dashed line)

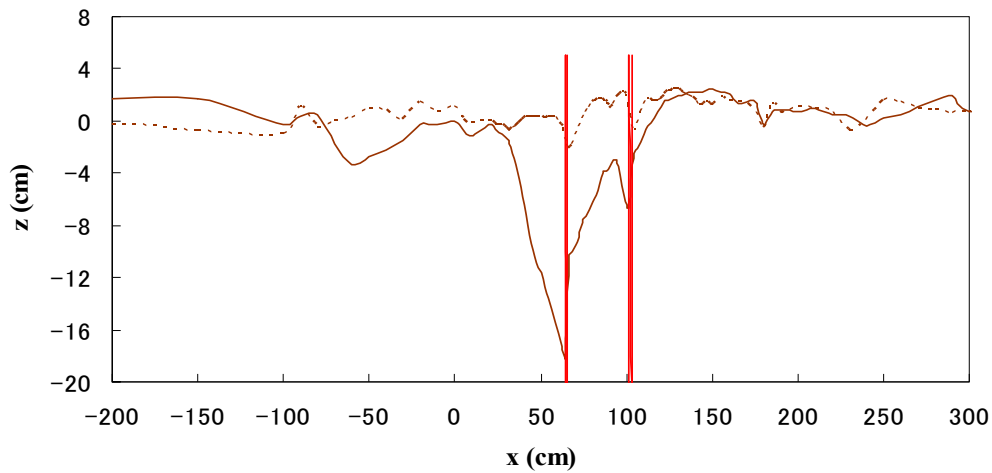


Figure 2.64 Longitudinal bed profile in plane XZ at $y=70.0\text{cm}$ – Case 4 (straight line) and Case 5 (dashed line)

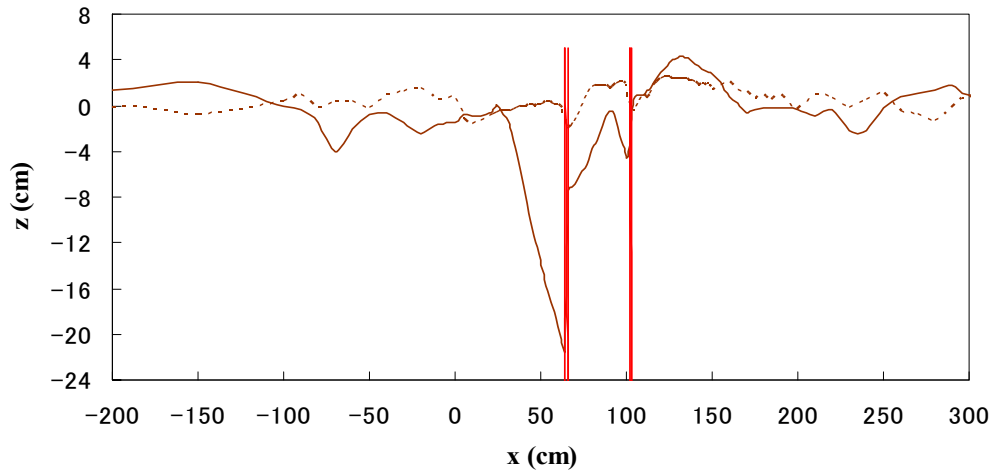


Figure 2.65 Longitudinal bed profile in plane XZ at $y=75.0\text{cm}$ – Case 4 (straight line) and Case 5 (dashed line)

2.6.2.3 Bandal-like Structures

In the bandal-like structures cases, the final bed deformation contour is shown in Figures 2.66 and 2.67. The scour hole around the upstream bandal resulted smaller and flatter in shape compared to the impermeable groins cases due to the small downward flow magnitude caused by the flow separation from the bandals head. One portion of the flow was seen to be moving towards the bank side at an angle perpendicular to the bandal structure axes. The sediment was deposited in the bandal structures field. These phenomena were observed from the bed features and visual flow observation. Development of scour hole in front of bandal B is much less pronounced than the bandal A due to the flow at downstream of upstream bandal (structure A) is concentrated mainly in the main channel region which causes weak effects on the bandal B. The

local scour around the bandal-like structures, especially at the bandal A was much less than the impermeable groins case showing the effect to reduce the erosion around the structures. In the submerged case (Figure 2.67), as time passed the scour hole towards the main channel grew bigger and moved along the longitudinal direction, showing deeper main channel formation.

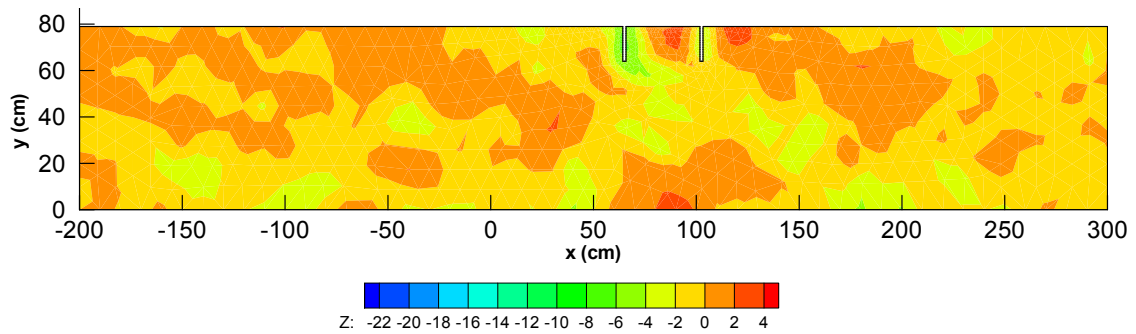


Figure 2.66 Bed contours at equilibrium condition – Case 3 (bandal-like structures)

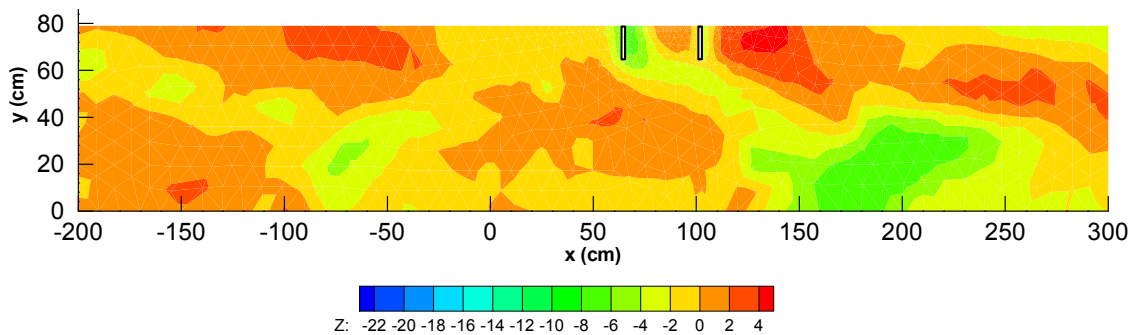


Figure 2.67 Bed contours at equilibrium condition – Case 6 (bandal-like structures)

After 6 hours of experimental run the flow seemed to have reached equilibrium. The comparatively bed level contours of non-submerged cases (Figure 2.68) and submerged cases (Figure 2.73) are shown with the longitudinal bed profiles of Cases 1, 2 and 3 (Figures 2.69 to 2.72), and Cases 4, 5 and 6 (Figures 2.74 to 2.77). The scour along the bandal structure axes had relatively much less deeper than impermeable groins with an increasing tendency in depth in the downstream direction. Bandal-like structures field deposition is much uniform and the bed form height and shape is much regular and uniform. Maximum local scour is seen around the upstream bandal-like structure axes area in the bed contour (Figures 2.66 and 2.67) and longitudinal bed profile (at $Y = 75.0\text{cm}$ line in Figures 2.72 and 2.77).

The YZ velocity vectors near the bandal A in the Figures 2.50 and 2.52 show almost vertically downward direction with higher magnitude around bandal structure axis. A considerable portion of the obstructed flow is also moving in downwards direction under the top plates. This has caused big scour holes around the bandal structure axes. Larger values are

concentrated near the bandal structure head area. This is reflected by the deeper scour around the bandal structure head. But because of the free passage at the bottom opening and absence of vortex the scour depth is about half of impermeable cases.

The XY velocity field in Figures 2.39 to 2.42 in Case 3 and Figures 2.43 to 2.49 in Case 6 show very active approach flow diversion towards the main channel from the front as well as back-side of the bandal structures, especially at the bandal A. As a result, the groin field velocity is reduced and the main channel velocity is increased. Because of the absence of the recirculation flow, the diverted flow is concentrated in the main channel and continued to degrade uniformly along the downstream direction. This is one of the reasons for the effective main channel formation, which did not happen for impermeable groins case and was weaker for permeable groins case.

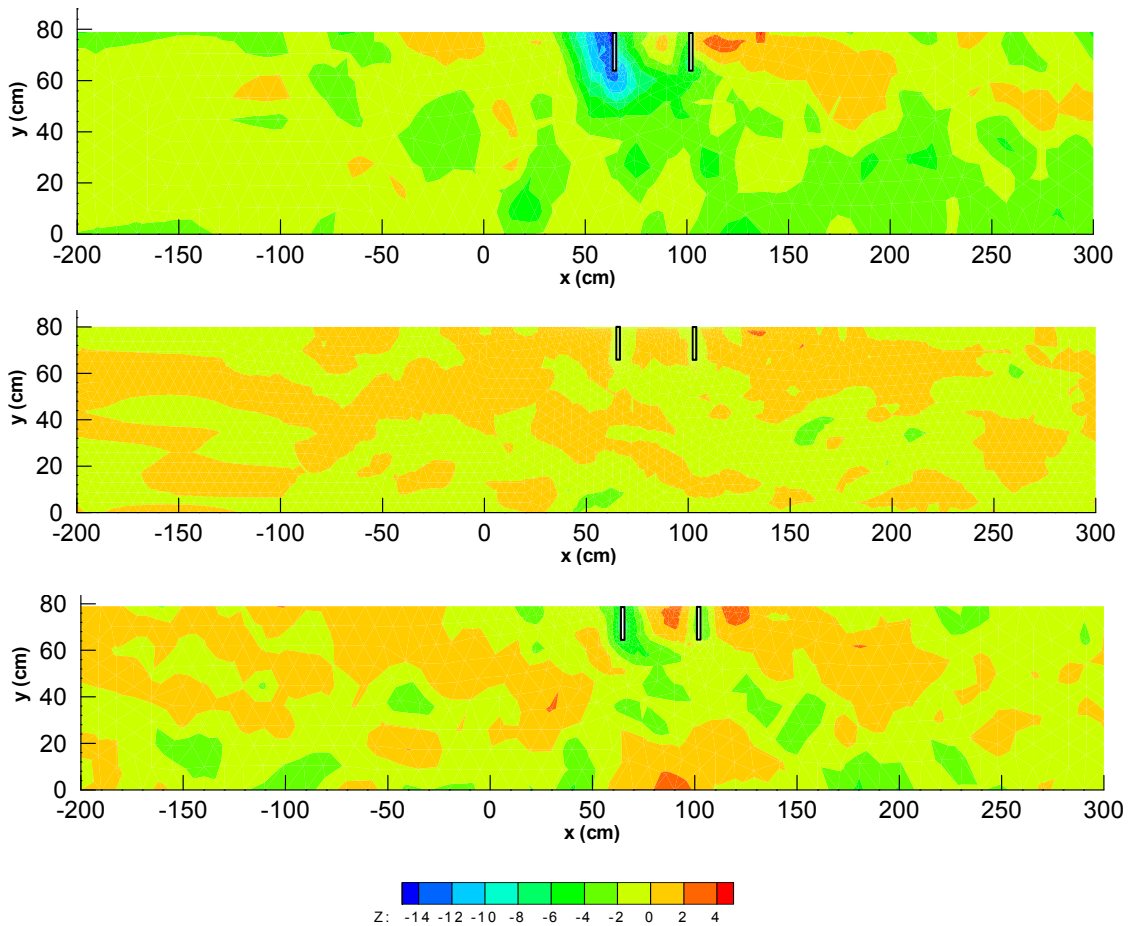


Figure 2.68 Bed contours at equilibrium condition – top: Case 1 (impermeable groins); middle: Case 2 (permeable groins); bottom: Case 3 (bandal-like structures)

From the XZ velocity vectors in longitudinal direction at $Y = 72.0\text{cm}$ in Figures 2.51 and 2.53, it is seen that the vectors having large magnitude is directed to the bed at the angle more than

impermeable or permeable case, which is causing very active bed degradation. The YZ vectors at $X = 62.0\text{cm}$ cross section in Figures 2.50 and 2.52 show almost vertical direction to the bed and are causing the main channel formation. It shows the concentration of higher values in the main channel and very small values in the groin field. This indicates the possibility of groin field deposition and deeper main channel formation.

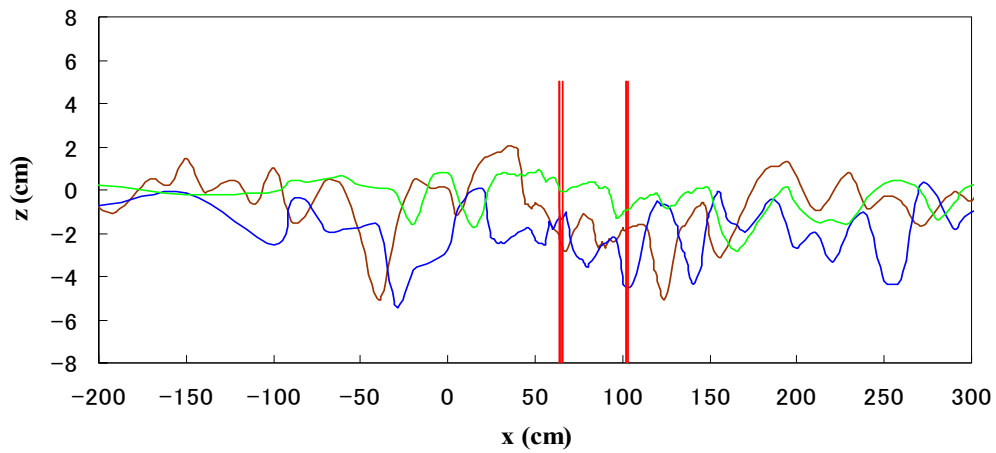


Figure 2.69 Longitudinal bed profile in plane XZ at $y=40.0\text{cm}$ – Case 1 (blue line), Case 2 (green line) and Case 3 (brown line)

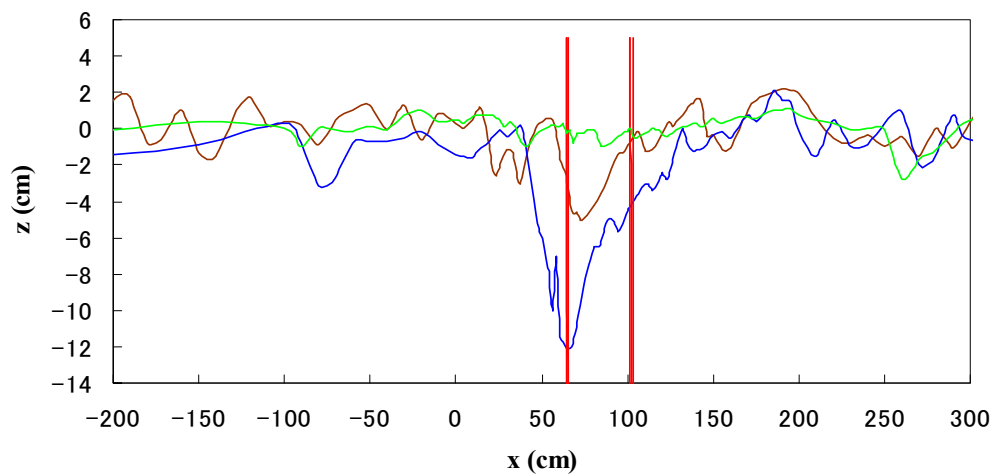


Figure 2.70 Longitudinal bed profile in plane XZ at $y=60.0\text{cm}$ – Case 1 (blue line), Case 2 (green line) and Case 3 (brown line)

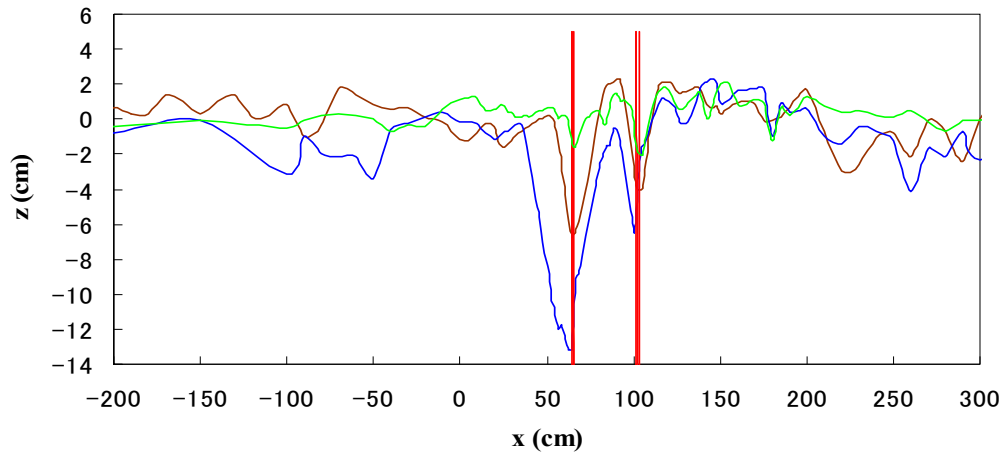


Figure 2.71 Longitudinal bed profile in plane XZ at $y=70.0\text{cm}$ – Case 1 (blue line), Case 2 (green line) and Case 3 (brown line)

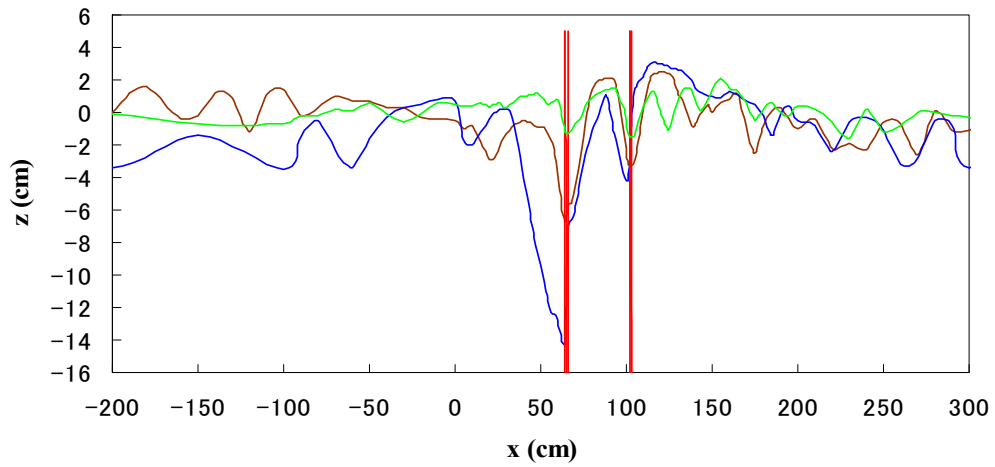


Figure 2.72 Longitudinal bed profile in plane XZ at $y=75.0\text{cm}$ – Case 1 (blue line), Case 2 (green line) and Case 3 (brown line)

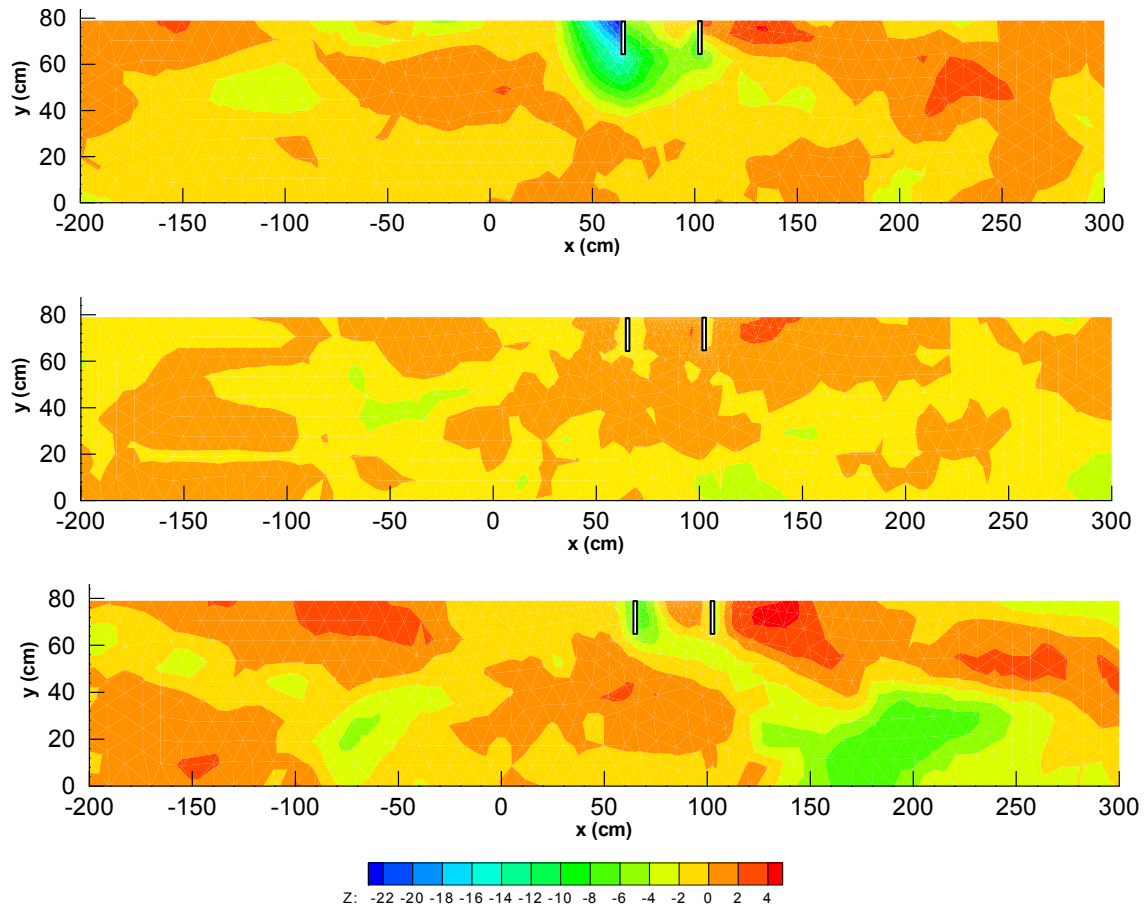


Figure 2.73 Bed contours at equilibrium condition – top: Case 4 (impermeable groins); middle: Case 5 (permeable groins); bottom: Case 6 (bandal-like structures)

