AN EXPERIMENTAL STUDY ON HYDRAULIC PARAMETERS AND MORPHOLOGICAL BEHAVIOUR OF BANK PROTECTION UNDER OBLIQUE FLOW

SUDIP SARKAR

Roll No- 0411162042 (F)

DEPARTMENT OF WATER RESOURCES ENGINEERING

BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY

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Sudip Sarkar

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CANDIDATE'S DECLARATION

It is hereby declared that this thesis work or any part of it has not been submitted elsewhere for the award of any other degree or diploma.

Signature of the candidate

Sudip Sarkar

(SUDIP SARKAR)

CERTIFICATE OF APPROVAL

We hereby recommend that the Master of Science in Water Resources Engineering thesis work entitled "AN EXPERIMENTAL STUDY ON HYDRAULIC PARAMETERS AND MORPHOLOGICAL BEHAVIOUR OF BANK PROTECTION UNDER OBLIQUE FLOW" submitted by Sudip Sarkar, Roll no-0411162042(F), Session-April, 2011 has been accepted as satisfactory partial fulfillment of the requirement for the degree of Master of Science in Water Resources Engineering on 28th September 2016.

Dr.Umme Kulsum Navera — **Chairman** (Supervisor)
Professor
Department of Water Resources Engineering
Bangladesh University of Engineering and Technology (BUET)
Dhaka,Bangladesh

Dr. Md. Ataur Rahman — **Member (Ex-Officio)**
Professor and Head
Department of Water Resources Engineering
Bangladesh University of Engineering and Technology (BUET)
Dhaka, Bangladesh

Dr. Md. Abdul Matin — **Member**
Professor
Department of Water Resources Engineering
Bangladesh University of Engineering and Technology (BUET)
Dhaka, Bangladesh

Mr. Abu Saleh Khan, PEng. — **Member (External)**
Deputy Executive Director (Operation)
Institute of Water Modelling (IWM)
House 496, Road No.32, New DOHS
Mohakhali, Dhaka-1206, Bangladesh

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LIST OF NOTATIONS

Symbol	Terminology	Unit
L_m	Horizontal Scale (Model)	-
L_p	Horizontal Scale (Prototype)	-
Y_m	Vertical Scale (Model)	-
Y_p	Vertical Scale (Prototype)	-
L	Length	m
T	Top Width	m
W	Width	m
F_m	Froude Number (Model)	-
F_p	Froude Number (Prototype)	-
V_m	Velocity (Model)	m/s
V_p	Velocity (Prototype)	m/s
Q_m	Discharge (Model)	m^3/s
Q_p	Discharge (Prototype)	m^3/s
V	Average Velocity	m/s
V_r	Resultant Velocity	m/s
Q	Discharge	m^3/s
Q_m	Main Channel Discharge	m^3/s
Q_o	Oblique Channel Discharge	m^3/s
Q_r	Discharge Ratio	-
θ_o	Oblique Angle	Degree (˚)
T_m	Time (Model)	hour
T_p	Time (Prototype)	hour
S_m	Slope (Model)	-
S_p	Slope (Prototype)	-
S_f	Water Surface Slope	-
D_{50}	Mean Diameter of Particle	mm
D_{90}	90% Finer Particle	mm
D^*	Dimensionless Particle Diameter	-

ρ_p	Particle Density	Kg/m^3
ρ_w	Water Density	Kg/m^3
H	Water Depth	m
A	Cross-sectional Area	m^2
P	Wetted Perimeter	m
R	Hydraulic Radius	m
D	Hydraulic Depth	m
u^*	Shear Velocity	m/s
u^*_{cr}	Critical Shear Velocity	m/s
R_e	Reynolds Number	-
V_{cr}	Critical Velocity by Shields	m/s
V_{cr}	Critical Velocity by Van Rign	m/s

LIST OF ABBREVIATIONS

BWDB	Bangladesh Water Development Board
IWM	Institute of Water Modelling
M.C	Main Channel
M/F	Main Channel Float
O.C	Oblique Channel
C/F	Oblique Channel Float
RRI	River Research Institute

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ABSTRACT

Braided river is one of the major river patterns of the alluvial river. It is a type of channel consisting of small branch channels with high gradient and sediment load separated by braid bars. This differentiation as well as further modification of the channel originating oblique flow to the existing channel. This oblique flow has influenced to the flow hydraulics and morphological behavior of the affected braided channel.

Discharge ratio and Oblique angle between main and oblique flow channel have been observed as essential parameters to investigate the dominant variables at the meeting point of these flow as well as downstream of combined channel. Time and flow dependent hydraulic parameters have been susceptible to erosion of bank protection works as well as the river bed itself. In the present study, a physical model has been carried out at River Research Institute (RRI), Faridpur, funded by Institute of Water Modelling (IWM), Dhaka to determine the hydraulic parameters and morphological behavior of bank protection work due to oblique flow. The basic variables such as discharge ratio and oblique flow angle have been considered in this research work. These two factors have influenced considerably to the hydraulic parameters as velocity distribution, scour depth and other related morphological parameters of the channel. There have been accomplished twenty-one (21) model run in this research work to fulfill the desired objectives. After a long trial and error process, the scale of the undistorted physical model has been selected as 1:50 but not to be done for bed material of the channel bed. In this study, there have been considered three oblique angles (20^0, 40^0, 60^0). For each oblique angle, three different discharge ratios 1.2, 1.4, 1.6 has also been taken into account. For the design of bank protection works, stone boulders and geobag have been used at the right bank of the combined channel. It has been observed that velocity distribution and scouring pattern of the channel inclusive with the behavior of bank protective material are being closely inter-related and influenced due to the presence of oblique flow.

CHAPTER ONE
INTRODUCTION

1.1 General

Bangladesh, a small territorial country, is very rich in diversity and complexity, especially in the water resources sector. Bangladesh lies in the South-East Asia between 20°25' and 38°40'N Latitudes and 88°01' and 92°40'E Longitudes (BBS, 2007). Most of the water that flows through the major rivers of the country is predominately responsible to cause flooding in Bangladesh. The combined river system of Ganges-Brahmaputra-Meghna (GBM) forms the biggest delta formation in the world which brings in three times the volume of water from the upper catchments beyond the country (India, Nepal, Bhutan and China and in total 1.72 million square meters) compared to the water generated within the country (BWDB, 2012). In addition to large quantities of water, these rivers carry about 1.1 billion tons of sediment every year (Sarker et al., 2003) and they are responsible for the occurrence of flooding and riverbank erosion in Bangladesh (Uddin et al., 2012).