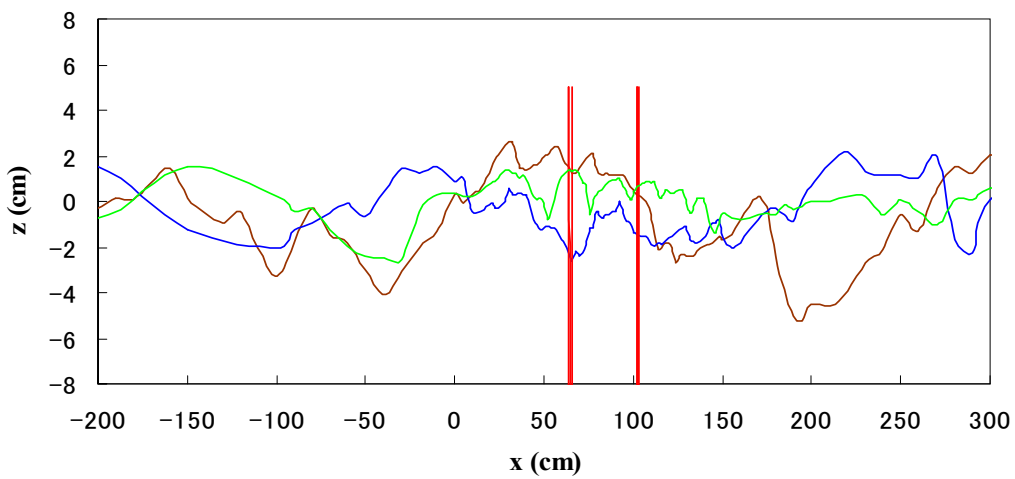


Figure 2.74 Longitudinal bed profile in plane XZ at $y=40.0\text{cm}$ – Case 4 (blue line), Case 5 (green line) and Case 6 (brown line)

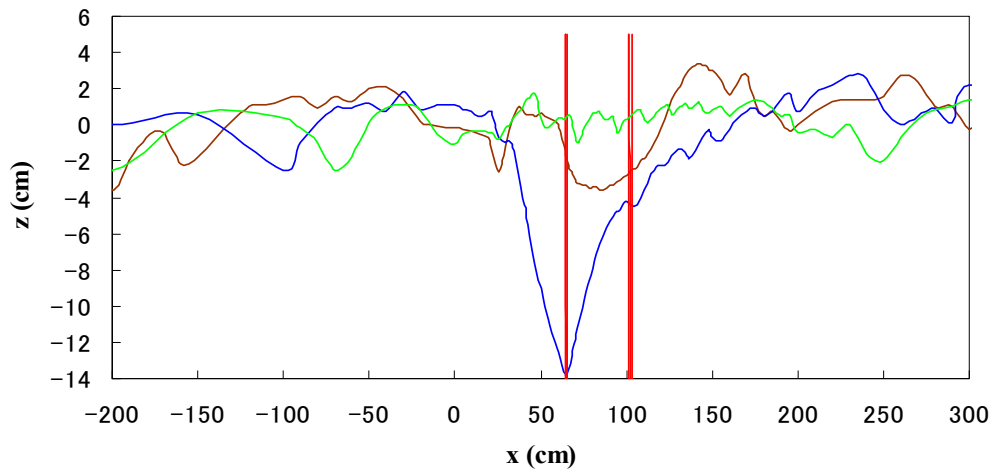


Figure 2.75 Longitudinal bed profile in plane XZ at $y=60.0\text{cm}$ – Case 4 (blue line), Case 5 (green line) and Case 6 (brown line)

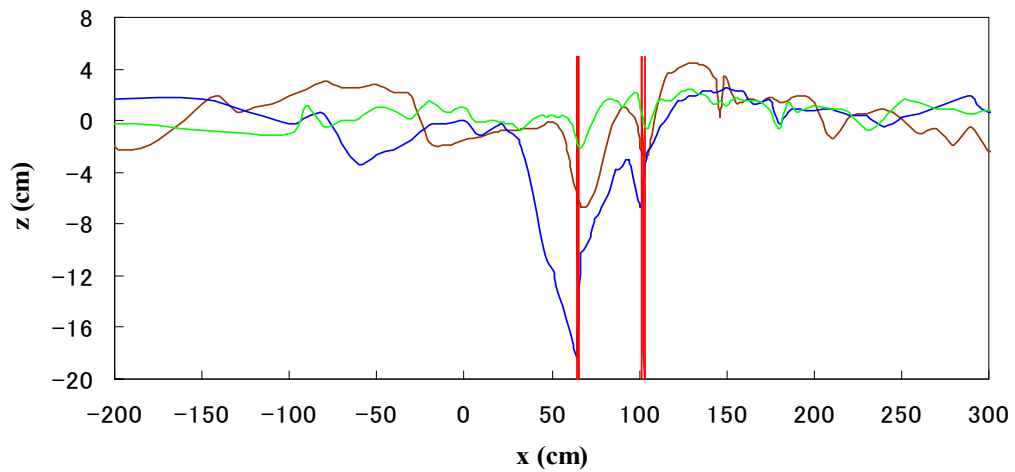


Figure 2.76 Longitudinal bed profile in plane XZ at $y=70.0\text{cm}$ – Case 4 (blue line), Case 5 (green line) and Case 6 (brown line)

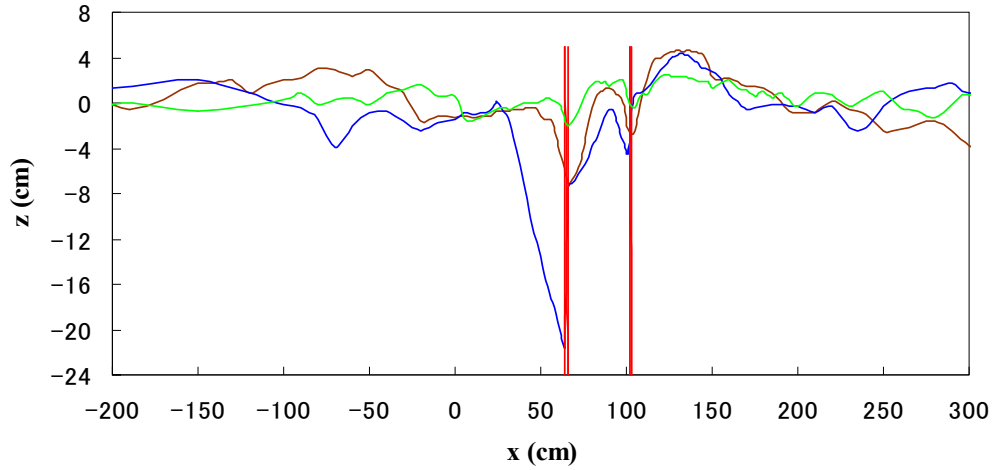


Figure 2.77 Longitudinal bed profile in plane XZ at $y=75.0\text{cm}$ – Case 4 (blue line), Case 5 (green line) and Case 6 (brown line)

2.6.2.4 Analysis of deposition/erosion process around the structures

In the previous items, the analysis of the results of bed deformation measurements was made qualitatively considering the observed differences on the deposition/erosion patterns due to the influence of each type of structure on flow and sediment transport near the structures. However, a quantitative analysis is also needed to identify based on data comparison, for example, which type of structure has better performance considering the erosion process around the structure A or the effect of the second structure in the erosion/deposition process.

(1) Verification of equilibrium local scour depth

The scour hole around the structure A (upstream) was analyzed and the equilibrium local scour depth was calculated based on the studies of Melville (1997) and Nasrollahi (2008), and compared with the experimental measurements.

Melville (1997) proposed a simple design method based on the several laboratory experimental data for local scour depth at bridge abutments and piers. Through these data, the effects on scour depth of abutment length, flow depth, and abutment shape and alignment was demonstrated. The following equation proposed by Melville (1997) is used.

$$d_s = K_{yW} K_L K_d K_s K_\theta K_G \quad (1)$$

here, d_s = equilibrium scour depth; L = structure length measured perpendicular to the flow direction; b = diameter of the pier (for circular piers); y = approach flow depth; and the K -factors

accounting for the effects on scour depth of flow depth and structure length ($K_{yW} \equiv K_{yL}$ for abutments and K_{yb} for piers); flow intensity (K_I); sediment size (K_d); structure shape (K_s); orientation angle (K_θ) and channel geometry (K_G). These factors were estimated by analysis of various experimental data.

Nasrollahi (2008) proposed new equation for prediction of the maximum scour depth for permeable spur dikes based on the studies of Melville (1992, 1997) and incorporating the effects of opening ratio of spur dike.

$$\frac{d_{se}}{L} = aK_f K_{yL} K_d K_R K_n \quad (2)$$

where, a is empirical constant ($=1.19$); K_f accounts for the effect of approach Froude number

$F(=u/\sqrt{gy})$, K_{yL} accounts for the effects of ratio of spur dike length to the flow depth, K_d

accounts for the effect of sediment size d_{50} , K_R accounts for the effect of opening ratio of spur dike R and K_n accounts for the effects of ratio of spur dike length to the channel width.

In Table 2.3, the estimated scour depth using the equations described above is presented. The scour depth calculated by the Melville's (1997) equation overestimate the measured one in non-submerged case, however in submerged case it is underestimated, probably because this formula do not account the effect of submergence of the structure. The estimation of scour depth for permeable groins and bandal-like structures was calculated using the Melville's formula considering the piles as a group of piers in one row due to this formula not consider the permeability of the structure and the complex structure shape of bandal-like structures. Then, the results are very different compared to the measured ones.

Table 2.3 Equilibrium scour depth around structure A (upstream one)

Type of structure		Impermeable groins		Permeable groins		Bandal-like structure	
Case		1	4	2	5	3	6
Submergence condition*		Non-sub.	Sub.	Non-sub.	Sub.	Non-sub.	Sub.
Local scour depth (cm)	Experiment	14.86	23.37	3.12	3.29	6.72	7.38
	Melville	15.49	20.49	3.718	4.918	1.859	2.459
	Nasrollahi	15.36	20.91	2.28	3.02	5.13	6.79
Ratio estimated/measured (Melville)		1.042	0.877	1.192	0.758	0.277	0.333
Ratio estimated/measured (Nasrollahi)		1.034	0.895	0.731	1.318	0.763	0.920

*Non-sub.=Non-submerged condition; Sub.=submerged condition

Comparing the estimated scour depth by using the equation of Nasrollahi et al. (2008), the impermeable groins cases showed a little different result than that obtained using the Melville's formula probably due to the same problem of considering the submergence of the structure. In the permeable groins, the equilibrium scour depth overestimates the measured ones in both submergence conditions due to this formula accounts the effects of flume width and the opening ratio of groin for permeable case.

In the bandal-like structures case, the calculated scour depth resulted smaller than that measured one, probably due to the particular characteristics of this structure as the shape of structure that is not considered in the equation, and also the effect of submergence in all cases. Thus for the present experimental data the equations described above need to be modified accounting factors for submergence of the structure and structures with complex geometries as bandal-like structures to accurate prediction of local scour depth.

(2) Influence of the structures on deposition/erosion process

In the present study, the effect of different type of structures on morphological processes in straight channel is investigated. As discussed in the previous sections, the flow patterns and bed deformation are greatly influenced by the upstream structure (structure A), especially in the erosion process around the structure, however the presence of the second structure (structure B) has a meaningful effect in this process that can be evaluated through the analysis of flow distribution and induced bed deformation contours. This analysis is realized using also the longitudinal profiles of the final equilibrium bed at two longitudinal sections showed in Figures 2.68, 2.71, 2.72 and 2.75.

These figures show the formation of deeper local scour at the upstream area of impermeable groins in non-submerged and submerged conditions, respectively. As discussed previously, the effect of blockage of flow (Figures 2.16, 2.19, 2.31, 2.38, 2.42 and 2.49) and the downward flux in this region (Figures 2.24 to 2.27 and 2.50 to 2.53) is responsible for the huge erosion which can be dangerous for the safety of structure foundation. In comparison with impermeable groins, the other types of structures (permeable groin and bandal-like structure) showed very small erosion in the same area. The main reason for small erosion in other structures is due to the permeability of the structure which reduces the velocity of flow passing through the structure which contributes to minimize the formation of downward flow and the vertical horseshoe vortex at upstream face of the structure. In all cases the second structure (structure B) also suffers erosion; however the scour depth is much smaller than that around the structure A. In the case of a series of structures, this feature can be useful to the riverbank protection.

The deposition of sediment is clearly observed at the downstream of the structure B based on the bed profiles shown in Figures 2.68 and 2.72, in which the bandal-like structure shows the

largest deposition area, followed by the impermeable groins case in which the recirculation currents formed by the flow separation at the groins toes, especially the upstream groin (structure A), transport part of the eroded sediment to this region. The permeable groins case also shows the deposition with small quantities of the sediments. In the case of impermeable groins, part of the eroded sediment near the structure A is transported to the main channel region reducing the erosion depth in this area.

The presence of the second structure (structure B) in these cases shows the characteristic of the sediment deposition at the downstream area of both structures. It is due to the recirculation currents formed by the flow separation at the head of structure A in the case of impermeable groins and the reduction of flow velocity at downstream of two structures for all cases. In the bandal-like structures case, the second structure (bandal B) deviating the flow to the main channel cause a new reduction of flow velocity which contributes to the deposition of a largest volume of sediment compared to the effect of the bandal A. This result can be useful to design the distribution of a series of structures in river channels.

The bed profiles in Figures 2.71 and 2.75 shows the formation of deeper erosion in the center line of the flume (main channel), especially in the submerged condition due to the higher shear stress resulted from the higher flow discharge. It can be seen the relatively great variation of the bed profile along the center line for impermeable groin and bandal-like structure cases, however in the permeable groins cases due to the fewer disturbances on flow and consequently in the sediment transport process, the variation of bed profile is very small in both non-submerged and submerged conditions. The influence of the structure B can be noted in the flow field diverted to the main channel direction (Figures 2.16, 2.19, 2.31, 2.38, 2.42 and 2.49).

2.7 Summary

A brief explanation of different equipments used during the experimental studies and details of operation and measurement procedure was discussed. Moreover, the experimental procedures and the studied cases were summarized. Finally, an analysis of the measured results was realized through the comparison between the each type of structure.

In impermeable groins cases, flow concentration and separation is very strong at the groins head. High concentration of velocity, bed shear stresses, vortices, downward flows and turbulence at the upstream of groin head causes extremely large local scour holes around them. The toe protection is needed if this type of structure will be used. However, impermeable groins show good performance in formation of deeper main channel. Strong recirculation currents return to the groins field causing erosion in the groins field area and near the bank. Groin field deposition and bank building is not so effective for this type of groin. The influence on the

experimental results caused by the submerged condition resulted in some differences in the water surface velocity field, local scour depth and erosion in the main channel due to the higher discharge and the downward flow formed at downstream of groins from the overtopping flow, but the flow patterns and deposition/erosion process show similar results that was observed in the non-submerged case.

Very weak flow separation and no formation of recirculation flow were observed in permeable groins cases. The reduced flow velocity contributes to sediment deposition at downstream of them and near the bank but with very small amount. This can enhance stable bank building process. Degradation of main channel caused by increasing in the main channel velocity is less than impermeable groins cases. It is expected that the absence of dead water zone within the groins field would ensure conservation of river ecology. Because of the less main channel degradation, permeable groins can be used for the rivers having much less sediment flow, to maintain the main channel bed level within an allowable range of scour-deposition. Due to much less local scour around groins heads the toe protection cost will be less for permeable groins cases.

The bandal-like structures are found to provide most efficient flow diversion to the main channel area without having negative impact on bank side. The reduction of flow field velocity near the riverbed causes the sediment deposition near the bank minimizing the occurrence of erosion at riverbank. It can be concluded that bandal-like structures can also provide the formation of deeper navigation channel due to the flow diversion to this direction. These characteristics of bandals can also play an important role for stabilization and restoration of rivers channels.

The results of this study are discussed in order to provide the qualitative and quantitative relationship between the main hydrodynamic and morphological patterns around hydraulic structures with emphasis on the bandal-like structures. These results, when interpreted in conjunction with the other numerical and experimental studies, provide important information for the advanced, environmentally oriented design of hydraulic structures in river channels.

Chapter 3

Numerical modeling (three-dimensional flow model and sediment transport model)

3.1 Introduction

The study of natural river changes and the interference of man in natural water bodies is a difficult but important research topic. The basic principles for these studies are well established, a complete analytical solution is not known but for the most basic cases is not difficult to find the exactly solution. The complexities of the flow movement and its interaction with its boundaries, which are deformable, have precluded the development of closed form solutions to governing equations that describe the mechanical behavior of fluid and solid-fluid mixtures. As a result, alternative techniques have been developed to provide quantitative predictions of these phenomena as an aid to engineering projects and river restoration efforts. Modeling is one of such technique.

There are two types of models: numerical model, which is based on computation techniques and physical model, which is based on traditional laboratory techniques and equipments for experimental measurements of the necessary parameters to solve the problem. Numerical modeling has become very popular in the past decades, mainly due to the development of data processing and storage capacity and increasing availability of more powerful and affordable computing platforms. Much progress has been made, particularly in the fields of sediment transport, water quality, and multidimensional fluid flow and turbulence (Nezu and Nakagawa, 1993).

This chapter describes the numerical model developed for the prediction of three-dimensional flow distributions and bed level changes around river training structures as groins (impermeable and permeable) with emphasis on bandal-like structures. The basic equations, the initial conditions and the boundary conditions are given, and information of the numerical solution method is presented. The numerical model description is divided into hydrodynamic and sediment transport models to facilitate the comprehension of each part. The unstructured mesh system (Zhang, H., 2005) was adopted in this study to represent the complex geometries of the structures investigated as the permeable groins (piles) and the bandal-like structures (upper half – bended – plate and lower half – permeable part).

3.2 Three-dimensional flow model

3.2.1 General

The turbulent flow is characterized by chaotic movement of the fluid flow as opposed to the ordered structure of laminar flow. This occurs, when inertial forces are large compared to viscous forces so internal friction is no longer able to damp out chaotic fluctuations coming from in ever present and inevitable disturbance (e.g. at the inflow, boundary, etc.). According to Rodi (2000), the turbulence is related to vortex movements which have for high Reynolds number a wide range of dimensions and velocities. Silveira Neto et al. (1993) noted that in the current state of knowledge, any attempt to define the turbulence phenomenon would be incomplete then are convenient to characterize the turbulence rather than define it. In fact, it is noted that in the absence of a general definition of turbulence, the comprehension of their characteristics provides a better understanding of the phenomenon.

It is known that the Navier-Stokes equations taken in its primitive form is sufficient to model flows in any scheme for any number of Reynolds. The problem is that the increase of Reynolds number increases the energy spectrum of the flow, giving rise to a greater number of scales to be resolved. This requires the allocation of a mesh and a time step greatly refined in order to capture the smaller scale of the spectrum, which imposes computational costs unviable. These are constraints that guide the experimentalists the utilization of numerical models of turbulence, which are based on the hypothesis of division of scales.

The modeling of the turbulence phenomenon has attracted many researchers and more and more advanced models suitable for the description of large variety of flows evolved over the last decades. Due to its complexity, a general model embracing all aspects of turbulence is still out of reach. Nevertheless, there has been an enormous progress in the understanding of turbulence. Nowadays, Direct Numerical Simulations (DNS) and Large Eddy Simulations (LES) provide data that were previously obtained only by high-precision laboratory setups, and they have large impact on the development of new turbulence models. However in this thesis we shall not consider LES or DNS modeling. Turbulence in natural waters is extremely rich in scales and process. Their modeling are notoriously difficult and even the most advanced second-order and third-order closures are known for their deficiencies (Canuto, 1994; Sander, 1998).

The method based on the RANS (Reynolds-averaged Navier-Stokes) equations is widely used for many researchers (Olsen and Melaaen, 1993; Olsen, 2003; Salaheldin, 2004) in which the turbulence is represented by the mean values (velocity and pressure) and the fluctuations around these values. Thus, the instantaneous magnitude can be calculated as the sum of the mean value and the fluctuation, according to the statistical approach of Reynolds. The application of the Reynolds hypothesis in the governing equations (Navier-Stokes and Continuity) and the

integration of these equations with a time scale larger than the scale of turbulent motions (so-called relaxation time) provide the continuity and Navier-Stokes equations for average values of velocity and pressure.

3.2.2 Governing equations

The law of conservation of mass states that mass can neither be destroyed nor created, but it can only be transformed by physical, chemical or biological processes. All mass flow rates into a control volume through a control surface are equal to all mass flow rates out of the control volume plus the time change in mass inside the control volume. The law of conservation of momentum describes the motion of a flow particle at any time at a given position in the flow field. Together they are the governing equations for the calculation of the three-dimensional flow field. The so-called Reynolds-averaged Navier-Stokes equations for incompressible, fully turbulent flow, including the continuity (3.1) and momentum (3.2) equations are written as follows.

$$\frac{\partial u_j}{\partial x_j} = 0 \quad (3.1)$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = f_i - \frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j \partial x_j} + \frac{1}{\rho} \frac{\partial \tau_{ij}}{\partial x_j} \quad (3.2)$$

u_i is the velocity averaged over time t ; x_i is the Cartesian coordinate component; ρ is the density of the fluid; p is the pressure averaged over time t ; ν is the molecular kinematic viscosity of the fluid; $\tau_{ij} = -\rho \overline{u_i' u_j'}$ are the Reynolds stress tensors, and u_i' and u_j' are the fluctuating velocity components.