The large rivers in Bangladesh are mainly meandering and braided in nature and riverbank erosion is an endemic and recurrent natural hazard (Mosselman, 2009). In order to protect and save the land from the severity of bank erosion, bank protective works have been constructed at several critical locations of the river erosion affected reaches in Bangladesh. These bank protection structures such as revetment, groyens, etc. face two types of flow phenomenon in terms of its direction. One is parallel to the structure as straight flow and another is inclined with respect to the structure that is known as oblique flow. When a flow path is obstructed by sand bar generally in braided river like the Jamuna, an oblique flow criterion is developed at the meeting point of combined channel that merging again as the main channel. Due to this condition, oblique flow hits upon directly either to the natural bank or to the existing bank protection works.

Generally, river and its identical planform dominates greatly the whole fluvial process directly by affecting on the hydraulic parameters. Due to the activity of the hydraulic parameters such as sediment load, discharge, velocity, oblique flow, ground water contribution over all channel morphology incorporates to the whole fluvial process. Bank erosion, deposition, outflanking of channel alignment, channel migration or shifting and channel pattern – these are very much common scenarios in the country. A pronounced local scour at the meeting point of a main and oblique channel occurs when channel bed elevation between the main and oblique channel is similar (Roca, 2009). In the research work it has been the prime objective to determine the effect of oblique flow on hydraulic parameters and morphological behavior of bank protection works under with different angles and flow criteria.

1.2 River Systems of Bangladesh

In Bangladesh, about seven hundred (700) number of rivers have flown toward the southern region, but according to BWDB (2012) about 405 number of rivers have conveyed discharge to the river system.. These rivers also drain the excess monsoon rainfall from the respective drainage basin or watershed into the Bay of Bengal. Thus, the great river system is at the same time the country's principal resource and sometimes it's greatest hazard (Wikipedia, 2010)

Basically rivers of Bangladesh are being divided into five major networks. These are described as follows:

a) The Brahmaputra-Jamuna river system is 292 kilometers long and extends from northern Bangladesh to its confluence with the Padma, which is generally Originated as the Yarlung Zangbo Jiang in China's Xizang Autonomous Region (Tibet) and flowing through India's state of Arunachal Pradesh, where it becomes known as the Brahmaputra (Son of Hindu deity Brahma). It intakes discharge from five major tributaries that total some 740 kilometers in length. At the point where the Brahmaputra meets with the Tista River in Bangladesh, it becomes known as the Jamuna. The Jamuna is susceptible for its shifting behavior as sub-channels and for the formation of fertile silt islands like chars or sand-bars. No permanent settlements can exist along its banks. Oblique flow plays a dominating role for the erosion of bank and bank protection work. In the research, it has been observed that hydraulic and morphological parameters of bank protection work has especially exposed under the action of oblique flow.

b) The second system is the Ganges-Padma river system, which is divided into two sections: one is a 258-kilometer segment known as the Ganges and other is 126 kilometer segment, the Padma, which runs from the Ganges-Jamuna confluence to where it joins the Meghna River at Chandpur. The Padma-Ganges is the central part of a deltaic river system with hundreds of rivers and streams.

c) The third network is the Surma-Meghna system, which courses from the north-eastern border of India to Chandpur, where it joins the Padma. The Surma-Meghna, at 669 kilometers by itself the longest river in Bangladesh, is formed by the combination of six lesser rivers. Below the city of Kalipur, Habiganj it is known as the Meghna.

d) When the Padma and Meghna join together, they form the fourth river system known as the Lower Meghna which flows 145 kilometers to the Bay of Bengal. This mighty network of four river systems flowing through the Bangladesh Plain drains an area of some 1.5 million square kilometers.

e) A fifth river system, unconnected to the other four, is the Karnaphuli flowing through the region of Chittagong and the Chittagong Hills (Wikipedia, 2010).

These above described river system dominate to the total river system of the country. The Jamuna-Brahmaputra river system is considered as one of the major river systems of the country. The river system is classified as braided river system that is almost developed by sediment concentration and its identical fluvial process. Moreover the river system is the most dynamic and complex in behavior at all (Wheelock, 2002).

1.3 The Brahmaputra-Jamuna River and its Morphology

The Brahmaputra-Jamuna is one of the 1argest rivers in the world, ranking fifth in terms of discharge, eleventh in terms of drainage area and third in terms of sediment discharge. The river is braided with meta-stable islands and nodal reaches, mobile sandbars, shifting anabranches and severe bank erosion.

Figure 1.1: Major River Systems of Bangladesh (Source: Banglapedia.org, 2012)

Its large dimensions make it difficult to understand its behavior and morphological changes. Also because the river is highly mobile due to its fine sediments and the large floods it is experiencing almost every year, its platform is changing completely in a few years only. An analysis has shown that the discharge starts increasing in April and the first peak flood generally occurs in June-July and is characterized by a rapid rise, the peak flood of the Jamuna is generally earlier than the one in the Ganges River (Hannan, 1993).

Braided rivers are very unstable, and they wander across their flood plains unpredictably through a combination of rapid localized bank erosion and frequent channel changes. It is investigated from an analysis of the historical map that the

Jamuna river has migrated westward at a rate of 50 m/year since the avulsion of the river from the east of the Madhupur Tract to its present course about 200 years ago (BWDB, 2008; CEGIS, 2005). The river shifted its course towards western direction up to 10 km in some reaches (Klaassen and Vermeer, 1988). From 1973 to 2009, erosion and accretion along the Jamuna river was 90,830 ha and 10,140 ha respectively (CEGIS, 2005). The rate of erosion varied over time. From 1970 to1990 the Jamuna river widened at a very high rate and both the banks migrated outward at an average rate of about 70 m/year. Since the early 1990s, the rate of outward migration of both banks has reduced to 30-50 m/year (CEGIS, 2005). Due to the dynamic equilibrium characteristics of the Jamuna river, it always changes its courses within the braided belt (FAP 24, 1996).

1.4 Background of the Study

Erosion of riverbank generally occurs at the outer bends of a meandering channels but it behaves apparently different for a braided river. In a braided river, bank and bed scour is interactively associated with channel confluence and bends (Halcrow, 2002). For the development of frequent bars and islands in a braided river that generates oblique flow to the existing channel. It is mostly responsible for bank and bed erosion. Moreover, bank and bed materials are also susceptible to erosion that have been categorized into two groups- highly erodible and less erodible. The rate of erosion is 1 to 20m/yr if the bank is composed of less erodible materials due to the intrusion of oblique flow into river bank. On the other hand, the rate of erosion would be several hundred meters per year in the case of highly erodible bank material (BWDB, 2013).