3.2.2.1 Turbulence closure

Most of flows which occur in natural rivers are of a turbulent nature. This means that irregular fluctuations are imposed on the main motion. Turbulence has disorder, performs efficient mixing and transport and has vortices irregularly distributed in all three spatial dimensions. The large eddies are the main carriers of kinetic energy in the fluctuations. They obtain their energy from the mean motion. In a cascade process they decay and pass their energy to several small eddies. At these smaller scales of motion, energy is dissipated by the action of viscosity, i.e. a transfer from mechanical energy to molecular energy. This observation is of great importance for numerical modeling of turbulence. To resolve these effects, a very fine grid

is required increasing the computational time. Consequently the small-scale motion is modeled with a certain turbulence closure scheme. The stress term $\overline{u_i' u_j'}$ represents the fluctuation part of the velocities. They cause an enhanced turbulent momentum transport. To solve these unknowns in order to calculate the turbulence, the equations must be supplemented by additional equations. This lack of equations is called a closure problem and therefore the Reynolds stresses must be connected with the mean flow quantities. This is done by using the Boussinesq approximation (3.3). This concept suggests that in analogy to Newton's second law, the turbulent stresses are proportional to the mean velocity gradients. For general flow situations, the turbulent stresses may be expressed through the linear constitutive equation (3.3).

$$-\overline{u_i' u_j'} = 2\nu_t S_{ij} - \frac{2}{3} k \delta_{ij} \quad (3.3)$$

where, k is the turbulent kinetic energy; δ_{ij} is the Kronecker delta; ν_t is the eddy viscosity and S_{ij} is the strain-rate tensor.

$$\delta_{ij} = \begin{cases} 1 & \text{if } i = j \\ 0 & \text{if } i \neq j \end{cases} \quad (3.4)$$

$$\nu_t = C_\mu \frac{k^2}{\varepsilon} \quad (3.5)$$

$$S_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \quad (3.6)$$

Here, $\nu_t(x,y,z,t)$ is not a physical property and not a constant value, but rather a function of position and time, i.e. it depends on the flow under consideration. Consequently, the distribution of ν_t across the flow field must be estimated. The calculation of ν_t from the given parameters is then realized by the k - ε turbulence closure. The k - ε model is a two equation model. The two unknowns in Eq. (3.5) are replaced by transport equations for k and ε and consequently the equations system is closed (Rodi, 1980). The values of k and ε are calculated by the following two equations.

$$\frac{\partial k}{\partial t} + u_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\left(\nu + \frac{\nu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] \quad (3.6)$$

$$\frac{\partial \varepsilon}{\partial t} + u_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\left(\nu + \frac{\nu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + (C_{1\varepsilon} G - C_{2\varepsilon} \varepsilon) \frac{\varepsilon}{k} \quad (3.7)$$

where, G is the rate of production of the turbulence kinetic energy k and defined as:

$$G = -\overline{u_i u_j} \frac{\partial u_i}{\partial x_j} \quad (3.8)$$

The model constants suggested by Rodi (1980) has the following values:

$$\sigma_k = 1.0 \quad \sigma_\varepsilon = 1.3 \quad C_{1\varepsilon} = 1.44 \quad C_{2\varepsilon} = 1.92 \quad (3.9)$$

In this study, the standard $k-\varepsilon$ model is used. Since ν_t is equal in all directions, the turbulence is isotropic. Even though the $k-\varepsilon$ turbulence model is known for its universal area of application, its isotropy can be a drawback for some complex geometry.

3.2.3 Discretization methods

3.2.3.1 Finite Volume formulation

The analytical solution of the Navier-Stokes equations exists only for simple flows under ideal conditions. For solutions of the real flow, a numerical approach should be adopted so that the equations are replaced by algebraic approximations which can be solved using a numerical method.

The finite volume method is a discretization procedure which is well suited for the numerical simulation of various types (elliptic, parabolic or hyperbolic, for instance) of conservation laws; it has been extensively used in fluid mechanics. Some of the important features of the finite volume method are that it may be used on arbitrary geometries, using structured or unstructured meshes, and it leads to robust schemes.

The study domain is divided into a number of continuous polyhedral CVs (Control Volumes). Integrating the governing partial differential equations over a CV, the following general form is obtained.

$$\frac{\partial}{\partial t} \int_V dV + \int_S \mathbf{u} \cdot \mathbf{n} dS = 0 \quad (3.10)$$

$$\frac{\partial}{\partial t} \int_V \phi dV + \int_S \phi \mathbf{u} \cdot \mathbf{n} dS = \int_S \Gamma \nabla \phi \cdot \mathbf{n} dS + \int_V b dV \quad (3.11)$$

where V is the volume of the CV; S is the CV surface with a unit normal vector $\mathbf{n}$ directing outwards; ϕ is the general conserved quantity representing either scalars or vector and tensor field components; $\mathbf{u}$ is the fluid velocity vector whose Cartesian components are u_i (u, v, w); Γ is the diffusion coefficient and b is the volumetric source of the quantity ϕ . In this equation the first term on the left side represents the transient term and the second term the convective term, on the other hand the first term on the right side the diffusive term and the second term the source term.

An additional feature is the local conservativity of the numerical fluxes which means that the numerical flux is conserved from one discretization cell to its neighbor. This last feature makes

the finite volume method quite attractive when modeling problems for which the flux is of importance in fluid mechanics problems. The finite volume method is locally conservative because it is based on a “balance” approach: a local balance is written on each discretization cell which is often called “control volume”; by the divergence formula, an integral formulation of the fluxes over the boundary of the control volume is then obtained. The fluxes on the boundary are discretized with respect to the discrete unknowns.

3.2.3.2 Mesh system

Structured grids, which make the flow solver more efficient, may confront difficulties in modeling complex flow geometries. In these cases, unstructured grids can alleviate the problems associated with structured grids. It is a quite attractive technique for modeling rivers due to the complex geometry of river channels, in most of times is difficult to treat when using structured grids. The unstructured grid is flexible to treat complex geometries and has an adaptive refinement capability. However, the use of unstructured grid method sometimes increases the computational time due the necessity of memory space to store the information of CVs and their neighbors. A hybrid grid comprised of hexahedrons, tetrahedrons, prisms and pyramids is normally used to solve the problems related to the unstructured grid methods as the stiffness of the flow solver caused by the necessity of very fine grids near the wall surface for an accurate resolution of thin boundary layers. A hybrid mesh system is basically comprised of structured or semi-structured grids for viscous boundary surfaces and tetrahedral unstructured grids for the rest of computational domain. The connectivity of the CVs is defined by a simplified data structure used by some researchers as Ferziger and Perić (2002).

In this study with the FVM procedure, a collocated mesh system was utilized for the variable arrangement. Using this arrangement, all variables can share the same CV and can be defined at the center of the CV. As a result, only one mesh system is needed in the calculation domain, reducing the computational memory required for storage of the mesh data.

The variables are defined at the center of the CV when considering the collocated FVM procedure. A second order midpoint rule is generally used for the integral approximation. If the transient term is absent for the time being, the control volume equation (Eq. 3.11) may be discretized term by term and written as

$$\sum_f \phi_f (u_f \cdot S_f) = \sum_f \Gamma_f \frac{\partial \phi}{\partial n} \bigg|_f S_f + b_p - s_p \phi_p \quad (3.12)$$

here $u_{f\perp}$ is the fluid velocity normal to the surface; b_p is the part of source term containing all the contributions excluding unknown variables and $-s_p \phi_p$ is part of the source term including the

unknown variables which can be treated implicitly. The subscript P represents the present CV and the subscript f the face of CV.

In the Eq. 3.12, the variables defined at the center of the CVs are not explicit expressed then an interpolation method is needed to calculate the values of variables at other locations. The diffusive term contains the gradient of a quantity, which necessitates some numerical differentiation techniques.

An arithmetic interpolation method is commonly used to evaluate the surface values. For a quantity ϕ on the surface,

$$\phi_f = \alpha_f \phi_f + (1 + \alpha_f) \phi_A \quad (3.13)$$

where

$$\alpha_f = \frac{d_{Af}}{d_{Af} + d_{fP}} \quad (3.14)$$

in which the script A is the adjacent CV, d_{fP} and d_{Af} are the distances from the surface to the present CV and to the adjacent CV, respectively.

3.2.3.3 Spatial discretization

The FVM (finite volume method) approach involves a spatial discretization into finite control volumes. The governing equations are integrated in each CV (control volume), and the relevant quantities (mass, momentum, energy, etc.) are stored in distinct values for each control volume. The power law scheme is used to the spatial discretization of Eq. 3.12 as follows

$$\sum_f \{ [D_f A(P_f)] + \max(-F_f, 0) (\phi_P - \phi_A) + F_f \phi_P \} = b_P - s_P \phi_P \quad (3.15)$$

where the strength of the convection F_f , diffusion conductance D_f and the ratio of them are given as

$$F_f = u_f \perp S_f, \quad D_f = \frac{\Gamma_f S_f}{d_{AP}}, \quad P_f = \frac{F_f}{D_f} \quad (3.16)$$

and

$$A(P_f) = \max[0, (1 - 0.1|P_f|)^5] \quad (3.17)$$

The harmonic mean which can represent the physics of the process with reasonable values, especially near the boundary is used to determine the diffusive coefficient.

$$\Gamma_f = \frac{\Gamma_A \Gamma_P}{\alpha_f \Gamma_P + (1 - \alpha_f) \Gamma_A} \quad (3.18)$$

The use of a simple arithmetic mean for the surface flux can be responsible for the checkerboard variable distribution causing the slow acceptance of the use of collocated mesh.

The interpolation method proposed by Rhie and Chow (1983) can solve this problem introducing an additional term related to the pressure gradient to the calculation of the surface fluxes.

After the discretization, the unknown value of the present CV is expressed by the all of neighboring CVs. Thus, the momentum equations for u at present CV and one of its adjacent CVs are written as

$$a_P u_P = \sum_{nb} a_{nb} u_{nb} \Big|_P - \int_V \frac{\partial p}{\partial x} dV \Big|_P + b_P \quad (3.19)$$

$$a_A u_A = \sum_{nb} a_{nb} u_{nb} \Big|_A - \int_V \frac{\partial p}{\partial x} dV \Big|_A + b_A$$

where a is the coefficient for the unknown at the center of the approximated CV and nb is the neighboring CV.

From the conservation principle of the FVM procedure, the velocity at the common face of the two neighboring CVs must also have a discretized momentum equation of the similar form as that of Eq. 3.19, i.e.

$$a_f u_f = \sum_{nb} a_{nb} u_{nb} \Big|_f - \int_V \frac{\partial p}{\partial x} dV \Big|_f + b_f \quad (3.20)$$

Approximating the solution u_f of Eq. 3.20, the information from Eq. 3.19 can be used. By using some linear interpolation and simplification, the following equation is obtained.

$$u_f = \bar{u}_f + \frac{1}{a_f} \left(\int_V \frac{\partial p}{\partial x} dV \Big|_f - \int_V \frac{\partial p}{\partial x} dV \Big|_f \right) \quad (3.21)$$

where

$$\begin{aligned} \bar{u}_f &= \alpha_f u_P + (1 - \alpha_f) u_A \\ a_f &= \alpha_f a_P + (1 - \alpha_f) a_A \end{aligned} \quad (3.22)$$

$$\overline{\int_V \frac{\partial p}{\partial x} dV|_f} = \alpha_f \int_V \frac{\partial p}{\partial x} dV|_P + (1 - \alpha_f) \int_V \frac{\partial p}{\partial x} dV|_A$$

$$\int_V \frac{\partial p}{\partial x} dV|_f = S_{fx} (p_A - p_P)$$

in which S_{fx} is the projected area of the surface to the yz plane (perpendicular to the x axis). The extension to other velocity components is straightforward.

3.2.3.4 Temporal integral

At the end of the spatial discretization, is possible to obtain

$$\frac{\partial}{\partial t} \int_V \phi dV = F$$

where

(3.23)

$$F = \sum_{nb} a_{nb} \phi_{nb} + b_P - a_P \phi_P$$

Using the second order implicit Crank-Nicolson scheme as follows

$$\frac{\phi^{m+1} - \phi^m}{\Delta t} V = \frac{F^{m+1} + F^m}{2} \quad (3.24)$$

where the superscript m and $m+1$ stand for the previous and the current time step. The algebraic equations results

$$a_P \phi_P^{m+1} = \sum_{nb} a_{nb} \phi_{nb}^{m+1} + b_P$$

in which

$$a_P^{m+1} = \sum_{nb} a_{nb} \phi_{nb}^{m+1} + \sum_f F_f + s_P^{m+1}$$

$$a_P = a_P^{m+1} + \frac{2V}{\Delta t} \quad (3.25)$$

$$b_P = b_P^{m+1} + \frac{2V}{\Delta t} \phi_P^m + \left(\sum_{nb} a_{nb} \phi_{nb} + b_P - a_P \phi_P \right)^m$$

It is seen from Eq. 3.25 that after the time integral, a time-related term is introduced to the coefficient of a_P comparing with the steady case. And besides a temporal term, there is another contribution from the previous time step to the source term.

3.2.3.5 Pressure-velocity coupling

Due to the fact that the pressure in the Navier-Stokes equation is unknown, it has to be calculated by an additional algorithm. This algorithm is summarized in the *SIMPLE* (Semi-Implicit Method for Pressure Linked Equations) method (Patankar, 1980). As there is no explicit equation for the distribution of the pressure, the convergence and stability of a numerical solution of flowing incompressible fluids depends largely on how pressure gradients and velocities are evaluated in the equation of mass and momentum. The main idea is to guess a value for the pressure and use the continuity effect to obtain an equation for the pressure correction used in the next time step. When the pressure correction is then added to the pressure, water continuity is satisfied.

An equation for the pressure is not solved directly, only an equation for the pressure-correction. The pressure is obtained by accumulative addition of the pressure-correction values. The *SIMPLE* method can give instabilities when calculating the pressure field. Therefore, the pressure-correction is often multiplied with a number below unity before being added to the pressure. The number is a relaxation coefficient. The optimum factor depends on the flow situation and can be changed to give better convergence rates.

3.2.3.6 Mesh movement

To simulate the interaction between the flow and the bed variation influenced by the hydraulic structures as bandal-like structures which is an object of the present study, the mesh movement needs to be considered.

The governing equations considering the mesh movement with the FVM method (Ferziger and Peric, 2002) can be written as

$$\frac{\partial}{\partial t} \int_V dV + \int_S (\mathbf{u} - \mathbf{u}_m) \cdot \mathbf{n} dS = 0 \quad (3.26)$$

$$\frac{\partial}{\partial t} \int_V \phi dV + \int_S \phi (\mathbf{u} - \mathbf{u}_m) \cdot \mathbf{n} dS = \int_S \Gamma \nabla \phi \cdot \mathbf{n} dS + \int_V b dV \quad (3.27)$$

here $\mathbf{u}_m$ is the velocity vector of CV face movement whose Cartesian components are u_{mi} or (u_m, v_m, w_m) . The governing equations for movable mesh CVs may be derived from those of fixed CVs by just replacing the velocity vector $\mathbf{u}$ in the convective terms with the relative velocity vector $\mathbf{u} - \mathbf{u}_m$.

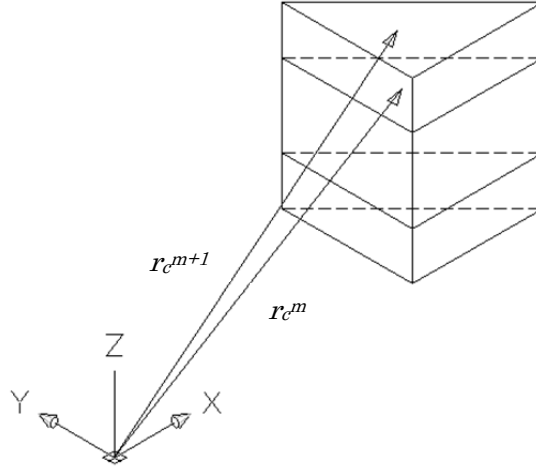


Figure 3.1 Movement of a CV face at two consecutive time steps

The mesh movement may introduce artificial mass sources in the discretized equations, which have a potential to accumulate and spoil the simulation. Therefore, the conservation of the space should also be satisfied when the CV changes its shape and/or position with time. A mathematic interpretation is

$$\frac{\partial}{\partial t} \int_V dV - \int_S \mathbf{u}_m \cdot \mathbf{n} dS = 0 \quad (3.28)$$

In the present study, the mesh system is allowed to move only in the vertical direction for the time being. This makes possible to use some simple approach to evaluate the volume fluxes and that the space conservation law Eq. 3.27 is automatically guaranteed at the same time. The velocity of the movement of a CV face is determined from the difference in the mesh locations at two consecutive time steps m and $m+1$ (see Figure 3.1), i.e.

$$\mathbf{u}_m = \frac{\mathbf{r}_c^{m+1} - \mathbf{r}_c^m}{\Delta t} \quad (3.29)$$

here r_c =center of the CV face, Δt =time.

3.2.4 Boundary conditions

As described previously, unknown variables in the cell center are determined as a function of the variables in the surrounding cells. However, there are cells in the computational domain having no neighbor, i.e. they are defined as boundary cells. Usually the boundaries do not provide additional equations and then the introduction of additional unknowns' parameters is not desirable. Instead of getting information from a neighboring cell, boundary conditions have to be defined at the following locations in the computational domain:

➤ **Inlet**

Variables at the inflowing boundary were defined by a Dirichlet boundary condition, i.e. the variables are set to a certain value. In the discretized equation for the CV near the inlet boundary, as the boundary value is given directly, the contribution from the boundary turns into a source term and is no need to be calculated implicitly. In the pressure-correction equation, as the velocity field is given, the velocity correction is zero. And the Neumann boundary of zero gradients is suitable for the pressure.

➤ **Outlet**

At the outflow boundary, the Neumann boundary is assumed in which the variables has a zero-gradient boundary condition, i.e. they were set equal to the values of the cell next to the cells at the outflow. To minimize the propagation of errors, an alternative is to set the outlet boundary as far downstream of the study domain as possible.

The global mass conservation is guaranteed through the following procedure: firstly, an initial estimation of the velocity at the outlet is acquired by extrapolation from the near boundary CVs; after that the velocity is corrected by making the outlet mass flux the same as the inlet mass flux. This procedure also provides a way to correct the velocity field at the outlet; the velocity is no need to be corrected again in the SIMPLE procedure.

➤ **Free surface**

At the water surface, u , v , p and ε have zero gradient boundary conditions. w is set to a certain value and k is equal to zero, respectively. For the time being, the free surface is considered as a symmetrical plane. This presumption can greatly simplify the solution process and is acceptable for many hydraulic problems.

➤ **Side-wall**

The wall function approach is used to avoid the possible integration through the viscous sub-layer and implement the wall roughness more flexibly. The wall function approximation is applied to the region closed to the rigid wall, by assuming that no-slip flow condition prevails in the region close to the wall with the near wall CV velocity assumed to be parallel to the wall and denoted by $u_{//}$.

Defining the dimensionless distance y^+ and dimensionless velocity u^+ as

$$y^+ = \frac{u_* y_{\perp}}{\nu} \quad (3.30)$$

$$u^+ = \frac{u_{//}}{u_*} \quad (3.31)$$

where u_* is the friction velocity near the bed and $y_\perp$ is the normal distance from the center of the near wall CV to the wall surface, the universal logarithmic velocity distribution can be expressed by

$$u^+ = \frac{1}{\kappa} \ln(Ey^+) \quad (3.32)$$

where κ is the von Karman universal constant equal to 0.41 and E is the wall roughness coefficient. Assuming that the flow is in local equilibrium, i.e. the production and dissipation rate of the turbulence are nearly equal

$$u_* = C_\mu^{1/4} k_p^{1/2} \quad (3.33)$$

And the wall shear stress is

$$\tau_w = \rho u_*^2 = \frac{\rho C_\mu^{1/4} k_p^{1/2} u_{||}}{u^+} \quad (3.34)$$

In the momentum equations, the link with the wall is suppressed by setting it to zero and adding the wall force from Eq.3.34 as a source term. The normal derivative of k at the wall boundary CV is set to be zero in the k - ε equation, and the production in the wall region is computed from

$$G_P = \frac{\tau_w}{\rho} \frac{\partial u_{||}}{\partial n} = \frac{\tau_w}{\rho} \frac{u_{||}}{y_\perp} \quad (3.35)$$

ε in the near wall CV is directly set to

$$\varepsilon_P = \frac{u_*^3}{\kappa y_\perp} = \frac{C_\mu^{3/4} k_p^{3/2}}{\kappa y_\perp} \quad (3.36)$$

The roughness parameter E in Eq. 3.32 is related to the roughness Reynolds number

$$k_s^+ = \frac{u_* k_s}{\nu} \quad (3.37)$$

by

$$E = \exp[\kappa(B - \Delta B)] \quad (3.38)$$

where B is an additive constant, ΔB is a roughness function related to the standard roughness, k_s such as (Cebeci and Bradshaw, 1977):

$$\Delta B = \begin{cases} 0 & k_s^+ < 2.25 \\ B_m \sin[0.4285(\ln k_s^+ - 0.811)] & 2.25 \leq k_s^+ < 90 \\ B_m & k_s^+ \geq 90 \end{cases} \quad (3.39)$$

in which

$$B_m = B - 8.5 + \frac{\ln k_s^+}{\kappa} \quad (3.40)$$

here B is equal to 5.2. The equivalent roughness height k_s quantify the influence of roughness elements such as sand grains, sand waves (including ripples, dunes and antidunes) and other bed forms. For smooth bed, $k_s=0$, and for a stationary flat bed in laboratory experiments, k_s is usually set to the median diameter d_{50} of bed material because there is only sand-grain roughness on the bed. For stationary flat bed in real rivers, k_s should theoretically also be about d_{50} , but in practice usually somewhat higher values are adopted, e.g. $3d_{90}$ suggested by van Rijn (1984c). For sand wave bed, k_s should be related to the height of the sand waves, van Rijn (1984c) proposed the following relationship, which is used in the present study:

$$k_s = 3d_{90} + 1.1\Delta(1 - e^{-25\Psi}) \quad (3.41)$$

here $\Psi = \Delta / \Lambda$, is the bed-form steepness, and Δ and Λ are the height and length of the bed forms. The length $\Lambda = 7.3h$ and the bed-form steepness is calculated from

$$\Psi = \frac{\Delta}{\Lambda} = 0.015 \left(\frac{d_{50}}{h} \right)^{0.3} (1 - e^{-0.5T}) (25 - T) \quad (3.42)$$

where T = the bed shear stress parameter, is defined as

$$T = \frac{\tau_g - \tau_c}{\tau_c} \quad (3.43)$$

where τ_c is the critical shear stress for sediment motion which will be introduced in the next chapter, and τ_g is the grain-related shear stress which is evaluated with the following expression

$$\tau_g = \rho g \left(\frac{\bar{u}}{C'} \right)^2 \quad (3.44)$$

in which, $\bar{u}$ is the depth averaged velocity, and C' is the grain-related Chezy coefficient. The latter is calculated from

$$C' = 18 \log \left(\frac{12h}{3d_{90}} \right) \quad (3.45)$$

3.2.5 Solution methods

The equations are solved in an implicit decoupled way. The final algebraic equation systems are under-relaxed before submitted to the linear equation solver. The method proposed by Patankar (1980) is used in this study. It has been found to be very efficient owing to its increasing of the diagonal dominance of coefficient matrices.

The linear systems are solved by means of conjugate gradient method in its stabilized version namely the Bi-CGSTAB (Bi-Conjugate Gradient Stabilized Method) using Krylov accelerators. In this study, the preconditioned GMRES (Generalized minimal residual method) solver with an ILUTP (Incomplete LU factorization with threshold and pivoting) preconditioner is integrated in the program with the Bi-CGSTAB solver. The detailed information about the two solvers may be found in the publications by van der Vorst, 1992; Sleijpen and Fokkema, 1993 and Saad, 2003.

3.3 Sediment transport modeling

3.3.1 General

The transport of sediment particles by a flow of water can be in the form of bed load and suspended load, depending on the size of the material particles and the flow conditions. The suspended load may also contain some wash load, which is generally defined as that portion of the suspended load which is governed by the upstream supply rate and not by the composition and properties of the bed material. Although in natural conditions there is no sharp division between the bed load and the suspended load layer, thus it is necessary to define two distinct layers for mathematical representation. Usually, three modes of particle motion are distinguished: (1) rolling and sliding motion or both; (2) saltation motion; and (3) suspended particle motion. When the value of the bed-shear velocity just exceeds the critical value for initiation of motion, the particles will be rolling and sliding or both, in continuous contact with the bed. For increasing values of the bed-shear velocity, the particles will be moving along the bed by more or less regular jumps, which are called saltations. When the value of the bed-shear velocity exceeds the fall velocity of the particles, the sediment particles can be lifted to a level at which the upward turbulent forces will be comparable with or of higher order than the submerged weight of the particles and as a result the particles may go in suspension.

The trajectories and velocities of bed load particles were studied in detail by Kalinske (1947), Einstein (1950) and Bagnold (1966). Van Rijn (1984a) studied the motion of bed load particles by solving the equation of motions for a saltating particle. A general equation for equilibrium suspended sediment concentration profiles was introduced by Rouse (1937). This equation can be used to compute the equilibrium sediment concentration as a function of height above the bed when the particle settling velocity, the sediment mixing coefficient and the reference concentration are known. Einstein (1950), Engelund and Fredsoe (1976) and later Van Rijn (1984a) proposed expressions for the reference concentration as a function of sediment properties and flow conditions. The experiments of Coleman (1970) provided a better understanding of the vertical distribution of the sediment mixing coefficient. The experimental data of Coleman were used by Van Rijn (1984a) to study the relationship between the transfer of sediment mass and fluid momentum.

As shown in Fig. 3.2, the flow domain is subdivided into two layers vertically. Bed load is confined to move in a thin layer in the proximity of the riverbed, above which is the region occupied by suspended load. The exchange of sediment between the two layers is through the upward and downward fluxes at the interface.

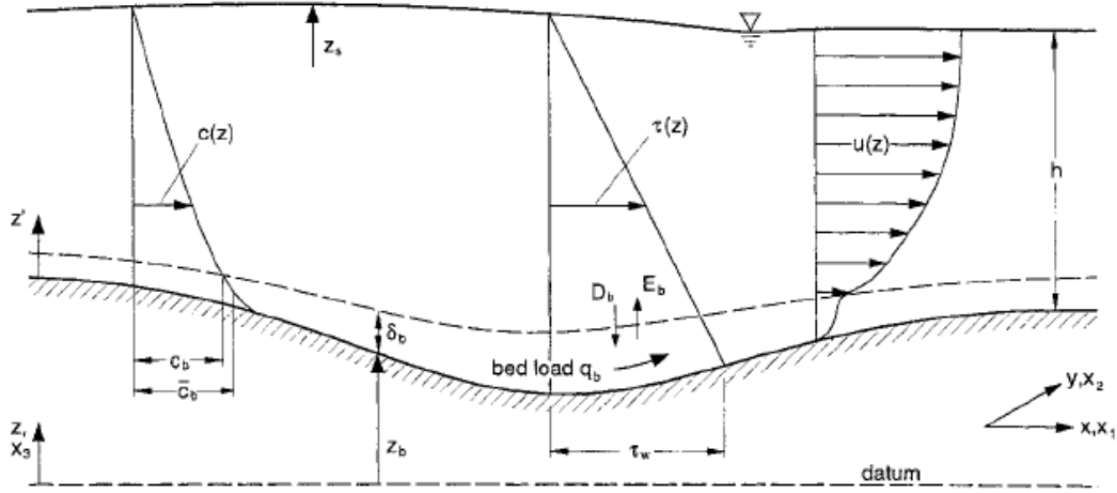


Figure 3.2 Flow configuration (Van Rijn, 1984a)

3.3.2 Bed load transport calculation

As mentioned in the previous sub-section, bed load transport is calculated in the area where the cells are close to the bed (see Fig. 3.2). The amount of bed load transport rate was calculated by the equation of Ashida and Michiue (1972a).

$$\frac{q_b}{\sqrt{(s-1)gd^3}} = 17\tau_{*e}^{\frac{3}{2}} \left(1 - \frac{u_{*c}}{u_*}\right) \left(1 - \frac{\tau_{*c}}{\tau_*}\right) \quad (3.46)$$

where q_b is the bed load discharge; s is the specific gravity of sediment; d is the diameter of sediment; τ_* , τ_{*c} , τ_{*e} are the dimensionless shear stress, critical shear stress and effective shear stress, respectively; u_* , u_{*c} are the friction velocity and critical friction velocity, respectively. These parameters are calculated through the following relations:

$$\tau_* = \frac{u_*^2}{\left(\frac{\sigma}{\rho} - 1\right)gd}, \quad \tau_{*c} = \frac{u_{*c}^2}{\left(\frac{\sigma}{\rho} - 1\right)gd}, \quad \tau_{*e} = \frac{u_{*e}^2}{\left(\frac{\sigma}{\rho} - 1\right)gd} \quad (3.47)$$

where u_{*e} is the effective friction velocity.

The critical friction velocity u_{*c} for the sediment size d was evaluated with the Iwagaki formula (expressed as dimensionless critical shear stress).

$$\tau_{*c} = \begin{cases} 0.05 & \text{if } R_* \geq 671.0 \\ 0.00849R_*^{\frac{3}{11}} & \text{if } 162.7 \leq R_* \leq 671.0 \\ 0.034 & \text{if } 54.2 \leq R_* \leq 162.7 \\ 0.195R_*^{\frac{7}{16}} & \text{if } 2.14 \leq R_* \leq 54.2 \\ 0.14 & \text{if } R_* < 2.14 \end{cases} \quad (3.48)$$

where

$$R_* = \frac{\sqrt{(s-1)gd^3}}{\nu} \quad (3.49)$$

The critical friction velocity and shear stress in Eq. 3.48 and Eq. 3.49 are valid only for a horizontal bed. The bed slope factor that will be commented in sub-section 3.3.5 should be added to the equations so that they can be used in sloping bed conditions.

3.3.3 Suspended load transport calculation

In the sediment transport model, the distribution of the sediment concentration in the suspended-load layer is governed by the following convection-diffusion equation. For non-transient transport processes the equation reads as follows

$$\frac{\partial C}{\partial t} + (u_j - w_s \delta_{j3}) \frac{\partial C}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\left(\frac{\nu_t}{\sigma_c} \right) \frac{\partial C}{\partial x_j} \right] \quad (3.50)$$

where C is the local sediment concentration; w_s the settling velocity of the sediment; δ_{ij} is the Kronecker delta with $j=3$ indicating the vertical direction and σ_c the turbulent Schmidt number (equals 1.0 in this study) relating the turbulent diffusivity of the sediment to the eddy viscosity ν_t . The Einstein summation is used for the variables with repeated subscript in this equation. Eq. (3.50) is solved with the control volume approach in a similar way to how Eq. (3.2) is solved. Due to its partial differential origin, boundary conditions are needed. However, a sediment settling velocity has been included in the convective term. According to the suggestion of Wu et al. (2000) it is treated as a source term. In this study, the settling velocity is calculated by the Rubey's Formula (1933).

$$w_s = \sqrt{\frac{2}{3} \left(\frac{\sigma}{g} - 1 \right) gd + \frac{36\nu^2}{d^2}} - \frac{6\nu}{d} \quad (3.51)$$

where σ is the sediment density and d is the representative size of the sediment fraction.

a) Inlet

The concentration at the inlet is set to a certain user defined value. During this study, the equilibrium sediment concentration profile is used and calculated by the Lane-Kalinske formula

$$\frac{C}{C_e} = \exp \left[-15 \left(\frac{z-a}{h} \right) \left(\frac{w_s}{u_*} \right) \right] \quad (3.52)$$

where a is the reference level (in this model a is equal to $0.05h$ (h is the water depth), is the same as the interface of the bed load layer and the suspended load layer); C_e is the near-bed equilibrium concentration; z is the depth in vertical direction. The near-bed equilibrium concentration is calculated using the van Rijn empirical formula (1984b).

$$C_e = 0.015 \frac{d}{a} \frac{T^{1.50}}{D_*^{0.3}} \quad (3.53)$$

where T and D_* are defined by Equations (3.31) and (3.32), respectively.

T is the dimensionless transport stage parameter for sediment particle size defined in the following equation,

$$T = \left(\frac{\tau - \tau_c}{\tau_c} \right)^{1.50} \quad (3.54)$$

and D_* the dimensionless particle parameter defined as

$$D_* = d \left(\frac{\left(\frac{\rho_s}{\rho_w} - 1 \right) g}{v^2} \right)^{\frac{1}{3}} \quad (3.55)$$

b) Outlet

For the outlet boundary, the gradient of the sediment concentration is usually assumed to be zero, i.e.

$$\frac{\partial C}{\partial s} = 0 \quad (3.56)$$

where s stands for the longitudinal direction of the channel.

c) Free surface

At the free surface (water surface) the vertical sediment flux is set to zero, then

$$\frac{v_t}{\sigma_c} \frac{\partial C}{\partial z} + w_s C = 0 \quad (3.57)$$

d) Near-bed boundary

In the near-bed boundary that represents the interface between the suspended load layer and bed load layer the sediment exchange is expressed by the downward flux and the upward flux. The downward flux is calculated from

$$D = w_s C_a \quad (3.58)$$

where C_a is the ambient concentration near the bed (i.e. the interface of the bed load layer and the suspended load layer a). As the calculated concentration is at the center of the CV, the ambient concentration near the bed has to be obtained from the neighboring CVs. This may be achieved by assuming a linear concentration distribution. And the upward flux is generally assumed to be the one under the equilibrium condition, i.e.

$$E = w_s C_e \quad (3.59)$$

3.3.4 Bed deformation

The bed level changes were computed from the information about bed load and suspended load transport rates using the mass-balance equation applied to the bed load layer, where the bed load is part of the equation and the suspended load is included as the difference between the sediment fluxes near the bed.

$$(1 - \lambda) \frac{\partial z_b}{\partial t} + \frac{\partial q_{bx}}{\partial x} + \frac{\partial q_{by}}{\partial y} + (E - D) = 0 \quad (3.60)$$

where λ is the sediment porosity; q_{bx} , q_{by} are the bed load transport rate in x and y directions, respectively; E is the upward near-bed flux and D is the downward near-bed flux. Solution of Eq. 3.59 results the bed variation at one time step.

3.3.5 Critical shear stress and sloping bed

The critical shear stress is responsible for mobilizing the sediment. This criterion for incipient motion of a sediment particle was calculated according to the Shields (1936) curve. In cases where the sediment particle is exposed to a significant lateral slope, the criterion of incipient motion differs from that for particles on a flat bed. This physical process may have great influence on the bed evolution in a channel bend, when the 3D modeling of local scour around a hydraulic structure is considered. In the present study a slope factor relation proposed by Nakagawa et al., 2004 and Zhang et al., 2005 is implemented where a 3D analysis of the bed slope effect is considered.

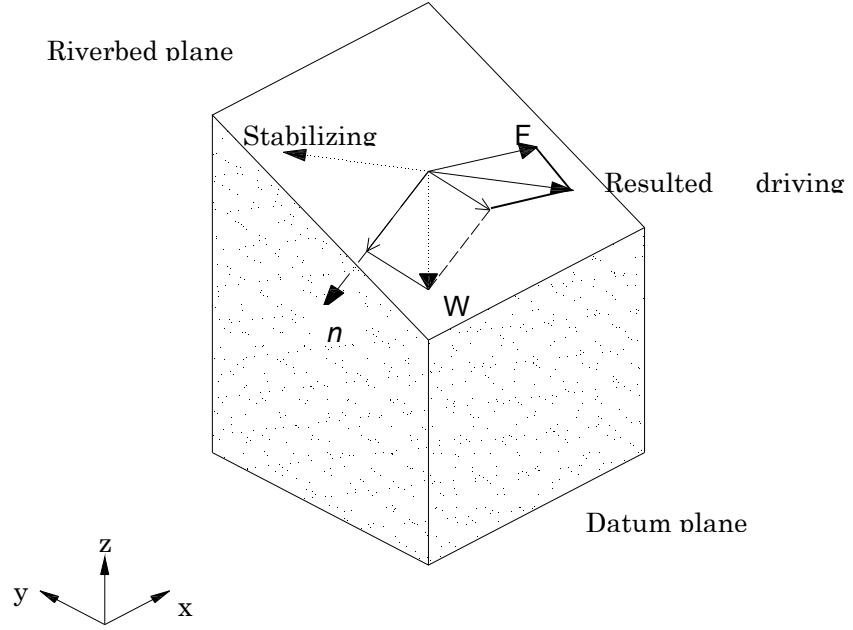


Figure 3.3 Forces acting on a particle on sloping bed.

The Figure 3.3 shows the forces acting on a particle on a sloping bed (Zhang, 2005), which is the submerged weight of the particle $\mathbf{W}$ and the hydrodynamic force $\mathbf{F}$ described in Cartesian coordinate system as

$$\mathbf{n} = \cos \alpha \mathbf{i} + \cos \beta \mathbf{j} + \cos \gamma \mathbf{k} \quad (3.61)$$

$$\mathbf{W} = W \cdot \mathbf{k} \quad (3.62)$$

$$\mathbf{F} = F(f_x \mathbf{i} + f_y \mathbf{j} + f_z \mathbf{k}) \quad (3.63)$$

here $\cos \alpha$, $\cos \beta$ and $\cos \gamma$ are the direction cosines of the vector $\mathbf{n}$, which is the normal direction of riverbed; f_x , f_y and f_z are the direction cosines of the fluid force $\mathbf{F}$. The resulted driving force is written as

$$\mathbf{F}_R = (W \cos \gamma \cos \alpha + f_x F) \mathbf{i} + (W \cos \gamma \cos \beta + f_y F) \mathbf{j} + (-W \sin^2 \gamma + f_z F) \mathbf{k} \quad (3.64)$$

Considering that the fluid force $\mathbf{F}$ is parallel to the solid wall due to the assumption made in the wall function approach in the turbulence model. The stabilizing force is given by

$$F_S = -W \cos \gamma \tan \phi \quad (3.65)$$

The threshold condition can be written as

$$F^2 + 2WmF + nW^2 = 0 \quad (3.66)$$

with

$$m = f_x \cos \gamma \cos \alpha + f_y \cos \gamma \cos \beta - f_z \sin^2 \gamma \quad (3.67)$$

$$n = (\cos \alpha \cos \gamma)^2 + (\cos \beta \cos \gamma)^2 + \sin^4 \gamma - \cos^2 \gamma \tan^2 \varphi \quad (3.68)$$

Then the positive root of Eq. 3.66 is

$$F = W \left(\sqrt{m^2 - n} - m \right) \quad (3.69)$$

Comparing the force above with that on a horizontal bed, the difference may be expressed by the bed slope factor K . In terms of shear stress, the threshold condition reads

$$K = \frac{\sqrt{m^2 - \sin^2 \gamma + \cos^2 \gamma \tan^2 \varphi} - m}{\tan \varphi} \quad (3.70)$$

The direction of the sediment movement does not coincide with the flow direction on a sloping bed. A reasonable treatment is to assume that the sediment movement follows the direction of the resulted driving force.

For numerical simulation, another attention should be paid related to the bed slope is the angle of sediment repose. During the bed evolution process, the bed slope may increase to a level larger than the angle of repose, in particular around the scour holes. This phenomenon cannot occur, or it is not stable in the actual case. In the numerical simulation, an indicator and a sand slide process are introduced to avoid its occurrence (Zhang, 2005). On the riverbed, the topography of the surface mesh (all the mesh elements are assumed to be planar polygons) is shown in Fig.3.4. Each time before adjusting the mesh, the program checks all the mesh nodes and corresponding neighbors on the bed surface.

In Figure 3.4, supposing that an angle steeper than the angle of repose was detected connecting node A (x_A, y_A, z_A) and node B (x_B, y_B, z_B), if node B is higher, it should be adjusted vertically to node B' (lower level), and node A should move to node A' (higher level) at the same time. Then the angle connecting A and B is equal to the angle of repose.

$$(z_B - \delta z_B) - (z_A + \delta z_A) = \tan \varphi \sqrt{(x_B - x_A)^2 + (y_B - y_A)^2} \quad (3.71)$$

here z_A, z_B are the bed elevation at node A and node B , respectively; $\delta z_A, \delta z_B$ are vertical change amount (absolute value) for node A and node B , respectively.

In this case, the sediment conservation around node A and node B should be adjusted according to the relation:

$$(S_1 + S_2 + S_3 + S_4 + S_5) \delta z_A = (S_6 + S_7 + S_2 + S_1) \delta z_B \quad (3.72)$$

where S is the projected area of the bed surface in the x - y plane. It is noted that during this adjustment, the conservation is assured for all the meshes including node A and node B .

From Eq.3.69 and Eq.3.70, the new position of node A and node B can be determined. For each node on the riverbed, the process is repeated. As the change of one node has an influence on all the angles connecting the node and its neighboring nodes, new scans and possible adjustments are needed until all the angles are not greater than the angle of repose.

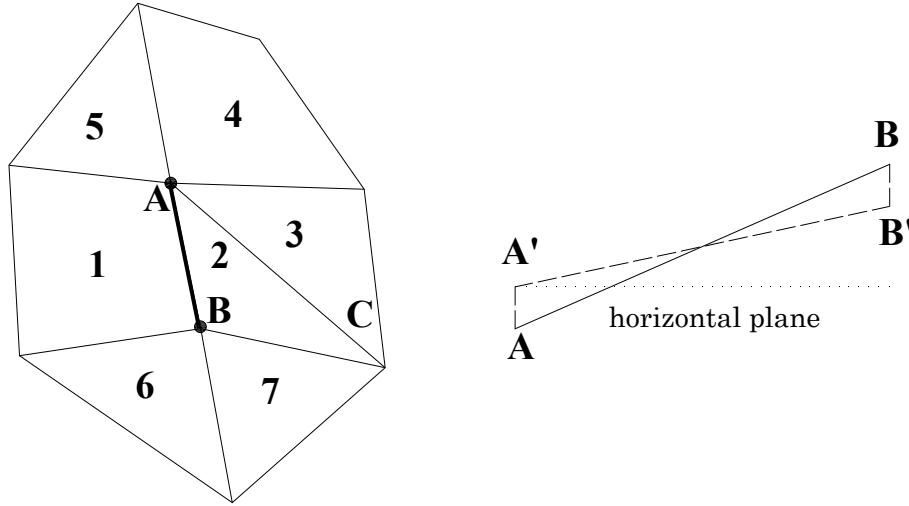


Figure 3.4 Sand slide algorithm (Zhang et al., 2005)

3.4 Summary

This chapter described the 3D hydrodynamic and sediment transport models in the morphological model. The numerical model is based on the unstructured mesh system. The hydrodynamic model solves the RANS with the standard $k-\varepsilon$ models for the turbulence closure. A standard $k-\varepsilon$ model is the most commonly used turbulence models in CFD modeling. However, this model has a well-known drawback, e.g. the isotropic eddy viscosity.

The pressure-velocity coupling is achieved by using the SIMPLE pressure correction algorithm and the momentum interpolation procedure of Rhie and Chow (1983). The discretized algebraic equations are resolved with the power law scheme for the spatial discretization and the second order implicit Crank-Nicolson scheme for the temporal integral. The mesh movement velocity is considered into the convective terms in the governing equations to calculate the mesh movement. To simplify this treatment, the mesh is limited to move only in the vertical direction. The evaluation of the mesh movement should assure that no artificial mass sources are introduced.

A model for sediment transport was implemented that comprises a bed load and suspended load transport model in which the interaction between the two parts occur through the net

deposition/entrainment flux of sediment at the top of the bed load layer (see Figure 3.2). The entrainment (upward flux) is assumed to occur at the same rate as it does under equilibrium conditions and is calculated with an empirical relation. The bed load model is based on the Ashida-Michiue formula (1972) with modifications to consider the influence of the bed behavior such as bed cohesiveness and bed slope (Zhang, 2005). The bed deformation is calculated from the sediment mass-balance equation integrated over the entire water depth.

In Chapter 4, the applicability of the described numerical model is verified through the simulations of the experimental cases described in Chapter 2.

Chapter 4

Application of numerical model

4.1 Introduction

In river engineering practice, river training structures are widely used for various purposes as river bank protection and improvement of navigation conditions. The primary objective of this type of structure is to provide a fairway of sufficient depth and width. However, the existence of hydraulic structures as groins generates large-scale turbulence causing complex local morphological changes. These changes are characterized by a local scour hole followed by a deposition area. With the development of numerical models, it now appears that these models can be used to answer practical questions related to morphological variations. Yet, the commonly used models, when applied to a river channel with structures like groins, poorly reproduce the morphological development in the vicinity of these structures, as well as in the main channel.