In our major river system, the Brahmaputra-Jamuna river system is a classic example of a braided river system and is highly sensible to channel migration and avulsion. These oscillations cause massive lateral movement of riverbank erosion. Most of the braided rivers in Bangladesh are affected by significant bank erosion but it's effect becomes most vulnerable when oblique flow develops in a channel due to the presence of permanent or temporary sand bar and also erosion pattern changes when secondary current contributes to a straight flow. For the bank protection work, c.c. block, geobag and stone boulders have been used extensively in Bangladesh. After the implementation of that protection work or river training works it has been observed that some problem have raised like i) retardation of velocity that results in closing of existing main channel, ii) flow diversion, iii) sudden erosion in near permanent char land, iv) severe bank erosion adjacent area of protective work due to direct attack of diverted flow (Rahman, 2012) etc. The dynamics of flow is further complicated in a natural stream due to wide differences in hydraulic properties and resistances of flow in the main channel and the subsidiary channels (NDMA, 2012).These type of problems could be overcome if fluvial process can be analyzed before implementation and extensive physical model study is the best procedure for the observation flow behavior of rivers (DHV Consultants, 2000).

So, the present research work has been carried out to understand the effect of oblique flow in different bank protection works as well as to the influence of hydraulic and morphological parameters of a braided river system.

1.5 Scope of the study

As a country of downstream zone as well as a deltaic country, Bangladesh is very much related to flood, river bank erosion, siltation, shifting of channels, failure of bank protection work, etc. Among these events flooding and bank erosion are the most susceptible to our geo-morphological environment. Now every year this kind of phenomenon behaves as a stochastic process. Moreover, Bangladesh is an alluvial deposited country due to the position of itself. And belong to the respective river system, most of the major rivers of Bangladesh classify with different channel pattern such as braided, meandering and some are anastomosing rivers.

The intensity of bank erosion varies widely from river to river as it depends on some characteristics of a channel such as bank material, water level variations, near bank flow velocities, planform of the river, flow discharge and sediment transport into the river. From these point of view, hydraulic and morphological parameters of a braided channel such as discharge, scour depth, flow velocity at where braid bar is very much responsible to divert the straight flow into oblique flow have been observed in this study for better understanding. This kind of phenomenon has influenced to a great vulnerability not only to the bank protection works but also for the erosion of existing river bank in every year. Every year, Jamuna and Brahmaputa river known as major braided rivers of our country have faced enormous erosion due to braided characteristics of the channel as well as for oblique flow phenomenon. Now-a-days it has already been defined as a regular behavior of these kind of rivers.

1.6 Research Objectives and Possible Outcome

The physical model has been carried out to observe the hydraulic and morphological behavior of bank protection work due to oblique flow basically in a braided channel.

Objectives of the present research work are:

1. To assess flow hydraulics and flow behavior of the straight channel affected by oblique flow.
2. To observe the velocity field in the main channel due to oblique flow.
3. To determine dominant velocity for scour and develop a relationship with scour.
4. To assess flow field criteria for different types of bank protection material.

The following several possible outcome can be expected from this research work.

1. Variation of flow field for different oblique flow channel angle (Θ_o) and discharge ratio (Q_r).
2. To better understand about scour pattern due to angle and discharge ratio variation.
3. To determine flow path and position for different oblique flow discharge.
4. Scour depth variation with respect to time.
5. Graphical representation and relationship between hydraulic parameters.
6. Efficiency of different types of bank protection material.

1.7 Organization of the Thesis

This thesis has been consisted of six chapters, those are given as follows:

Chapter One: Describes major river systems of Bangladesh, the Jamuna-Brahmaputra river, background and scope of the study in this chapter.

Chapter Two: Literature review have been summarized in this chapter based upon the classification of open channel, variables affecting river pattern and behavior, flow behavior at confluence, previous study about oblique flow criteria, several related research by physical modeling, mathematical modeling and numerical modeling analysis.

Chapter Three: Briefs about definition and features of braided stream, complex but dynamic phenomenon of braided system, reason and theory for the selection physical modelling. It has also been described the methodology of physical model set-up in this chapter.

Chapter Four: Describes briefly about physical modeling components, measurement techniques and ancillary works.

Chapter Five: Describes results and discussions of research objectives and its possible outcome finding from the physical model run.

Chapter Six: Describes at a glance about conclusive findings and observations of hydro-morphological parameters. Eventually, there have been recommended to some future observations in this chapter to develop its further objectives based upon oblique flow phenomenon.

CHAPTER TWO
LITERATURE REVIEW

2.1 General

The formation of oblique flow arises by the unique properties of a braided channel which is very dynamic in nature as well as very complex with respect to hydraulic behavior of a channel through fluvial process like erosion and accretion. During the last decade, the trend of braided river research has been modified and completely shifted from the static characteristics to study the dynamic aspects of flow behavior (Schumm, 1981). Jamuna, the large mighty river of Bangladeshis braided in nature whereas Ganges and upper and lower Meghna are meandering rivers (Wheelock, 2002). In this research work as a prototype sample the Jamuna river has been selected for its complex braided characteristics. Lane (1957) defined the braided river as having a number of alluvial channels with bars and islands between confluences and bifurcations again. Individual channels and bars in such rivers can include migration and switch position within days or hours of competent flow, so that the overall pattern is bewilderingly variable and complex (Fergunson et al., 1992). So these phenomenon's demonstrates the urgent need for a precise understanding of braided river dynamics and for the ability to forecast the evolution of the planform or morphological changes in the short and medium term future (Hossain et al., 2010).

2.2 Classification of Open Channel

Open channel can be classified into different categories. Many scientists described open channel based on material, planform, flow hydraulics, channel slope, etc. So, it in the following paragraphs three categorized parameters has been described. These are:

2.2.1 Classification Based on Sediment Properties

Open channels are classified as natural and artificial channel. Natural channel include all watercourses that exist in the nature and are carved and shaped by the erosion and sediment transport processes. Engineered (artificial) channels are those constructed by human intervention (Chow, 1959). It can be defined as-

a) Natural Channel

Watercourses are carved and shaped by natural erosion processes. Natural channels are also strongly influenced by urbanization in the watershed, which significantly alters the hydrology and therefore, the geometry of the natural channels. If the watershed imperviousness exceeds around 10 percent, it is likely that channel geometry will be altered such that a natural channel is no longer viable and mitigation measures will be required, such as bank and bed stabilization measures (Chow, 1959).

b) Artificial Channel

These type of channels can be defined as the type of construction and its materials. These are denoted as follows- a) Grass-Lined Channels b) Concrete-Lined Channels c) Riprap-Lined Channels d) Other Lined Channels.