Due to the complexity of three-dimensional flow and the bed evolution process in channels, especially with the presence of hydraulic structures, the computational results sometimes cannot reproduce with the desirable accuracy the studied phenomenon. However, the basic features related to the flow structures and bed deformation is reasonably reproduced by the computational results. The simulations under the same conditions that of the cases studied during the laboratory experiments (see Chapter 2) for bandal-like structures, impermeable and permeable groins are presented. It was adopted the same hydraulic conditions of Cases 1, 2 and 3 with the boundary conditions described in the following sections.

This chapter also discusses the applicability of bandal-like structures as an alternative method of river training structure concerning the riverbank protection issues, navigational channel formation through the stabilization of river channels. An analysis of the deposition/erosion volumes around the structures were realized to verify the performance of bandal-like structures compared with conventional structures as groins (impermeable and permeable ones).

4.2 Results from the numerical simulations

The computational meshes utilized in the numerical simulations for each type of structures are described below. The total numbers of cells for each case are described in the Table 4.1,

where the differences on the values are due to the implementation of different types of meshes on groins cases (impermeable and permeable) and the bandal-like structures. To represent the permeable piles and the bandal upper plate some refined meshes were used. Figure 4.1 shows the mesh strategy used for impermeable groins simulations and Figure 4.2 the mesh used for permeable groins. A similar computational mesh of permeable groins with some modifications in the boundary conditions to represent the upper plate was utilized in the bandal-like structures. However due to the extremely time consuming calculations, more “simple” mesh with a reduced number of cells were finally used to represents the bandal with same permeability of the lower permeable part used in the experiments with a small number of piles (5 piles - Figure 4.3).

Table 4.1 Number of computational cells

Type of structure	Condition	Total mesh number
Impermeable groins	Non-submerged	28400
Permeable groins	Non-submerged	41780
Bandal-like structures	Non-submerged	32150

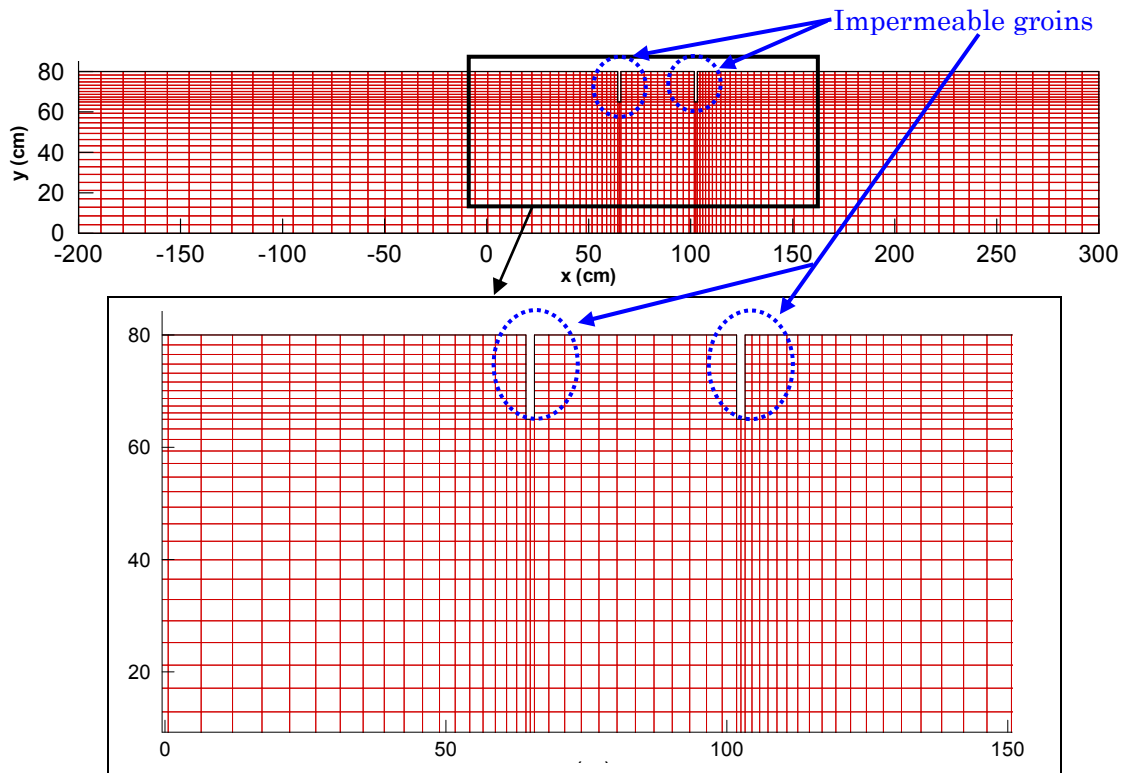


Figure 4.1 Mesh strategy - Case 1 (Impermeable groins) – top: 2D mesh; bottom: details of mesh around groins

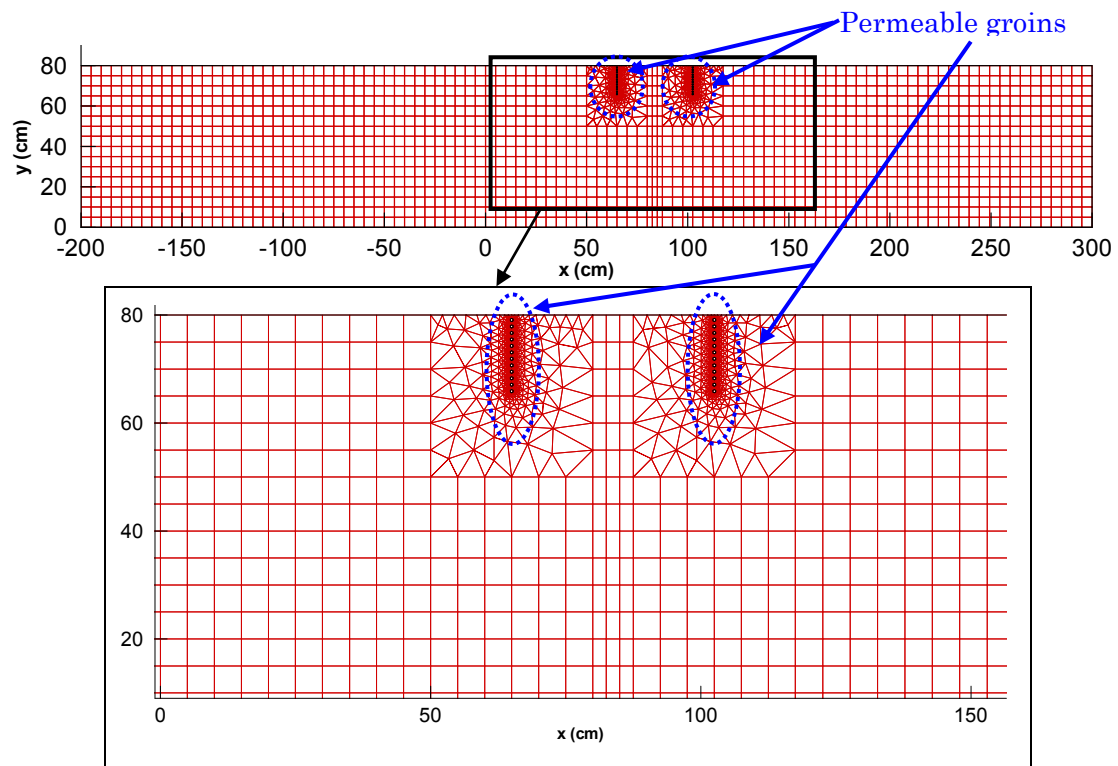


Figure 4.2 Mesh strategy - Case 2 (Permeable groins) – top: 2D mesh; bottom: details of mesh around groins

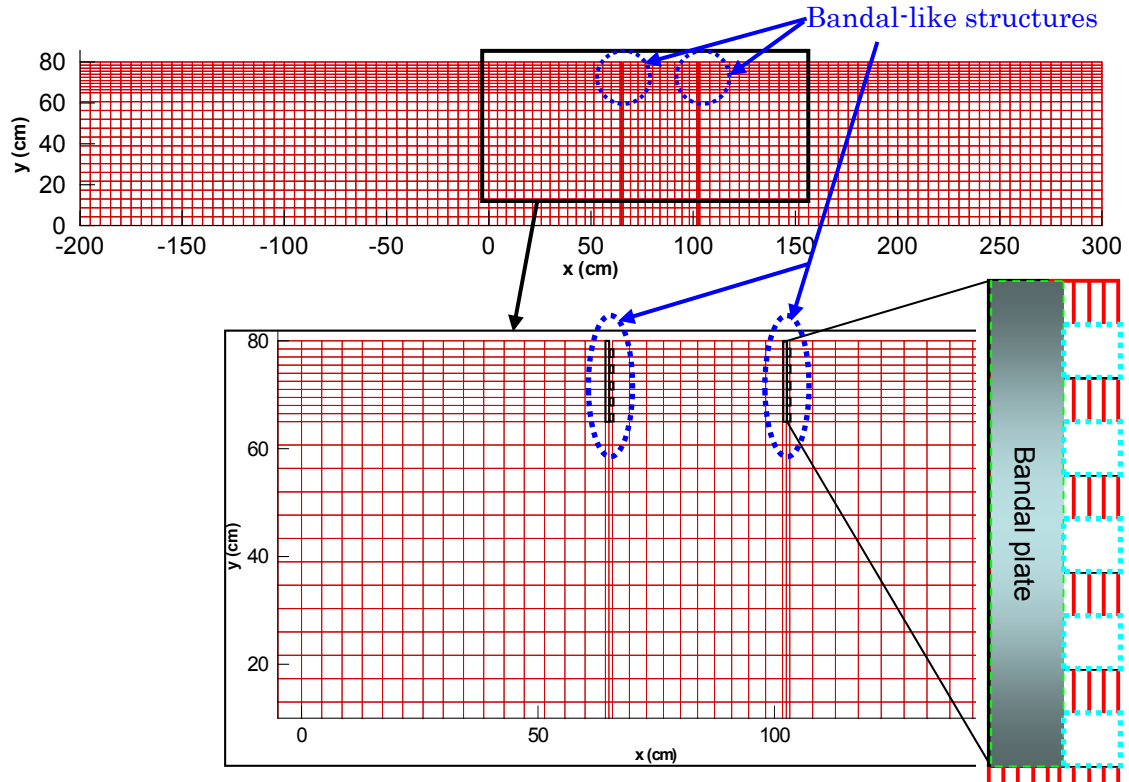


Figure 4.3 Mesh strategy - Case 3 (Bandal-like structures) – top: 2D mesh; bottom: details of mesh around the bandals

4.2.1 Flow patterns

The mean flow patterns for impermeable groins at water surface are shown in Figures 4.4 and 4.5 which represents the non-submerged condition. The confinement of the cross-sectional area increases the flow velocity in the main channel region. The non-submerged condition induces the formation of horizontal circulation pattern with a large primary recirculation current rotating in anticlockwise direction in between the structures and at downstream of groin B. The formation of downward flow at upstream of groin A (upstream one) and the occurrence of flow separation at groin head causes disturbance in the main flow patterns and in the mixing area, i.e. the region between the main channel and the embayment area. In view of riverbank protection, the formation of return currents in non-submerged case, even with reduced flow velocities can affects the stability of the riverbank. In the main channel, due to the flow separation at groins toe, the flow discharge to this direction becomes higher than that at upstream region which increases the flow velocity and bed degradation in the main channel region.

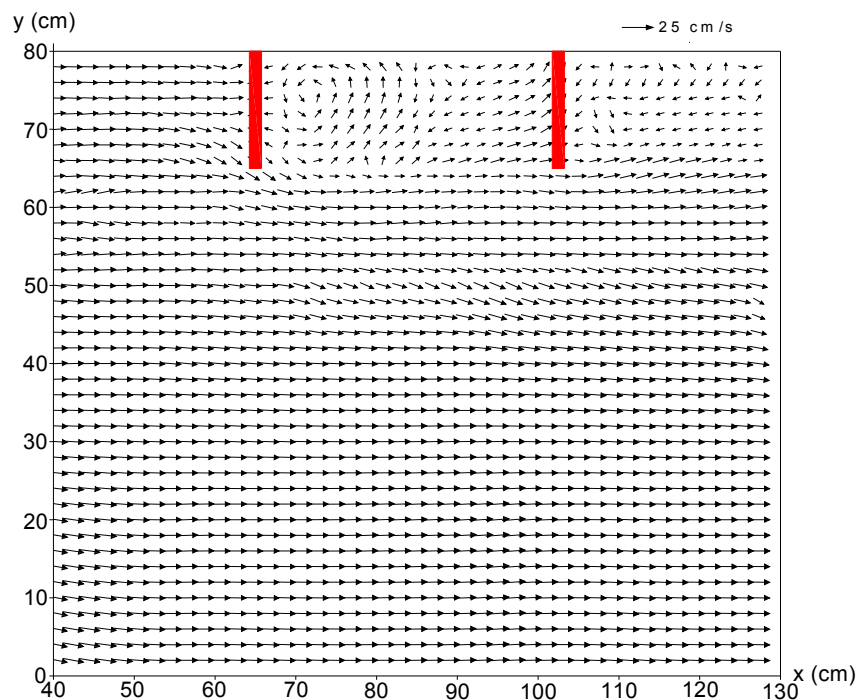


Figure 4.4 Velocity vectors around impermeable groins at water surface by PIV - Case 1
(experiment)

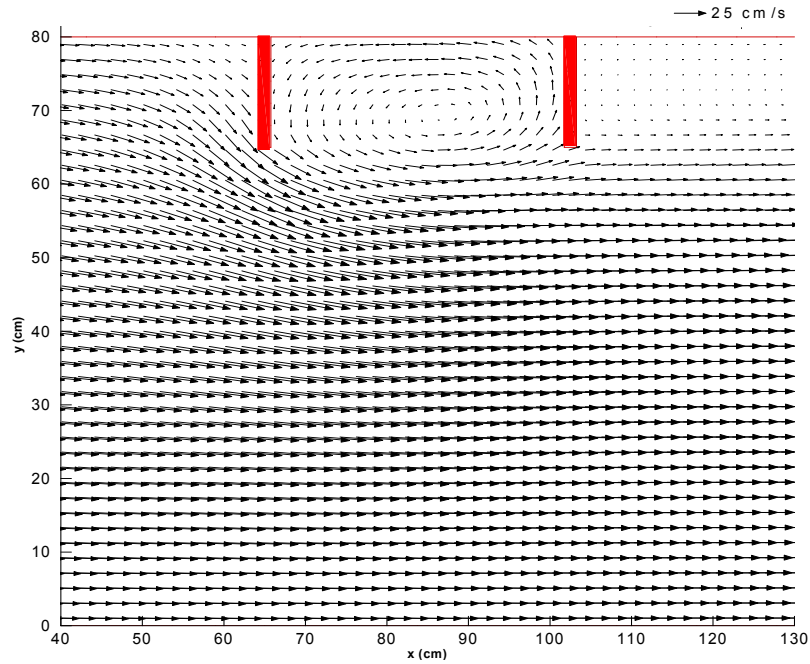


Figure 4.5 Velocity vectors around impermeable groins at water surface - Case 1 (simulation)

Figures 4.6 and 4.7 show the similarity between the computed and measured flow pattern at $z=2.0\text{cm}$ (half of flow depth) for impermeable groins on non-submerged condition. Several features expected on flow structures through a channel with impermeable groins are evident in these figures. First, the maximum velocity through the flume occurs at the right side of the channel corresponding to the main channel area due to the reduction of cross-section area caused by the presence of the groins. Second, the reduction of velocity magnitude inside the groins field (embayment area) due to the blockage of flow by the upstream groin and the recirculation current formed by the flow separation at the upstream groin head.

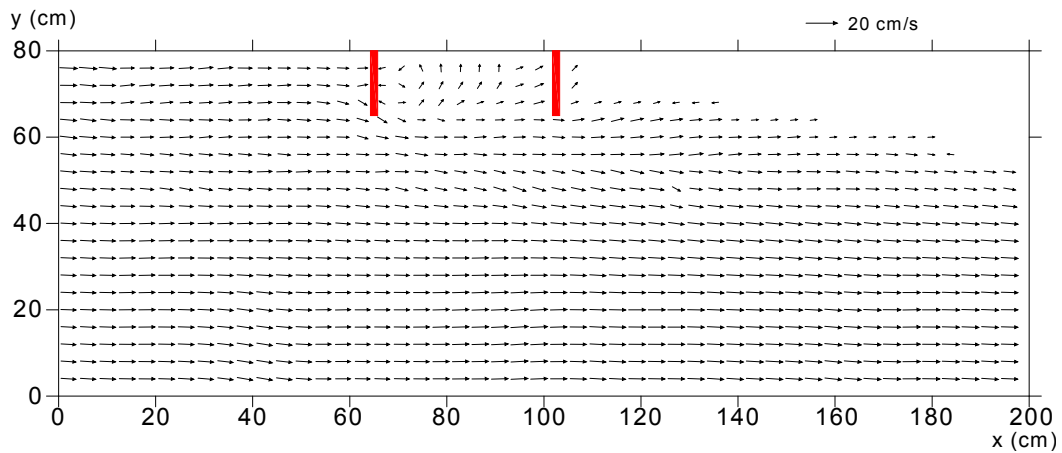


Figure 4.6 Velocity field around impermeable groins in plane XY at $z=2.0\text{cm}$ – Case 1 (experiment)

The calculated flow distribution shows clearly the details of flow structures when compared with measured data due to the fine mesh adopted in the area around the structures during the calculations (see Figure 4.1). Observing the flow passing near the groins field, it can be seen a reduction of flow velocity at downstream of groins. The magnitude of flow velocity reduces after passing this area due to the flow redistribution in the flume width. At downstream of groins field, the flow patterns return to the longitudinal direction. The simulated flow distribution shows reasonable agreement with experimental results, in which the strong three-dimensional flow around the groins field was verified.

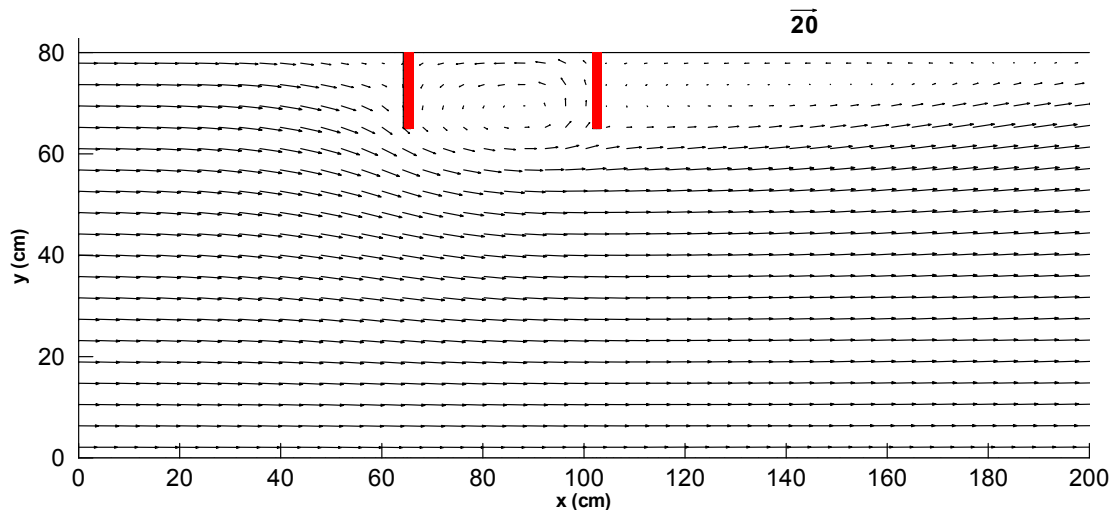


Figure 4.7 Velocity field around impermeable groins in plane XY at $z=2.0\text{cm}$ – Case 1 (simulation)

In Figures 4.8 and 4.9, the transverse cross-section at upstream of groin A (2.25cm upstream of groin face) shows the formation of downward flow and a vertical vortex due to the blockage of flow by the impermeable groins which can be observed in both experimental and simulated results. The increase of main channel flow velocity can be explained through these figures where the volume of water deviated from the left side (right side of the Figures 4.8 and 4.9) by the groins towards to the right side of straight channel, which corresponds to the main channel region in the transverse cross-section.

The longitudinal section in Figures 4.10 and 4.11 also show the downward flow at upstream of both groins. Whereas the flow near the groin B resulted mainly by the recirculation currents formed by the flow separation at toe of groin A, the intensity of flow velocity is very weak compared to the main channel flow.