2.2.2 Classification Based on Flow Hydraulics

According to the relative stage of adjustment, streams are divided into three classes, those are youthful, mature and old stage (Davis, 1899).Based on the river system, it is classified into three types such as straight, meandering and braided channels (Leopold & Wolman, 1957). On the other perspective streams are differentiated among straight, meandering and braided channels according to quantitative slope discharge relationship (Lane, 1957). Then it has been defined with channel types based on channel stability such as stable eroding and depositing and mode of sediment transport such as mixed load, suspended load and bed load (Schumm & Khan, 1972).

2.2.3 Classification Based on Channel planfrom

Classification of channel patterns proposed by Leopold and Wolman (1957) is popularly accepted all over the world. Leopold divided alluvial channel into three patterns that are straight, meandering and braided mainly based on the planform of a river. According to the composition of incoming sediment from the river basin, it has been divided alluvial rivers into three major patterns that are bed load type, wash load type and mixed type (Schumm, 1981). He further divided alluvial rivers into fourteen sub-patterns according to valley slope, stream power and amount of incoming sediment (Reza, 2011).

Classification proposed by Rosinski (1958) was rather popular in China in fifties and sixties. According to Rosinski's concept, depending on relative erodibility of river bed and bank, river can be divided into three categories: straight, braided and meandering. The corresponding fluvial processes are being periodically active with widening its stream, migrations of meanders and wandering. According to Rosinski (1958) and Leopold & Wolman (1957) channels are classified among three types:

a) Straight Channel

Straight channels are the first of a simple three part classification by early geo-morphologists, as reported by Leopold, Wolman and Miller (1957) and Schumm (1977). It is rare in nature stated by Leopold and Wolman (1957). A stream may have moderately straight banks but the thalweg of greatest depth along the channel is usually sinuous. It is only feasible for artificial channel. Sinuosity varies from 1 to 3. Sinuosity is taken as 1.5 to differentiate between straight and meandering channel defined by Leopold et al. (1964). A series of shallow crossings and deep pools is formed along the channels in a straight channel with a sinuous thalweg developed between alternate bars (Figure 2.1 and 2.2).

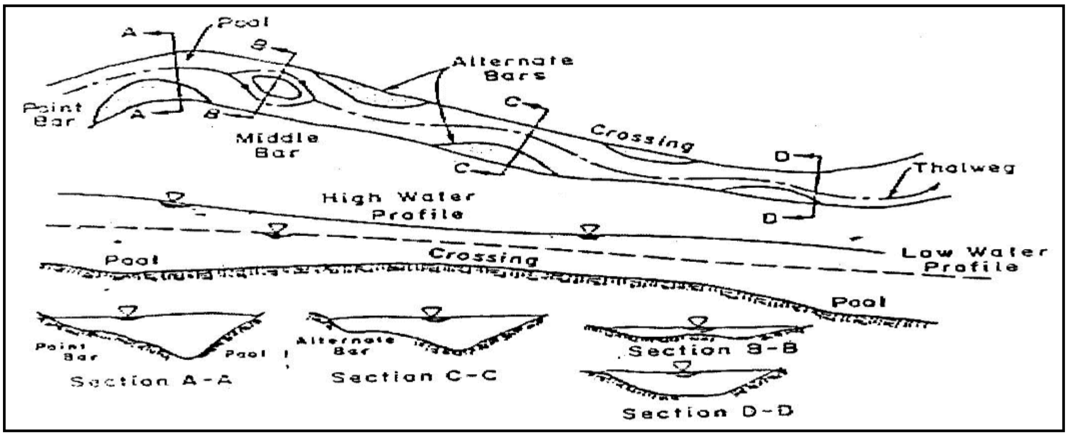


Figure 2.1: Differentiate between Straight and Meandering channel
(Source: Schumm, 1977)

b) Meandering Channel

Meandering channels are single channels that are sinuous in plan, but there is no criterion, except an arbitrary one, of the degree of sinuosity required as above 1.5 before a channel is called meandering (Lane, 1957). The spacing of bends is controlled by flow resistance, which reaches a minimum when the radius of the bend is between two and three times the width of the bed. In a meandering channel, thalweg flows from a pool through a crossing to the next pool forming the typical S curve of a single loop at higher stage (Figure 2.2). At highest stages it forms a chute channel across point bars in a channel (Lane,1957).

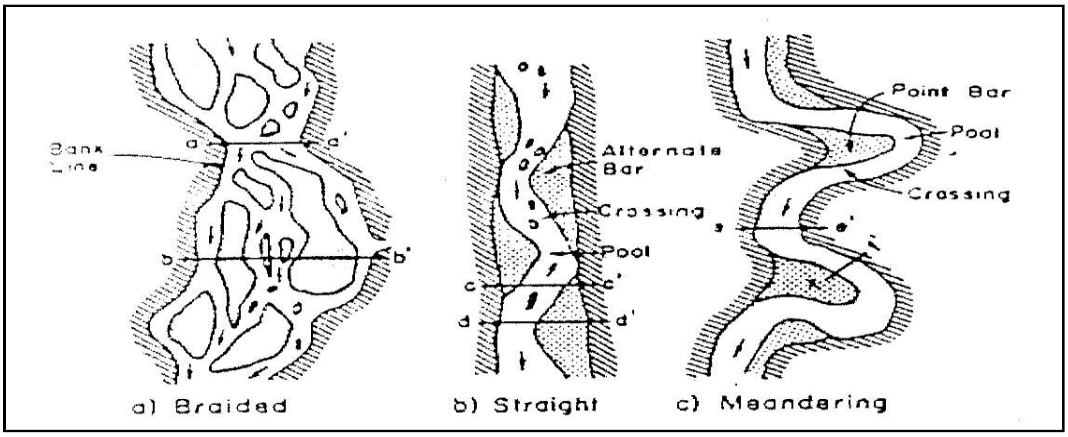


Figure 2.2: Pattern of Different Channels (Source: Schumm, 1977)

c) Braided Channel

A braided river is one of a number of channel types and has a channel that consists of a network of small channels separated by small and often temporary islands called braid bars. By Schumm & Khan (1972) has defined braided streams occur in rivers with high slope and/or large sediment load. The two primary reason that may be accountable for the braiding is stated by Lane (1957) as a) Overloading, that is the channel may be full with more sediment than it can transport consequently accumulating part of the load, deposition occurs, the bed aggrades and the slope of the channel increases in an effort to maintain a graded condition and b) steep slopes, which generate high velocity, multiple channels develop resulting the overall channel system to widen with rapidly forming bars and islands. The multiple channels are generally unstable and change position with both time and stage (Reza, 2011).