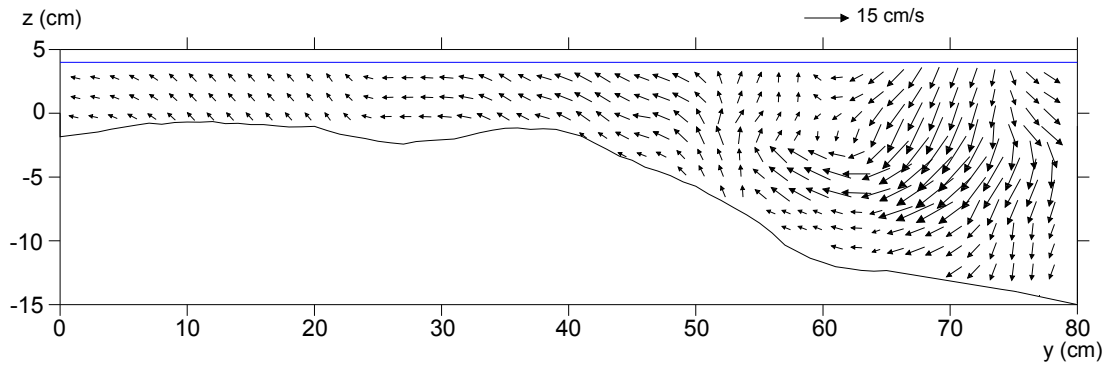


Figure 4.8 Velocity field around impermeable groins in plane YZ at $x=62.0\text{cm}$ – Case 1
(experiment)

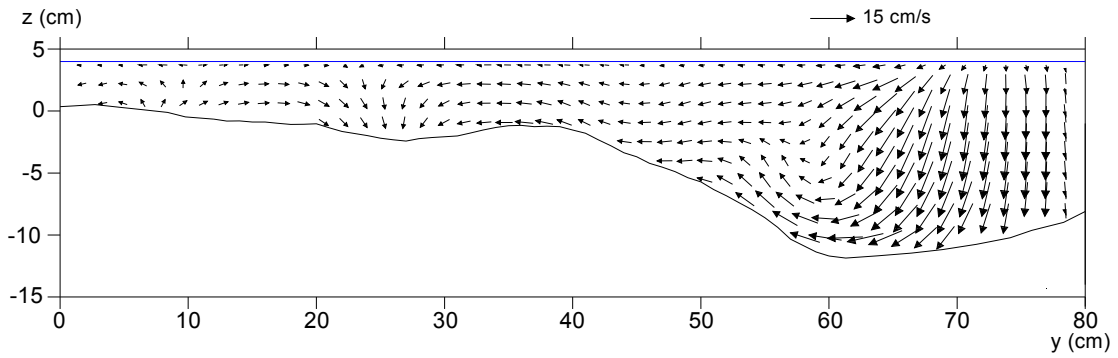


Figure 4.9 Velocity field around impermeable groins in plane YZ at $x=62.0\text{cm}$ – Case 1
(simulation)

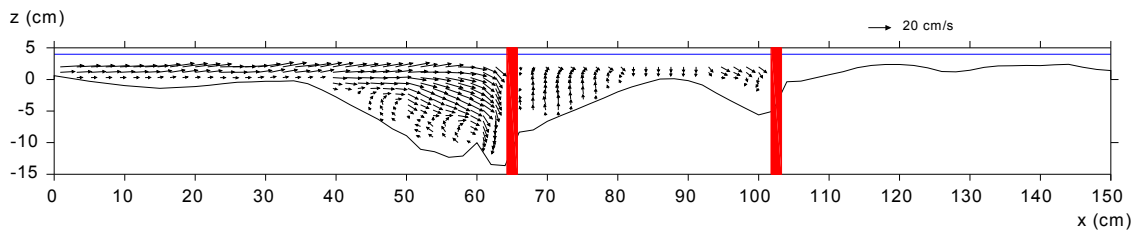


Figure 4.10 Velocity field around impermeable groins in plane XZ at $y=72.0\text{cm}$ – Case 1
(experiment)

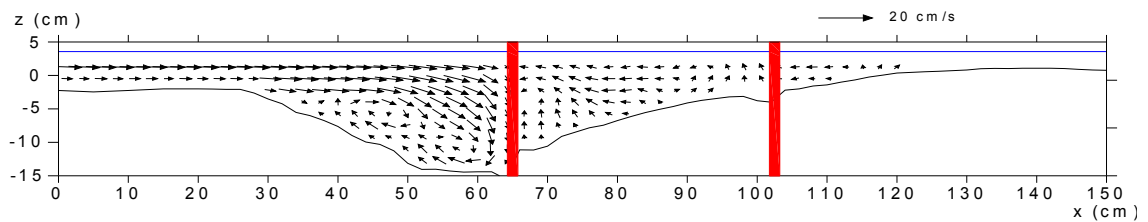


Figure 4.11 Velocity field around impermeable groins in plane XZ at $y=72.0\text{cm}$ – Case 1
(simulation)

In the permeable groins case, it can be seen the similarities between the experimental and simulated results. The reduction of flow velocity due the passage of flow through the piles and the weakly flow separation characterized by the diverted flow from the upstream permeable groin head are showed in the Figures 4.12 to 4.15.

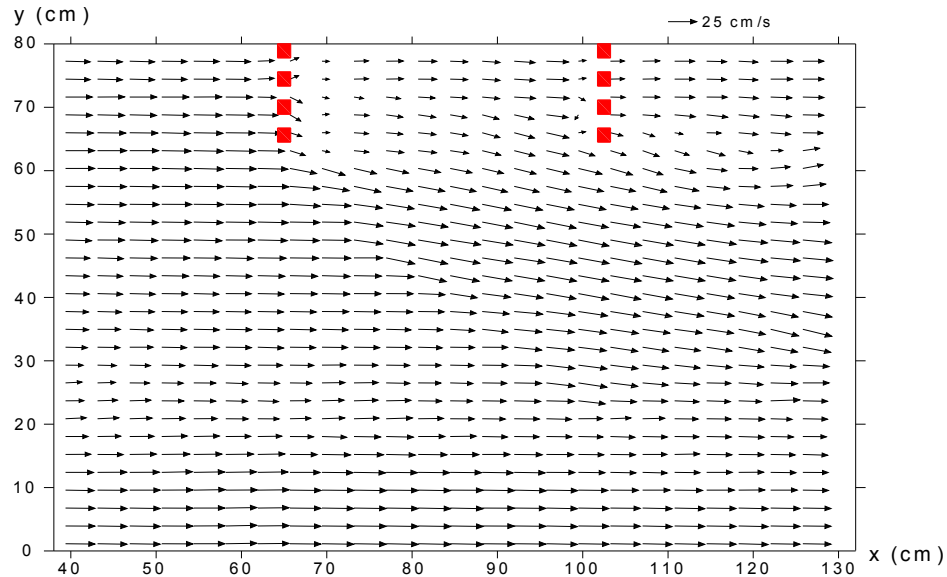


Figure 4.12 Velocity vectors around permeable groins at water surface by PIV - Case 2
(experiment)

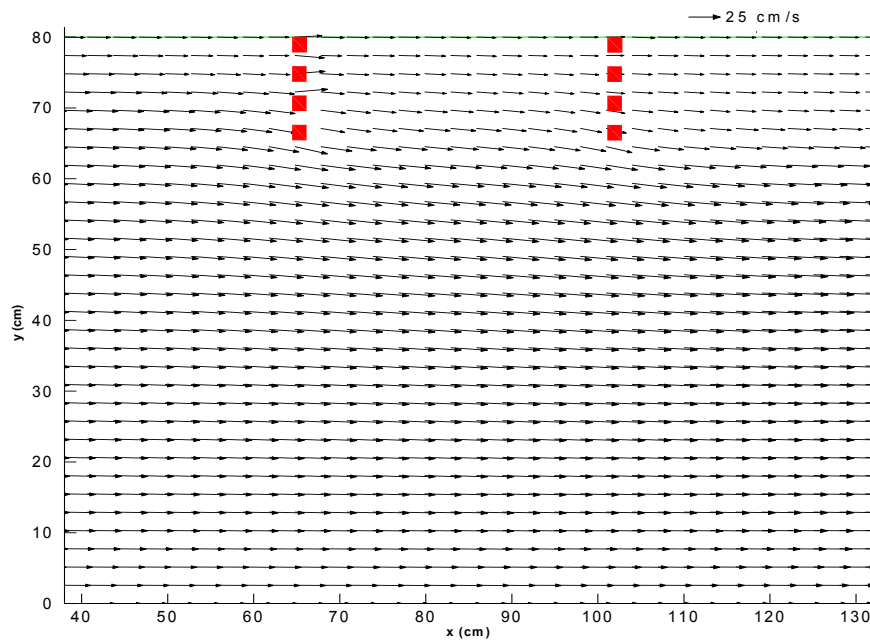


Figure 4.13 Velocity vectors around permeable groins at water surface - Case 2 (simulation)

Compared to the impermeable groins cases, the recirculation currents cannot be formed in between the groins near the water surface and the flow direction is practically parallel to the

flow direction (Figures 4.12 and 4.13). This fact added to the reduction of velocity in this area minimizes the possibility of flow towards to the side wall. In the present experiment, the permeability of this groin was fixed in 50%, however changing this permeability it is possible to obtain different levels of flow reduction and flow separation depending on the purpose of each study. The measurements of flow field at vertical cross-section was realized in the permeable groins case, however due to the passage of flow through the structures the similar flow patterns visualized on impermeable case can't be seen. Thus, the transverse cross-sectional velocity patterns don't appear in this section.

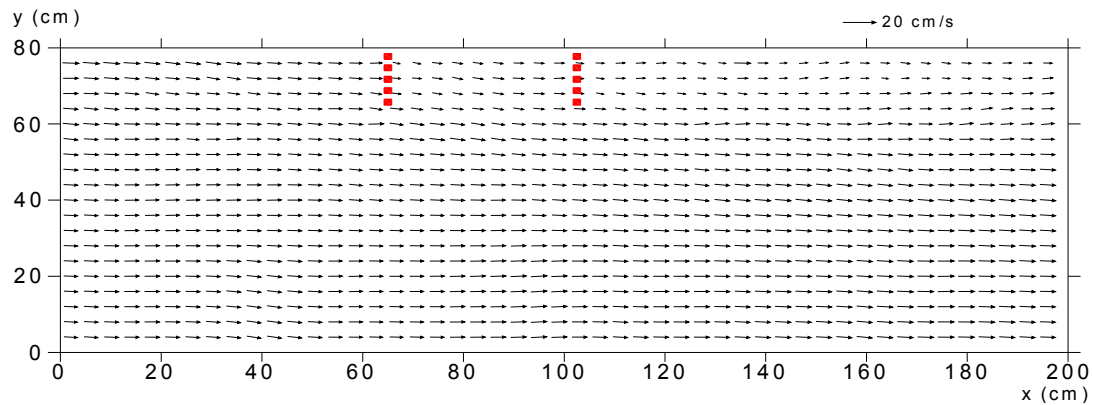


Figure 4.14 Velocity field around permeable groins in plane XY at $z=2.0\text{cm}$ – Case 2 (experiment)

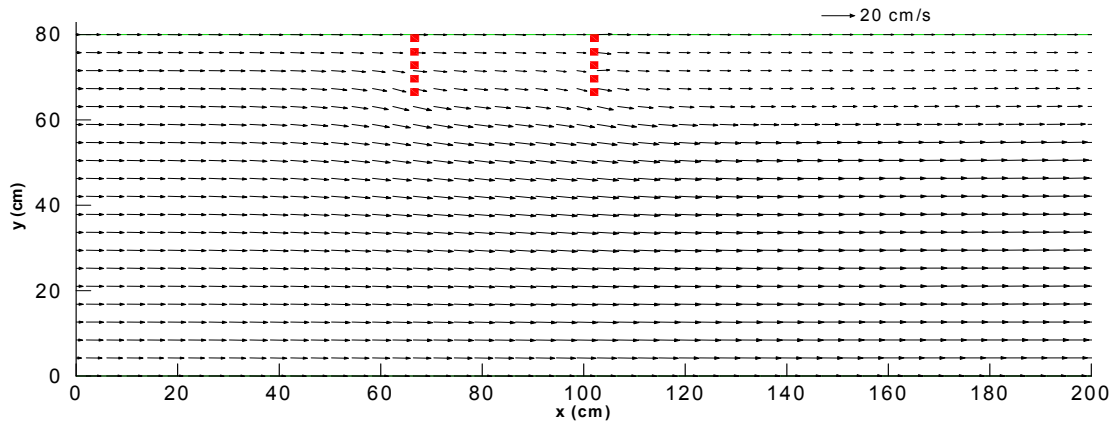


Figure 4.15 Velocity field around permeable groins in plane XY at $z=2.0\text{cm}$ – Case 2 (simulation)

Analyzing the flow structures in the bandal-like structures case, it can be verified some differences in the comparison with the impermeable and permeable groins cases due to the particular geometry of this structure with the upper part closed (impermeable) and the opened lower part (permeable). The flow near the water surface (Figures 4.16 to 4.19) mainly towards to the main channel as the impermeable groins case, however the downward flow formed in the

previous case appears with weak intensity due to the effect of the bended plate (Figures 4.20 to 4.23) which towards this flow to the main channel. And the flow passing at lower opening avoids the formation of return currents at downstream of bandal-like structure which results in a good effect of this structure to the bank protection. Moreover, the flow passing through the structure is deviated towards the main channel increasing the magnitude of flow over there.

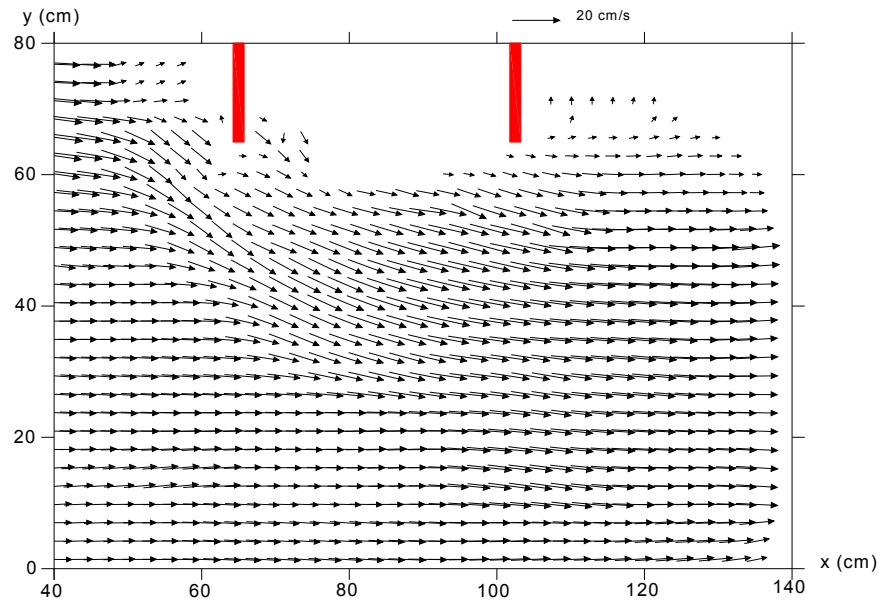


Figure 4.16 Velocity vectors around bandal-like structures at water surface by PIV - Case 3
(experiment)

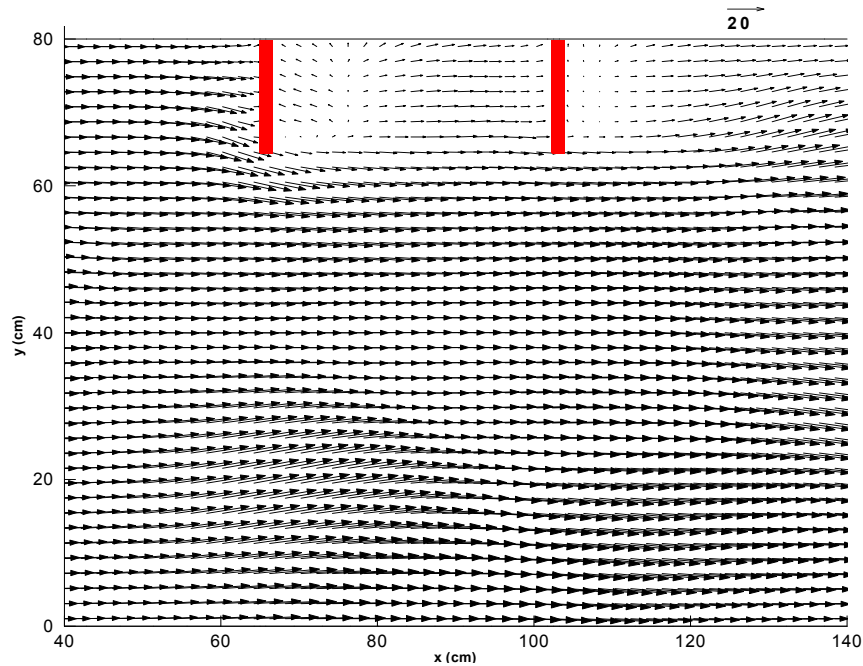


Figure 4.17 Velocity vectors around bandal-like structures at water surface - Case 3
(simulation)

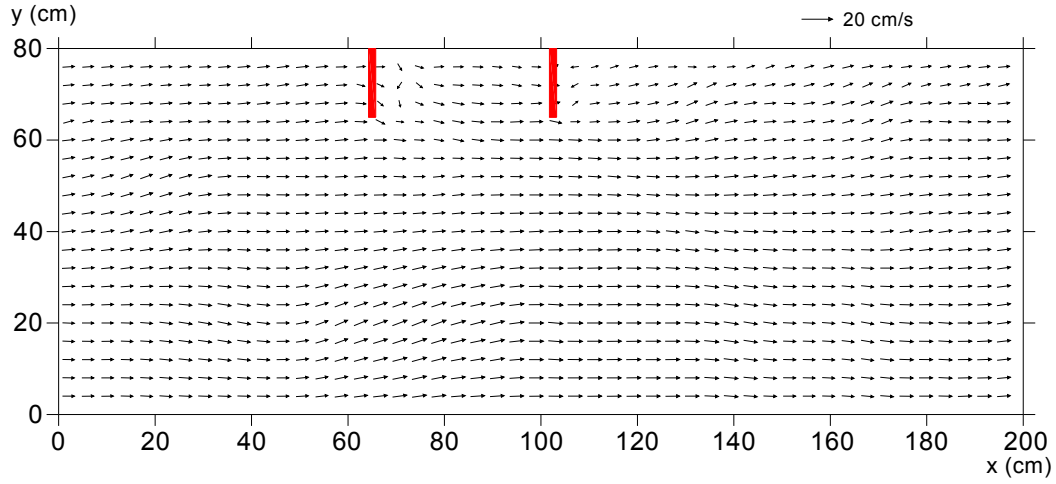


Figure 4.18 Velocity field around bandal-like structures in plane XY at $z=2.0\text{cm}$ – Case 3 (experiment)

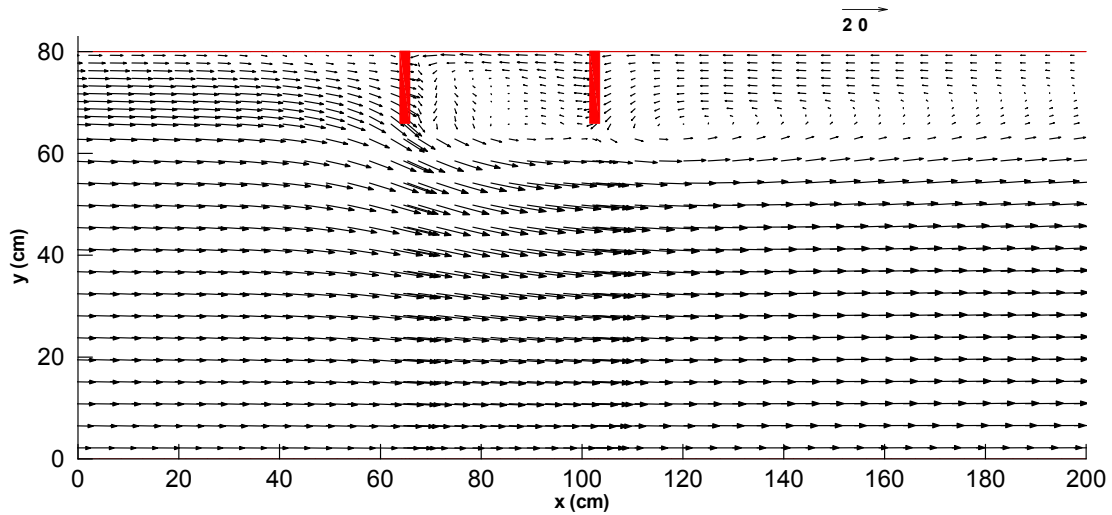


Figure 4.19 Velocity field around bandal-like structures in plane XY at $z=2.0\text{cm}$ – Case 3 (simulation)

Figures 4.20 and 4.21 show the transverse cross-sectional flow vectors at upstream of bandal A (upstream one). From these figures the downward flow is clearly observed due to the effect of upper plate which blocks the passage of flow near the water surface and towards it to the main channel direction.

In the simulated result the flow is mainly deviated to the main channel direction (right side of Figure 4.20), however in the experiment due to the bed deformation at right side of channel, it can be seen flow in the opposite side, i.e. from right to left side. Of course to represent this kind of flow pattern the model needs improvements as the consideration of free surface variation or the non-linearity of turbulence model which may be influenced the formation of flow structures

similar to the experimental results.

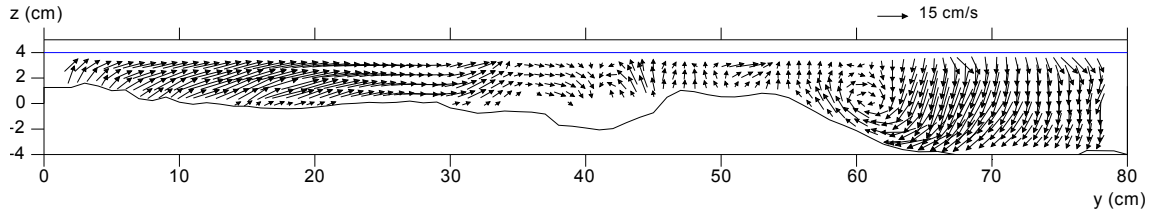


Figure 4.20 Velocity field around bandal-like structures in plane YZ at $x=62.0\text{cm}$ – Case 3 (experiment)

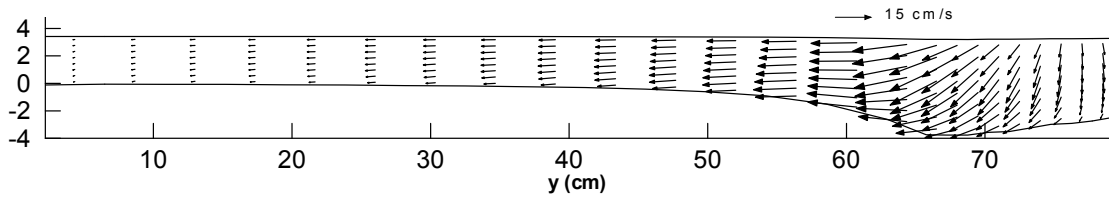


Figure 4.21 Velocity field around bandal-like structures in plane YZ at $x=62.0\text{cm}$ – Case 3 (simulation)

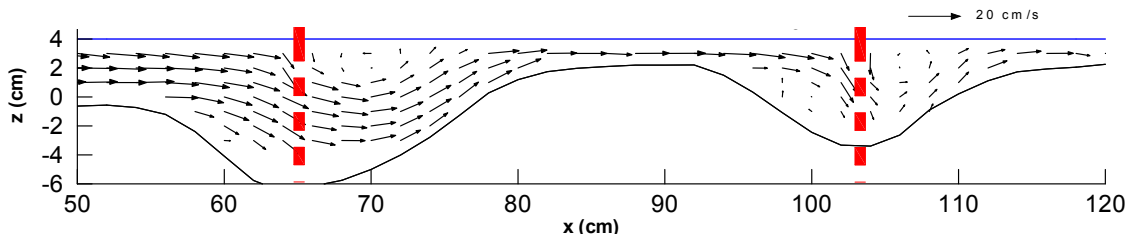


Figure 4.22 Velocity field around bandal-like structures in plane XZ at $y=72.0\text{cm}$ – Case 3 (experiment)

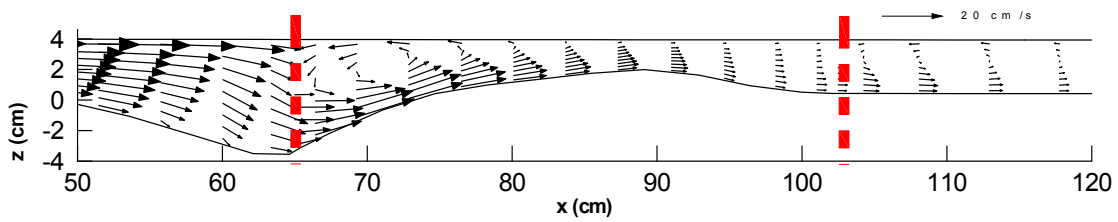


Figure 4.23 Velocity field around bandal-like structures in plane XZ at $y=72.0\text{cm}$ – Case 3 (simulation)

4.2.2 Bed deformation

The bed changes around the structures was calculated considering, firstly only the bed load transport rate in the sediment transport model, and after that including the suspended load transport to verify the influence of suspended sediment in the deposition/erosion process, especially near the structures field. In this subsection, the numerical results of the bed

deformation are analyzed for the different types of structures (bandal-like structure and groins).