2.3 Variables Affecting the Channel Pattern

In general, a natural channel system continually changes its position and shape as a result of hydraulic forces acting on its bed and banks. These changes may be slow or rapid and may result from natural environmental changes or from changes caused by human activities. When a natural channel is modified locally, the change frequently causes alteration in channel characteristics both upstream and downstream. Geometric characteristics of the stream, including the probable geometric alterations that developments will impose on the channel; Hydraulic characteristics such as depth, slope, velocity of streams, sediment transport, and the changes that may be expected in these characteristics over space and time and Ecological/biological changes that will result from physical changes that may in turn induce or modify physical changes (Mukharjee, 1995).

2.3.1 Aggradation or Deposition in Channels

Aggradations occur in a river if the amount of sediment coming into a given reach of a stream is greater than the amount of sediment going out of the reach. Part of the sediment load must be deposited and hence, the bed level must rise (Ranga Raju, 1980). In alluvial channels or streams bed aggradations evolves primarily from the passage of flood events. The bed profile consequently reduces the section factor of the channel. Sediment deposition along streams or in reservoirs is a complex and troublesome process. It creates a variety of problems such as, rising of river beds and increasing flood heights, meandering and over flow along the banks, chocking up of navigation and irrigation canals and depletion of the capacity of storage reservoir (Hossain, 1997).Deposition is also two types as channel siltation and flood plain deposition. Siltation in channels or branches can be called as channel siltation and deposition on flood plain is called as flood plain deposition (EU and Bangladesh, 1993).

2.3.2 Degradation or Erosion in Channels

Bed degradation occurs when the amount of sediment coming into a given reach of a river is less than the amount of sediment going out of it (Ranga Raju, 1980). The excess sediment required to satisfy the capacity of the river will come from erosion of the bed and there will be lowering of the bed level, which will result in shifting of thalweg line of the river. If the banks are erodible material can be picked up from the banks and widening of the river will also result. Hence the whole process of aggradations and degradation of rivers have potential effects on various hydraulic and geometric features of rivers such as cross-sectional area, section factor, shifting of thalweg line and others (Reza, 2011).

2.4 Variables Affecting River Behavior

Variables affecting alluvial river channels are numerous and interrelated. Due to the existence of complex properties, unlike rigid boundary hydraulic problems, it is not possible to observe the role of any individual variable. According to Lane (1957), the major factors affecting alluvial stream channel forms are:

(1) Stream discharge (2) Sediment load (3) Longitudinal slope (4) Resistance of banks and bed to movement by flowing water (5) Vegetation (6) Temperature (7) Types of sediment and (8) Artificial problem.

The fluvial processes involved are extremely complicated and the variables of importance are difficult to isolate. Many laboratory and field studies have been carried out in an attempt to establish relationships among these and other variables. The problem has been more amenable to an empirical solution than analytical one. In an analysis of flow in alluvial rivers, the flow field is complicated by the constantly changing discharge. Significant variables are, therefore, quite difficult to relate mathematically (Sumer, 2013).

2.5 Flow Behavior at Confluence of Two Individual Streams

A growing body of research focused on confluence dynamics revealed the complexity of flow structure at laboratory junctions (Mosley, 1976; Ashmore and Parker, 1983; Best and Roy, 1991), small natural confluences (Roy and Bergeron, 1990; Ashmore et el., 1992; McLelland et al., 1996; Rhoads, 1996; Sukhodolov and Rhoads, 2001) and through numerical simulations (Weerakoon and Tamai, 1989; Bradbrook et al., 1998, 2000, 2001). Based upon those studies, the nine (09) findings of these studies was identified a sequence of distinct hydrodynamic zones that are the basis for conceptual models of flow structure through confluences (Figure 2.3).

As channels converge at junctions, incoming flows initially meet and deflect one another along with a mixing interface thus introduce stagnant or low velocity fluid envelops at the junction apex and a zone of lateral flow separation from the banks of the downstream junction corner. The combined flows accelerate through the turbulent central region of the confluence before recovering further downstream in the receiving channel.

The spatial properties of these zones are largely controlled by geometric and hydrological relationships between the confluent flows (Mosley, 1976; Best and Reid, 1984; Best, 1987) including confluence planform geometry which consists of the spatial configuration of the approach channels with the receiving channel and the geometric angle between the approach channels as their convergence or junction angle and the momentum flux ratio (M_r) between the incoming flows. Other variables those may exert control over confluence flow structure including the extent of bed elevation difference or discordance between the confluent channels upon entering the junction (Biron et al., 1993; Biron et al., 1996; DeSerres et al., 1999; Boyer et al., 2006), feedback mechanisms of bed morphology on fluid motion (Best, 1987, 1988; Best and Roy, 1991; Biron et al., 1993; Rhoads and Kenworthy, 1995) and density differences between converging flows especially at the junction of large rivers (Parsons et al., 2008).

Variation in these factors can effect major changes in flow structure and bed morphology at confluences. Most confluence research had been focused on assessing the effects of variation in junction angle and momentum (M_r) on hydro-morpho dynamics. It has been observed in the present experimental physical model study that discharge ratio (Q_r) and oblique angle (Θ_o) effect on hydraulic parameters as well as morphological behavior of the braided river.