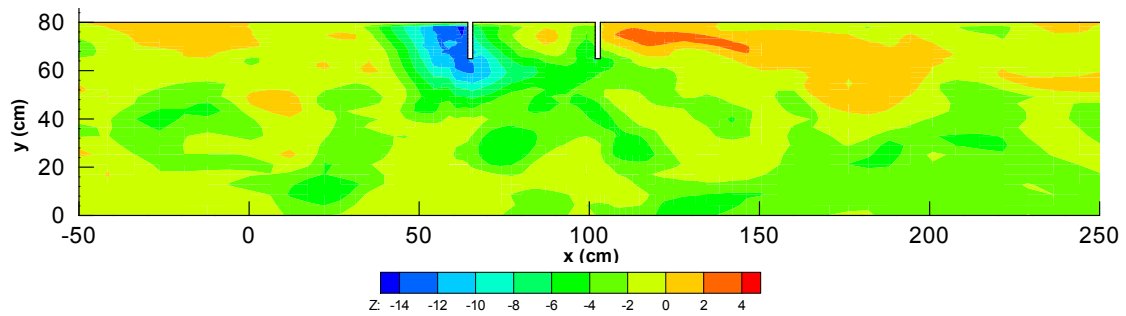


Figure 4.24 Bed contours at equilibrium condition – Case 1 (impermeable groins) – Experiment

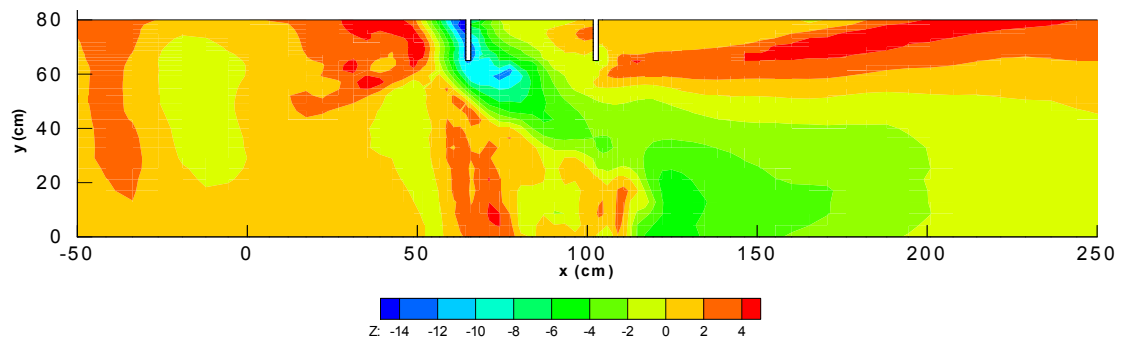


Figure 4.25 Bed contours at equilibrium condition – Case 1 (impermeable groins) – Simulation considering only bed load transport

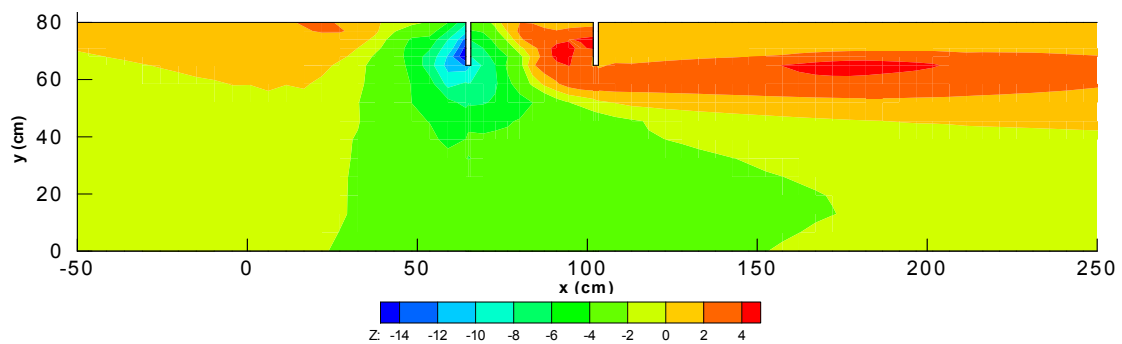


Figure 4.26 Bed contours at equilibrium condition – Case 1 (impermeable groins) – Simulation with bed load and suspended load transport

The bed deformation for impermeable groins case shows clearly the effect of the groins on the flow patterns which affects the sediment transport mechanism. From the results below, it is possible to verify some similarities between the experimental (Figure 4.24) and simulation results (Figures 4.25 and 4.26) as the deeper erosion at the toes of the groins due to the blockage of flow and the formation of downward flow and horse shoe vortex which accelerate the erosion

over there. Also, the previously described flow separation (Figure 4.4 and 4.5) occurs at groins toe, especially at upstream groin, which form a mixing zone between the groins field and the main channel. The flow deviated to the main channel direction increases the bed degradation and contributes to the formation of deep main channel for navigation purposes.

The differences between the experimental and numerical results can be seen clearly in the bed features around the structures. It can be seen the local scour area at groin A resulted small in the simulations for both cases, i.e. simulations considering only bed load transport and total load transport (bed load and suspended load transport). Probably, it is due to the commented drawback of standard $k-\epsilon$ model as the assumption of isotropic eddy viscosity. It is not able to reproduce clearly the turbulence-driven secondary flows in the region at upstream of groin caused by the formation of downward flow and horse shoe vortex. The deposition of sediments in between the groins and at downstream of groin B is common place in all cases due to the reduction of flow velocity and the return currents formed at downstream of the groins. However, the volume of deposited sediment is a little different in each case. In the experiments probably the supplied sediment amount is not uniformly distributed in all flume width during the running because it was made manually. On the other hand, the simulations are realized considering the supplied sediment equal to the experiments uniformly distributed in the channel width and in time during the experiment.

The permeable groins cause small disturbances in the flow and consequently in the bed deformation which results more or less uniformly in entire flume (Figure 4.27). Of course, in the left side due to the presence of groins (piles) the occurrence of erosion around the structures and deposition near the side wall, especially at downstream of groins B is very clearly in the experiment result.

The computational bed level changes in Figures 4.28 and 4.29 show quite similar effect with deposition/erosion occurring distributed in all flume width at upstream and downstream of permeable groins field, in which the main disturbance is clearly seen around the groins. It is possible to verify the very small erosion around the groins piles and the deposition in between and at downstream of groins due to the reduction of velocity of flow passing through the groins.

The differences between the simulations considering only the bed-load transport and total load transport are very similar due to the hydraulic conditions used in this case is not suitable to the occurrence of high concentration of suspended sediment ($u^*/w_s = 0.57$). In the next step, the submerged condition described in Chapter 2 should be simulated to verify the influence of suspended sediment on bed deformation around permeable groins.

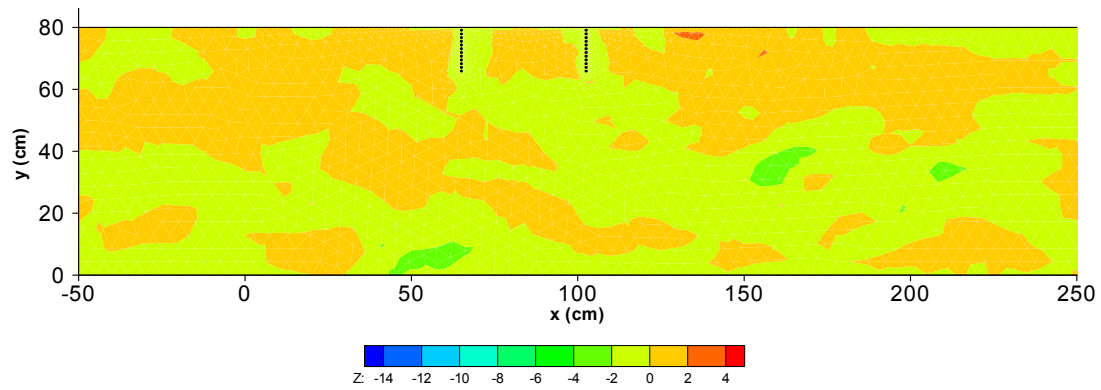


Figure 4.27 Bed contours at equilibrium condition – Case 2 (permeable groins) - Experiment

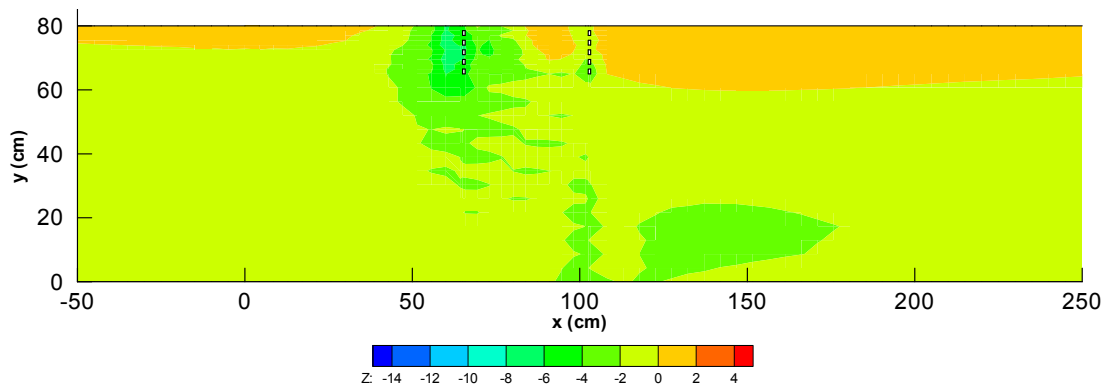


Figure 4.28 Bed contours at equilibrium condition – Case 2 (permeable groins) – Simulation considering only bed load transport

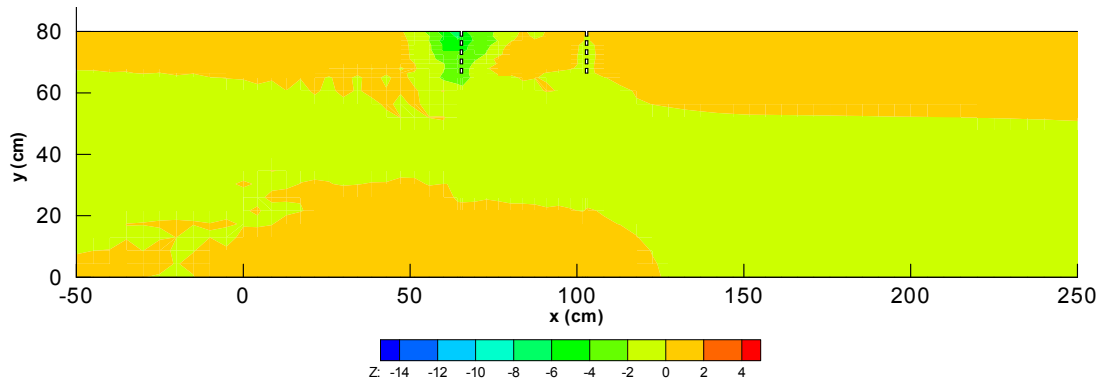


Figure 4.29 Bed contours at equilibrium condition – Case 2 (permeable groins) – Simulation with bed load and suspended load transport

The bandal-like structure case in Figures 4.30, 4.31, and 4.32 show the effect of structure geometry on bed changes around them. As described previously, the erosion around the structure A (upstream one) results very small in deep and occupied area due to the effects of lower permeable part. Another important point resides on the main channel degradation due to the flow separation at bandals toe which towards the near surface flow with high velocities to

the main channel direction.

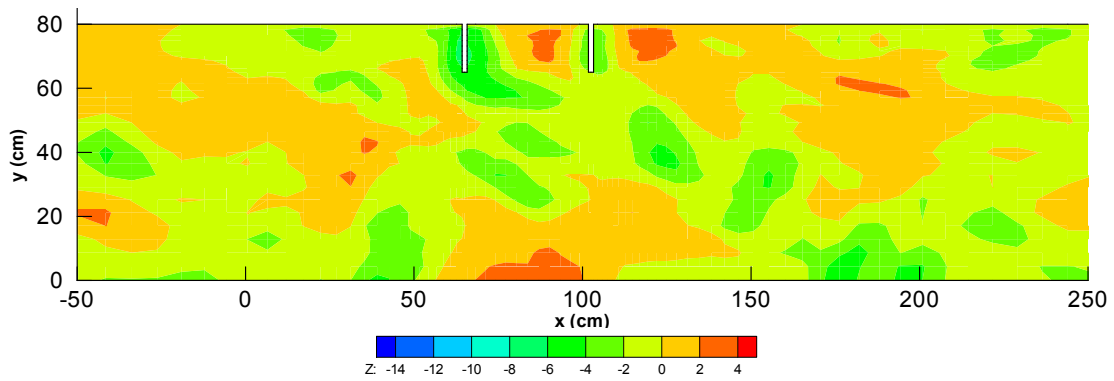


Figure 4.30 Bed contours at equilibrium condition – Case 3 (bandal-like structures) – Experiment

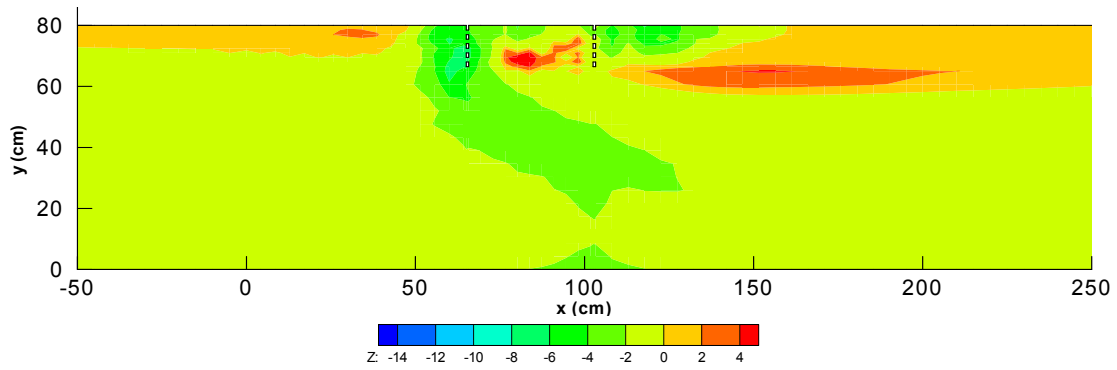


Figure 4.31 Bed contours at equilibrium condition – Case 3 (bandal structures) – Simulation considering only bed load transport

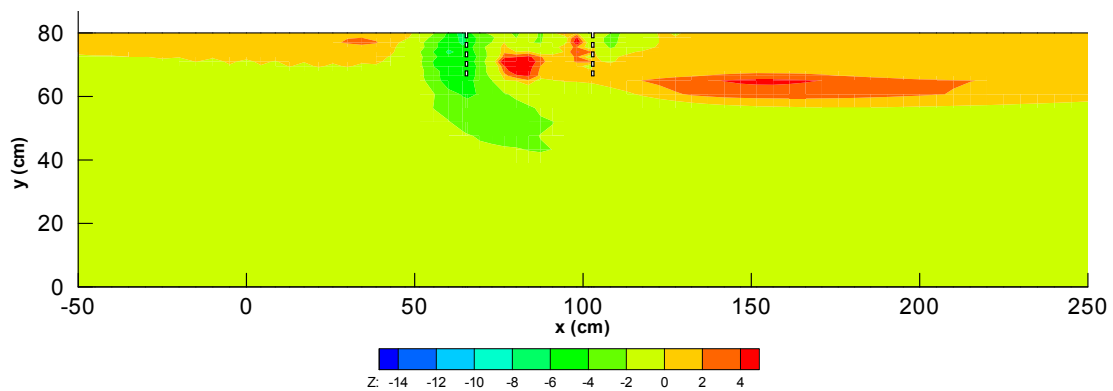


Figure 4.32 Bed contours at equilibrium condition – Case 3 (bandal structures) – Simulation with bed load and suspended load transport

In simulated results the latter features is not so clearly visualized, probably the reason is related to the computational mesh utilized during the calculations in which to reduce the

computation time the permeable lower half part were represented using piles with same permeability but different diameter. Thus, the volume of flow deviated to the main channel probably is different to that observed in the experiments.

The bed features results of simulations considering the total load transport do not shows significant differences compared with the case using only bed load calculation. Only, the maximum scour depth around the structure A (upstream one) shows deeper erosion in the simulations (see Table 4.2) compared to the measurements.

Table 4.2 Maximum scour depth around structure A (upstream one)

Type of structure			Impermeable groins	Permeable groins	Bandal-like structure
Case			1	2	3
Submergence condition			Non-submerged	Non-submerged	Non-submerged
Local scour depth (cm)	Experiment		14.33	3.12	6.72
	Simulation	bed-load	14.97	4.15	7.04
		bed-load and suspended load	15.08	5.18	8.39
Ratio calculated/measured (bed-load)			1.045	1.330	1.047
Ratio calculated/measured (bed load and suspended load)			1.052	1.660	1.248

4.3 Applicability of bandal-like structures

In current days, the knowledge of the river training works is mainly focused on the conventional structures as groins (or spur-dikes), revetments, weirs, etc., due to the great number of studies which can provide a number of data necessary to guide the correct and optimized utilization of these structures in the field applications. According to this point of view, the utilization of bandal-like structures as an alternative method for river training works still need more studies, especially in the field applications to verify the performance of this structure under real conditions. However, analyzing the results showed in Chapter 2 (experiments) and in previous section, it is possible to verify that bandal-like structure has a promising applicability in place of conventional structures as impermeable groins to minimize the erosion around the structure and near the riverbank as well as to create a deep main channel for navigation purposes.

As commented in previous chapters, in the last decades many researches was conducted considering the effects of hydraulic structures on channel flow and the bed features resulted

from that interactions. However, most of them are concentrated in conventional structures as groins (Garde et al., 1961; Rahman and Muramoto, 1999), especially impermeable ones. Few studies with permeable structures (Nasrollahi et al., 2008) or other type of structure were realized. Then, a detailed investigation of bandal-like structure is an important step to the development of alternative techniques which can solve the recently demand of low cost solutions that causes a minimum impact to the environment and is suitable to be utilized in various places under different hydraulic conditions.

Similar flow features have been found in the experiments with bandals carried out by other researchers (Rahman et al., 2004; Rahman et al., 2006). In their studies, it was found that under clear-water condition the bandal-like structure can minimize the occurrence of riverbank erosion due to the particular geometry of the structure which comprises an impermeable part at the upper half portion and a permeable part at the lower half portion. They investigated in their experiments the effects of a series of bandal-like structures positioned in both sides of a flume (ten pairs) with an angle of 40° to the side wall oriented to downstream direction. They emphasized the local scour hole around the structures and developed an analytical model to predict that erosion. The results showed reasonable accuracy compared to the experimentally measured scour depths. However, they pointed out the necessity to investigate different conditions as the live-bed scour condition to clarify the details involved in the bandal-like structures utilization.

From experimental and numerical analyses, it is found that bandal-like structures are capable for flow diversion towards the main channel leading to the formation of deeper navigational channel. On the other hand, flow velocities are reduced near the bank lines that ensure protection of riverbank. In addition, the local scour around these structures are much less than that in the impermeable groins case. Therefore, bandal-like structure would be less expensive solution over conventional methods.

The formation of deep main channel for navigation purposes is one of the main objectives to use river training structures as groins. However the impacts caused by the different types of groins in river channel should be considered under various aspects. One is the local scour around the structure which can compromise the safety of the structure or the maintenance of the river scenery without drastic interventions. Considering these kinds of aspects the performance of bandal-like structures concerning the main channel degradation is analyzed in comparison with groins (impermeable and permeable ones) and provides good perspectives to solve such kind of problems.

4.3.1 Comparison of deposition/erosion volume

A simple verification of these results can be done through the comparison of the

deposition/erosion volume around the structures between the experimental and simulated results.

Considering the length of the structure as a parameter, in Figure 4.39 were delimited 3 (three) areas. These were separated in the erosion area around the structure A (Area 1), the deposition area at downstream of both structures (Area 2) and another area at main channel (Area 3) which describes the eroded area for navigation purposes.