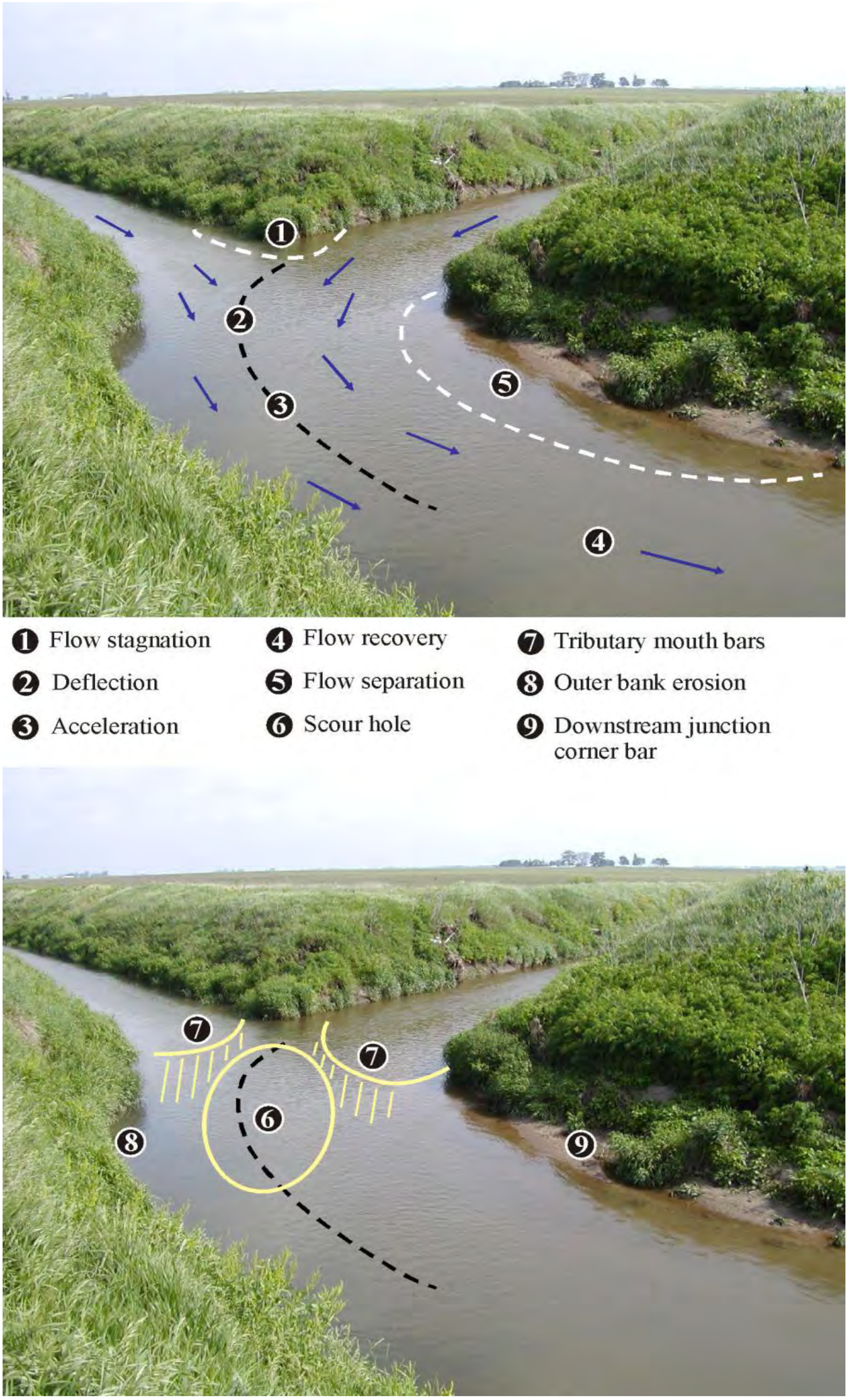


Figure 2.3 : Significant Observation at Confluence (Source: Riley, 2013)

2.6 Previous Studies about Oblique Flow Behavior

Most of the research about confluence had been focused on assessing the effects of variation in junction angle (Θ) and momentum flux (M_r) on hydro-morpho dynamics at either asymmetrical or symmetrical junction planforms with straight approach of receiving channels. Planform symmetry and junction angle defines the geometric relationship between the approach channels, thereby directing the orientation of the converging flows and imposing physical control on deflection of these flows within the confluence. At asymmetrical confluences (y-shaped), flow from the lateral tributary is forced to turn rapidly to align with the orientation of the receiving channel. Penetration of tributary flow into the confluence is enhanced by increasing the junction angle or M_r, which deflects the mixing interface toward the outer bank and produces slight curvature of main river flow (Best, 1987; Rhoads and Kenworthy, 1995, 1998; Rhoads, 1996; Rhoads and Sukhodolov, 2001). As planform symmetry increases, the confluence becomes more Y-shaped and both incoming flows must curve to align with the downstream channel. High junction angles intensify flow deflection and the position of the mixing interface shifts away from the incoming flow with the greatest momentum flux (Mosley, 1976; Best, 1986; Bradbrook et al., 2000).

A study was investigated by Ghobadian et al. (2007) that the sediment patterns at river confluence, where the entrance flow from the river branch into the main river causes extensive variation in flow pattern and creates vortex. Because of these a scour hole is developed just downstream of the river confluence. These phenomenon can accelerate the rate of bank erosion, bring problems for navigation and may causes failure of the bridge or structures nearby. In this study the geometric dimensions of scour hole was being studied. To reach such goal, at first by using the dimensional analysis, general non-dimensional equations were developed. In this equation, there were being introduced for the first time in the study of river confluence angles 60, 75 and 90 degrees under different hydraulic conditions. Finally, relationships were developed for prediction of scour hole and point bar dimensions.

The most important non-dimensional parameters, especially the discharge ratio and the densimetric Froude number, $F^*=U/[(S-1)gD]^{(1/2)}$ (where U=Mean velocity,

2.7 Physical Modelling and Laboratory study on River Hydraulics

An experiment had been done that defined the results of a quantitative investigation of sediment transport at channel confluences accomplishing through both scaled laboratory flume simulation and complementary monitoring of a natural channel confluence (James, 1988). An experimental study named "an experimental study of channel confluences" investigated that varying of tributary discharges with sediment loads and confluence angle ranged from 15° to 180° (Mosley, 1976). An experiment was being done earlier from which found three-dimensional data of the mean and turbulent structure of flow collected at a natural confluence of rivers with discordant beds to (1) describe the three-dimensional flow field of a natural junction of channels (2) assess the role of changes in bed morphology occurring during transport-effective events on the structure of flow at a confluence and (3) examine how the three-dimensional structure of flow varies with changes in the ratio of momentum flux between the two confluent streams (Serres et al., 1999)

A Joint study was being undertaken by the university of Nottingham and flood action plan 24 (FAP-24) to investigate patterns of secondary flow around a braid bar on the Brahmaputra river in Bangladesh. Some other research was conducted in Bangladesh especially supervised by Department of water resources engineering, BUET faculties. A review of scale model studies basically physical model study had been done to understand the physical modelling aspects (Kashem, 1988). Some other study related to river behavior of Bangladesh emphasizing on hydraulic properties those were, a laboratory study had been carried on about sediment distribution at channel bifurcation (Haider, 1995). And a study of general scour of alluvial rivers had done by physical modelling to know the details of general scour (Islam, 1996). However a study of morphological behavior of the Jamuna river was being conducted to determine the behavior of morphological parameters of a braided river (Mukharjee, 1995). Moreover a advance development of physical model facility and investigation of flow pattern due to the groyne at the right bank of the Jamuna river had been already observed with physical experiment (Sarker, 2001), and a physical model study had been carried on to observe the behavior of launching apron due to oblique flow in braided river (Das, 2014). These above experiments are very much incorporated to this study and physical model facilities.