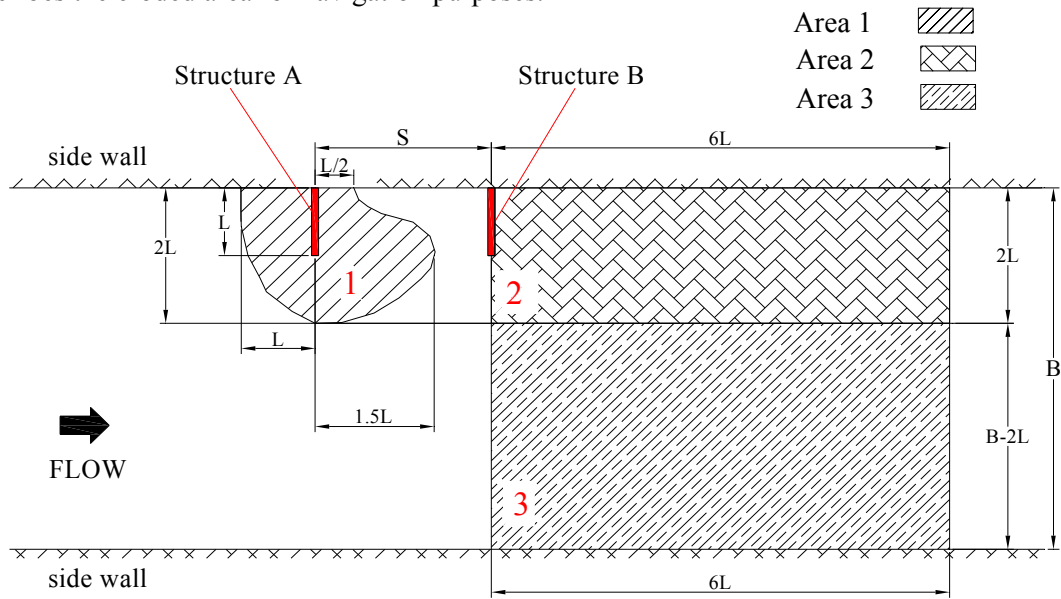


Figure 4.33 Division areas around the structures for comparison of deposition/erosion process

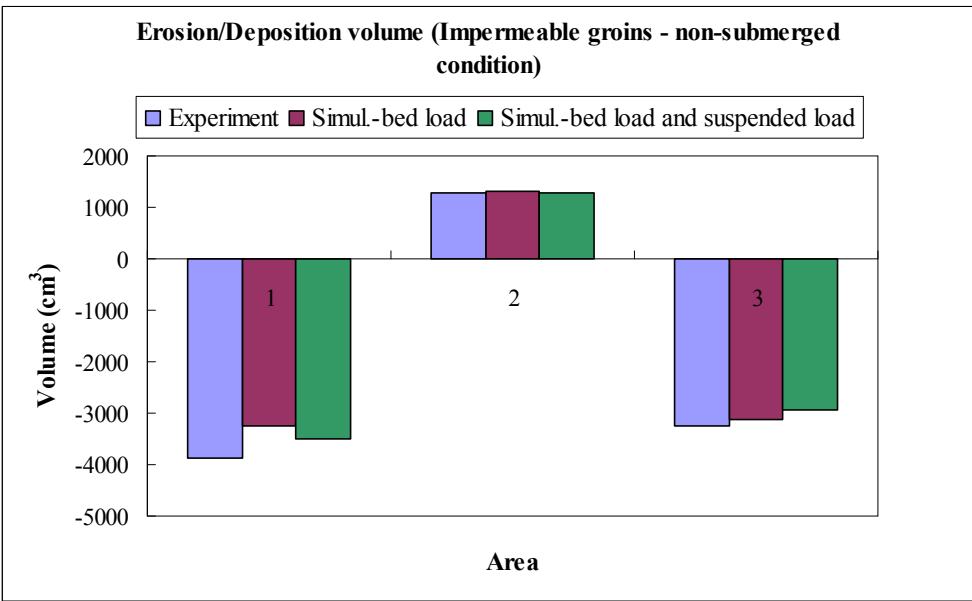


Figure 4.34 Comparison of deposition/erosion volume around impermeable groins with experimental and simulated data – Case 1

The compared results for each type of structure are shown in Figures 4.40, 4.41 and 4.42, respectively. In all cases the eroded sediment volume around the structure A (Area 1) resulted similar in each different structure in which the experimental ones are biggest followed by the simulation considering the total load (bed-load and suspended load) transport and then the simulations using only bed-load transport in the sediment transport model. As discussed previously, the bandal-like structure can reduce the erosion around the structure.

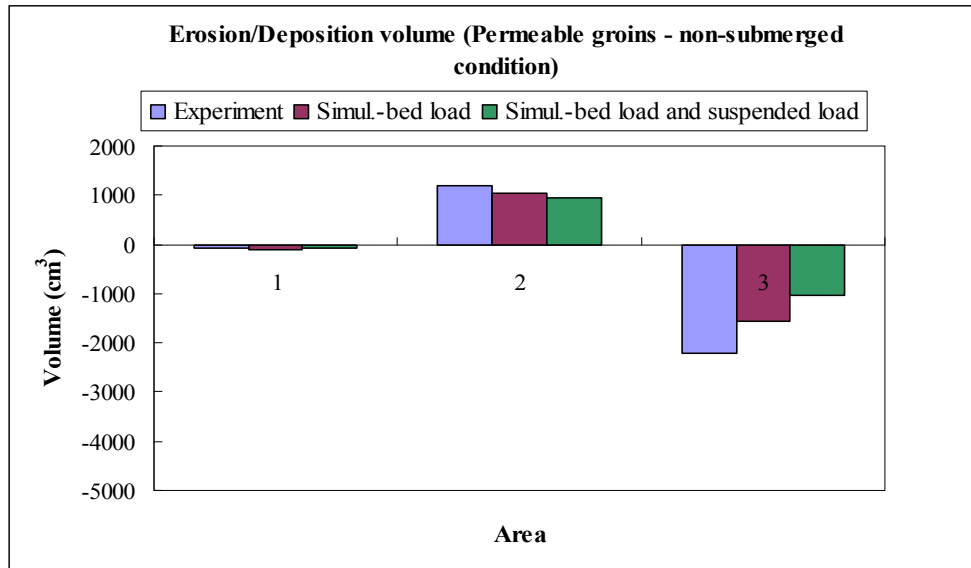


Figure 4.35 Comparison of deposition/erosion volume around permeable groins with experimental and simulated data – Case 2

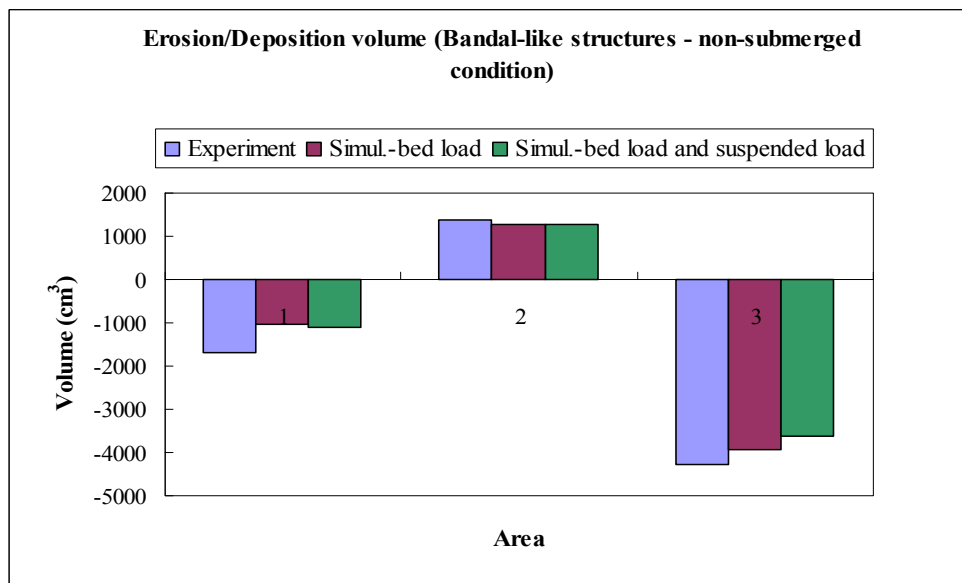


Figure 4.36 Comparison of deposition/erosion volume around bandal-like structures with experimental and simulated data – Case 3

Analyzing the Area 2 related to the deposition area at downstream of both structures the results are very similar. In this area, the experimental measurements shows the biggest volume probably due to the commented sediment supply in the experiments was done by hand which could affect the uniformity of sediment supplied in the flume width. However, the differences in the simulated results are very small proving that the effect of supplied sediment is not so critical to the final bed deformation.

At the main channel, the expected erosion due to the effect of flow separation at structures toes which causes the deviation of flow to the main channel (right side of the channel) is increased in the bandal-like structures. This result can be interpreted with the action of upper bended plate which contributes to increase the deviated flux towards the main channel and the eroded sediment around the bandals was deposited at downstream of structures. In the impermeable groins field, due to the blockage of flow by the structure, part of eroded sediment around the groins was deposited in the main channel covering the bed degraded by the flow.

Further investigations are necessary to confirm these results by other experimental studies with suspended sediment concentration measurements to compare with the simulated results and other tests considering different cases as the submerged condition in which the influence of submergence of the structure can be also verified.

4.3.2 River channel stabilization

The utilization of bandal-like structures as a river channel stabilization method was discussed by Rahman et al., 2004 with emphasis on the applicability as a gradual stabilization solution for long-term basis.

The conventional structures as impermeable groins usually are used to solve local problem in a short-term solution for riverbank protection. However, in large scale alluvial rivers the local effects caused by these structures are not suitable for the overall stabilization of river channels. Thus, bandal-like structure represents an alternative method for river stabilization that will be friendly to the environment and create minimum disturbance to river channels.

A gradual encroachment towards the lateral direction (main channel direction) using bandal-likes structures create small disturbances in the river flow and allowing a sufficient time for its adjustment to the changes on flow and bed morphology. The river response against such small intervention will be comparatively less than that the sudden interventions caused by structures as impermeable groins constructed at one time. The described method can be more suitable than conventional methods for restoration of river channel where deep and narrow main channels are required (Shields et al., 2003).

In Photos 4.1 and 4.2, it can be seen a pilot project in which the effectiveness of bandal-like

structures to serve as a gradual stabilization method for alluvial rivers are tested. This test site is located at the Jamuna River in Bangladesh. The information obtained from this kind of field observations will be an important step to optimize the utilization of bandal-like structures as a promising solution for river channel stabilization.



Photo 4.1 Bandal-like structures for river channel stabilization at Jamuna river – Bangladesh (January, 2010) – upstream side view



Photo 4.2 Bandal-like structures for river channel stabilization at Jamuna river – Bangladesh (January, 2010) – downstream side view

4.4 Summary

In this chapter, the proposed numerical model in Chapter 3 has been applied to simulate the flow patterns and bed level changes in a straight flume with hydraulic structures. A comparatively analysis of experimental and simulation results is made to verify the applicability of numerical model to simulate the flow patterns and bed deformation around the structures. The inclusion of suspended sediment load constituted in a new challenge due to the complexity of sediment transport, particularly when involving the presence of structures as bandal-like structures which cause the formation of complex flow structures compared to the straight channel without any structure.

The bandal-like structures show a different and interesting flow structures compared to the other types of structures due to the characteristics of its unique geometry. In particular, the flow passing through the lower half part of the structure avoids the formation of recirculation currents at downstream of the structures. The reduced flow velocity near the bank ensures bank protection at this point. Bandal-like structures are also capable for flow diversion towards the main channel leading to deep navigational channel formation. Also, the local scour depth is significantly smaller as compared with the conventional structures such as impermeable groins, and bandals would be less expensive and suitable for preserving or restoring river environment.

In the simulations, the flow structures compared to the experiments showed reasonable agreement as the disturbance caused by the recirculation currents in between the structures for the impermeable groins case in the horizontal plane. Also, the vertical vortex formed at upstream of the groin A due to the blockage of flow by the structure and the formation of down flow is well represented. In these cases, the shape of the structures is different and relatively complex, then the utilization of a model based on an unstructured mesh may be a good solution. From the calculations, many details of flow structure measured in the experiments have been verified. The bed morphology at the equilibrium state is found to be reasonably reproduced, in which the calculated bed changes are similar to the experimental ones. However, the accuracy of local scour depth needs to be improved due to the model limitation. The commented drawback of $k-\varepsilon$ model which consider the isotropy of eddy viscosity especially near the structures can be responsible for these differences. More simulations under different flow conditions could be made to better understand this kind of problem. Another problem refers to the great time consuming of calculations which can be solved using other methods as the parallel computation.

The reference concentration as computed in the model is a function of the depth-averaged flow velocity. In the vicinity of the structures and along the normal line, the velocity is lower than that in the main channel. Accordingly, the sediment transport capacity drops significantly over a rather short distance. Moreover, the velocity inside the structures field is close to (even

below) the threshold of motion, leading to a transport capacity close to zero just inside the structures field and at downstream of both structures. Hence, across the normal line a very steep gradient takes place, leading to the abrupt deposition of the entire bed-load. The response of the suspended sediment to local equilibrium conditions is delayed due to lag effects. In the recirculation zone inside the groins field, the velocity decreases considerably and falls below the validity range of the model. Consequently, the concentration drops over a short distance to the local equilibrium concentration, which is already very low across the normal line. Hence, similar to the bed load, the entire suspended load deposits just across the normal line.

It can be said that the numerical methods provide an effective way to understand the details of the local flow structures and scour processes, some of which are very difficult to resolve if not impossible with only experimental methods.

Chapter 5

Conclusions and Recommendations

The characteristics of groin structures with the comparison of conventional structures as groins (impermeable and permeable) and bandal-like structures on straight channel were investigated in this research. The governing sediment exchange processes between the structures field and the main channel of a flume were identified and the effects of the bandal-like structures on channel bed were investigated through the movable bed experiments to study the details of the flow and bed deformation behavior in the vicinity of the structures. A three-dimensional numerical model was developed to simulate the influence of these structures on flow patterns variation and riverbed changes considering the bed-load and the suspended load transport. The conclusions based on the studied cases are to be interpreted within this context. These conclusions are summarized in the following section. The final section gives some recommendations for implementation and future research.

5.1 Conclusions

The results of the present study have been extensively assessed and discussed in the previous chapters. In the following, the most important conclusions are summarized.

Flow patterns near the structures

In the non-submerged cases, the flow inside the impermeable groins field (embayment area) can be characterized by a primary eddy that forms in the downstream area of the structures field, a secondary eddy driven by the primary one with an opposite sense rotation, and a dynamic eddy that frequently sheds from the tip of the upstream structure. The whole circulation is driven by the main channel via exchange of momentum through the interfacial mixing layer. The permeable groins due to the passage of flow through the structures (piles) avoid the formation of such return currents in the groins field (embayment area). Only a small reduction of flow velocity can be observed especially near the sidewall (riverbank), which does not affect the flow direction.

The bandal-like structure shows a complex 3D flow structure which can be described as the formation of downward flux due to the blockage of flow by the upper half plate which also towards the high velocity flow near the water surface to the main channel direction. The flow

which passes through the lower permeable portion contributes to avoid the formation of recirculation currents at downstream of structure. The flow deviated to the main channel induces the bed degradation at the main channel.

In the submerged stage, the flow in the area between the structures does not show clearly the recirculation currents as observed in non-submerged condition for impermeable groins. It can be characterized as a low velocity region. The mixing layer in this case shows an alternate accelerating and decelerating flow pattern between flow over and around the structures. The mixing layer between the main channel and the structures field differs between the non-submerged and submerged flow conditions. In the non-submerged condition, it originates from the tip of the structure, especially from the upstream groin, and grows in width towards the next structure at downstream. In the submerged condition, it has a rather constant width due to the continuous generation of turbulence by the structures, which keep the total turbulence intensity along the normal line at a high level.

The permeable groins case show very similar effect that is observed in non-submerged condition with more disturbance of flow at water surface.

In the bandal-like structures case, the overtopping flow does not affect significantly the flow separation at the upstream bandal head, only a small acceleration of flow at downstream can be verified. The downward flux due to the blockage of flow by the upper half plate occurs and the deviation of near surface flow towards the main channel direction can be verified clearly. The flow at lower permeable portion and the overtopping flow avoids the formation of recirculation currents at downstream of structure. Due to the higher discharge compared to the non-submerged case, the bed degradation in the main channel resulted deeper and bigger in size proving that under submerged condition the bandal-like structures can provide similar bed features observed in non-submerged condition.

Interaction between the structures and riverbed

The mechanisms of sediment transport into the groins field differ according to the flow stage. In the non-submerged condition, the sediment is mainly advected towards the groins field following the direction of the primary recirculation cell. In the submerged case, the sediment is transported to the groins field across the whole length of the normal line, primarily by residual advective transport by large-scale coherent structures. Diffusion through the mixing layer and secondary flow circulation play a minor role in this case.

The bed deformation patterns resulted from the utilization of different types of structures were analyzed and discussed in the previous chapters. Comparing all cases, the bandal-like structures showed promising results as the reduction of erosion around the structures and consequently near the riverbank, and the deposition of transported sediments at downstream of bandals which can

be useful to planning river restoration projects. Also, the results of bed degradation forming a deep main channel are required for utilization of rivers as navigational channels.

Modeling of flow patterns and bed deformation process

In the case of a river with structures as bandal-like structures, it is important to use a numerical model that has the capacity to solve large-scale time-dependent turbulence structures caused by the interaction between the structures and main flow. Consequently, it is possible to reproduce the channel bed features associated with bandal-like structures and groins. The large eddies which form at the interface between the main channel and the structures field are an important mechanism underling the typical structures-induced bed pattern.

The numerical model described in the Chapter 3 was used to simulate the flow patterns and bed deformation around the bandal-like structures and groins. From the results showed in Chapter 4, it can be discussed that the model represents with acceptable agreement the flow structures and bed features around the groins under non-submerged conditions. However, in the case of bandal-like structures due to the complexity of the flow patterns around the structure, the simulations using movable bed conditions didn't show good results. Other tests are needed to confirm the applicability of the numerical model as the simulations for submerged cases.

Comparison of model predictions with experiments shows promising agreements, although the parameters investigated are limited due to the constraint of extremely time-consuming three-dimensional flow calculations. Thus, an improvement in the numerical model as the parallel computation is needed to minimize this problem.

Applicability of bandal-like structures in river channels

The bandal-like structure showed good performance to minimize problems that are usually encountered in river channels. This structure can be used to reduce the problem of riverbank erosion keeping away the flow patterns that can attack the bank and for the maintenance of navigational conditions of river channels as the necessary water depth and cross-sectional section.

Analyzing the characteristics of bandal-like structures showed in the results through the present dissertation, it is suggested the utilization of bandals not only for riverbank protection as extensively commented in this thesis but also to stabilize river courses for long-term bases in a step by step manner (Rahman et al., 2004). They discussed that the bandal-like structure can be extended gradually as a lateral intervention causing less disturbances in the large-scale alluvial rivers than the conventional structures as impermeable groins or revetments which are useful for

solution of local problems. Pilot projects in the field are very important to verify these solutions in real conditions.

5.2 Recommendations for future researches

This work has led to a better understanding of several important issues related to the design and assessment of bandal-like structures and details of flow patterns and sediment transport affected by these structures. It has also verified the development of a numerical model to serve as a tool to predict the flow patterns and bed morphology around the structures. For instance, the model proposed in this work need additional testing and development. In this optic, computations on more practical configurations and systematic investigation would be necessary, and the model must account for the importance of the free surface variation. The application of the non-equilibrium models in non-homogeneous flows and their characterization still remains a task to be performed. The parallel version of numerical model will be an asset to reduce computational effort and cost when simulating suspended sediment transport and bed morphology. Below are some suggested issues for subsequent and future investigations.

Experimental and field investigations

The necessity of additional studies related to the utilization of bandal-like structures is pointed out in this thesis contents. Therefore, laboratory studies considering different configurations as the spacing between the bandal-like structures, the suspended sediment concentration measurements under appropriate hydraulic conditions, i.e. conditions favorable to measure accurately the sediment concentration, are needed to extend the range of bandal-like structures applicability in a variety of purposes.

Some investigations need to be done also in the field through the pilot projects, for example. In these field observations some parameters that can't be measured in laboratory experiments can be verified in real conditions as the natural sediment material. The interactions with the river and its boundaries are important to understand the advantages and disadvantages involved during the construction and especially during the operation of these kinds of structures.

Compound channel

Many researchers have been studied experimentally and through numerical simulations, the effect of compound channels on sediment transport process, especially the effect of non-parallel flow (e.g. oblique flow into floodplain) on the sediment balance. The next step in this kind of studies probably is the verification of the influence of hydraulic structures as groins when it is

positioned in series on the one side or both sides of the compound channel. The results could be used combining with the field measurements due to a compound channel is more close to the actual river channels.

Mixture sediment investigations

During this research, it was studied the sediment transport around river training structures by using uniform sediment as bed material. However in natural rivers the bed material is usually constituted by mixture of sediments with different diameters and types as cohesive (clay) and non-cohesive materials (rock, sand). Experimental studies and numerical simulations can be applied to clarify the mechanism of flow and sediment transport in these conditions.

Field observations indicate that there is a substantial difference in sediment size near the river bank close to the structures field (fine sediment) and in the main channel (sediment with bigger sizes). It is recommended to include graded sediment transport in modeling rivers with bandal-like structures using the procedures presented in this thesis.

Numerical modeling

As described in sub-sub-section 3.2.2.1, in the presented model the turbulence is modeled with the standard $k-\varepsilon$ model. This standard model is well known for its universal application range and its performance. However, the standard $k-\varepsilon$ model has two major drawbacks. On the one hand there is a slight over-estimation of the kinetic energy in some cases. This leads to an over-estimation of the shear stress and consequently the sediment transport capacity is over-estimated. On the other hand, the turbulence modeled by the standard $k-\varepsilon$ model is isotropic. That means the eddy viscosity ν_t is equal in all three directions. This might lead to weak development of the secondary flows especially in channels with hydraulic structures as bandal-like structures. In conclusion, one can say that the presented model can be considered to be a research tool for sediment transport phenomena. Although the widespread application range proves its universal character, the code has to be applied to other cases. Future investigations could show how far it is possible to use this model as a prediction tool in sedimentation engineering practice.

The water surface variation is another improvement that should be included in the numerical model due to the water level variation affects significantly the flow structures and consequently the bed evolution, especially near the hydraulic structures as bandal-like structures. Compared with the experimental results, the differences on bed deformation patterns in between the structures and at downstream of them may be resulted from the effect of water surface variation.

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