Furthermore some other physical model study had been done to observe the impact of the discharge ratio to the separation zone from bed bottom to surface of a channel. Some other physical model study found that consistent morphological changes in the anticipated directions occurred when the symmetry ratio (Q_2/Q_1) approached approximately .6 to .7, indicating a threshold relationship between tributary and main stem river sizes. Although different types of changes in channel and valley morphology due to large influxes of sediment from tributaries has been studied by small et.al (1973).

Some other study observed to determine the process of flow around bank protection structures. Haque (2010) investigated that the flow behavior around launching apron in a laboratory channel situated in the Hydraulics and River Engineering Laboratory of the Department of Water Resources Engineering, BUET. Since launching apron is a measure to limit scour in sand bed for riverine structures, initially the investigation incorporated flow behavior and then the scour study were observed. The extent of aerial coverage of launched apron was determined during the test runs in connection with the study. Tanzeeba (2002) was incorporated with a research that a physical model study has been used for the study on bank protection by revetment. In general, revetment structures are popular as bank protection work in Bangladesh. The different types of revetment, which are mainly used here, are cubical concrete blocks and loose stones. In the present study the performance of hexagonal block for bank protection work was evaluated and was compared with cubical blocks.

In Bangladesh, River Research Institute is only the institute which conducts physical modelling study to determine river hydraulics as well as river morphology. Many of these studies which conducted by RRI are very much incorporated to the present research. Those are briefed as follows: Comprehensive Physical Model Investigation of the Padma Multipurpose Bridge Design Project which had been investigated to all related hydraulic and morphological parameters of the river due to the construction of bridge. Additional test to carryout investigation regarding performance of falling aprons, drop tests for dumping of geobags and outflanking Problems to address the bank erosion problems of Bangladesh by physical modelling which had been assessed to the vision of the research. Physical modelling for the protection of left bank of the Padma river from Babupara to Indo-Bangladesh border in Shibganj upazilla under Chapainawabganj district that had been almost investigated to the erosion problem due to the influence of fluvial activity of the river. Another a research had been done for the effectiveness analysis of the bank protection technique and its effect on morphology of the river that was a research using bandalling structure as bank protection and its effect on river flow & morphology. These above mentioned studies had been done to know about river hydraulics and aspects of different types of bank protection work, but very fewer study have been accomplished related to oblique flow behavior around braid bar in the braided river and its effect on river bank protection work. In the present study, hydraulic parameters and morphological behavior of the bank protection work have been investigated under oblique flow developing by physical model at River Research Institute (RRI), Faridpur.

2.8 Mathematical Modelling on River Hydraulics

Significant observations of the hydro-morphological behavior in many rivers had been done by the numerical process like Mathematical modelling and Numerical modelling. These types of modelling had already been initiated for various complicated research to know the process accurately.

A numerical study had been done about floods in Atrai basin using hydrodynamic model of steady flow to know about inundation process of flood as well as flood hydrography by Alam (1988), another a researcher Islam (1993) observed the variation bed level at Ganges by numerical simulation; A numerical study on flood routing using kinematic and diffusion wave models had been done by Rahman (2003); By application of 2D mathematical model for verification on water velocity at coastal area of Bangladesh was analyzed by Zaman (2012) and other a computational study of gradually varied flow profiles by numerical method was conveyed by Mannan (2004). Now recently part of our research, Asmat (2014) has already been accomplished the research to determine the effect of oblique flow at both protected and unprotected bank protection work by using mathematical model.

Mardookhpour (2004) had worked with mathematical modelling to determine best hydraulic slope of a channel. Also, there had been done other variety of research with the proper assistance of mathematical model as well as numerical model.

Several research studies had been conducted however a few comprehensive three-dimensional (3-D) numerical study of flow characteristics in a confluence have been properly reported. A 3-D numerical model had been done by Ahmad Shakibainia et al. (2006) being to be validated and applied to investigate secondary currents, velocity distribution, flow separation, and water surface elevation in different conditions. The results of the study illustrate that flow structure and water surface variations in a confluence are highly influenced by confluence angle, discharge, and width ratios as well as Froude number because of their effect on flow deflection, separation and secondary currents.

2.9 Summary

In the present physical model study, it has been aimed to observe some basic hydraulic parameters (Velocity and Scour Depth) due to oblique flow. From the previous literature, it has been found that no studies have yet been carried out about the effect of oblique flow on different bank protection works. It has been also observed that since earlier the confluence properties of two individual rivers were analyzed. But for braided river system, diversion of channel due to braid bar and conversion of combined channel could not be considered as a confluence. The intensity of river bank erosion differs variably from river to river for the properties of bank material, water level variations, near bank flow velocities, planfrom of river, discharge, sediment load and position of braid bar in an active braided river system.
From this point of view, the present research work is based on physical modelling to observe the effect of an oblique flow on the hydraulic & morphological parameters of the river and also the bank protection works. Several parameters have been considered in this study these are velocity, discharge, scour depth and oblique angle. The materials have been selected for bank protection works are stone boulder and geobag.

CHAPTER THREE
THEORY AND METHODOLOGY

3.1 General

River system in Bangladesh is almost having different behavior of flow and morphological characteristics. These are considered as braided, wandering and meandering river. Braided river is mostly vulnerable on account of both river bank and bed erosion. Due to the morphological properties of a braided river, it influences on the fluvial process of the river. For a braided river, submerged char or sand bar formation initiates irregularities to the existing flow whether it generates oblique flow phenomenon to the hydraulic process. This kind of oblique flow is highly induced to the bank protection work depending upon the oblique flow angle and intensity of oblique flow (Mosley, 1976). Main objectives of this chapter have been aimed to brief description of the related theories regarding braided river and its behavior. Moreover, here it has been given a clear idea about theory of physical model and its related theory.

3.2 Theory of the Braided River System

Braided river is wide in physically with poorly defined and unstable banks and is characterized by a steep slope, shallow depth course with multiple channel divisions around alluvial islands (Wikipedia, 2016). Braided characteristics were studied by Leopold and Wolman (1957) in a 1aboratory flume. They concluded that the pattern of braided river is one of many patterns which can maintain quasi equilibrium among the variables of discharge, sediment load, and transporting ability.

Lane (1957) concluded that the two mandatory causes that may be responsible for the braided condition which are overloading, that introduces the stream may be supplied with more sediment than it can carry resulting in silting or deposition of part of the load and steep slopes, that produce a wide shallow channel where bars and islands develop spontaneously. Either of these factors individually or both, it could be responsible for a braided pattern.

If the channel is overloaded with sediment, deposition occurs, the bed aggrades, and the slope of the channel increases in an effort to maintain a graded condition. As the channel steepens, the velocity increases, multiple channels develop and cause the overall channel system to widen. The multiple channels generates when the additional sediments is being accumulated forming sand bars within the main channel, are generally unstable and change position with both time and stage (Lane, 1957).

Another cause of braiding behavior is easily eroded river banks. If the banks are easily eroded, the stream periphery widens at high flow and at low flow mid-bars form which become stabilized, forming island. In general, a braided channel has a steep slope, a large bed material load in comparison with its suspended load, and relatively small amounts of silts and clay in the bed and banks. The braided stream is difficult to work with in that it is unstable, changes its alignment rapidly, carries large quantities of sediment, is very wide and shallow even at flood flow and is in general unpredictable (Mukharjee, 1995). The Brahmaputra-Jamuna river (Figure 3.1) is an example of a braided river.

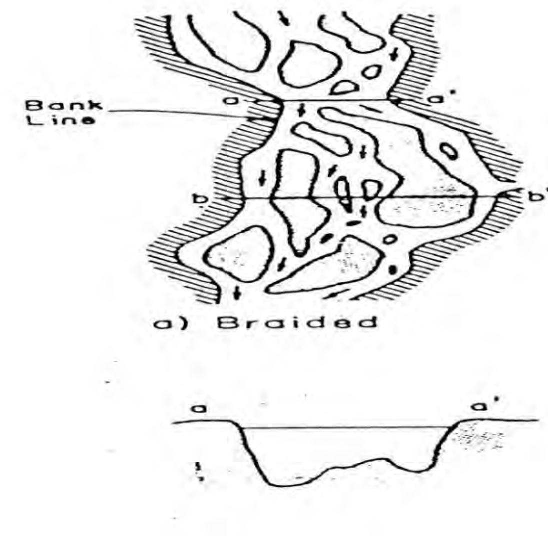


Figure 3.1: Planform of Braided Channel (Source: Lane, 1957)

3.2.1 Oblique Flow– a Complex Feature of Braided River System

Braided river may be progressed as a series of channel segments which divide and rejoin around bars in a regular or repeatable pattern. The divisions, channel bends and fluid dynamics are inter-linked to the braided properties of a channel. The planform appearance of a braided river can change radically with flow stage (Throne et al., 1993). Bars may disappear at high flow stages, reforming as discharge falls (Bluck, 1979) and similar observations were reported by Smith (1974). So, it has already been acknowledged that erosion and deposition modification relate to change in stage or discharge of flow.

a) Channel Bifurcations

Channel bifurcations are the most formative process in the braided river systems. Ashmore (1991) described that bifurcation may develop with i) Central bar mechanism and dissection of transverse unit bar ii) Chute cutoff mechanism iii) Multiple bars mechanism. Central bar mechanism and dissection transversely of unit bar are the two most commonly observed physical processes of braiding generation that had been first described by Leopold and Wolman (1957). In the research, dissection of multiple row bars mechanism has been developed to analyze oblique flow on bank protection work. The presence of the unit bar, forces the flow to diverge and the central nucleus (submerged bar) has eventually exposed.

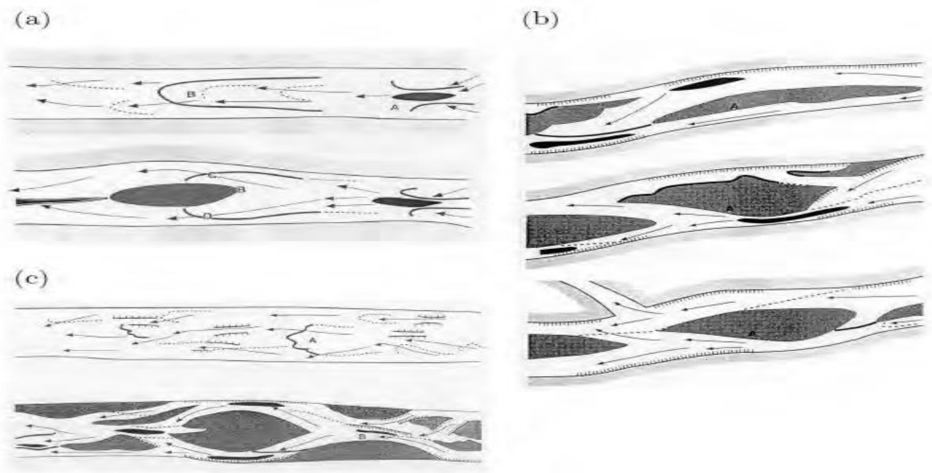


Figure 3.2: Braided Development Mechanism (Source: Ashmore, 1991)

Immediately downstream of the bar, the divided flows produce scour pools against the opposite banks. Ashmore (1991) suggested that the distinction between the central bar mechanism and the dissection of transverse unit bar is essentially due to higher sediment mobility which characterizes the latter process.

b) Development of Bar

Alternating bars develop in single branches of braided rivers, similar to those of the straight channels. Though their formation may be associated to an inherent instability of the sediment flow system, their development is crucially affected by local flow conditions like curvature and local widening. Channels confluences and alternating bars development are mainly responsible for the generation of scour holes.

c) Avulsions and Incision of Channel

Bar formation mainly governs to form avulsions in braided Channel. They occur under a variety of circumstances. The presence of bars plays a crucial role on the generation of avulsions both inducing bank erosion and raising the local water level allowing overtopping of the channels sides. When the water finds a definite path across the surface the incision of a new channel may occur.

d) Channel Migration

Channel migration in braided networks is subjected common phenomenon to observe. In general, the bank erosion and channel bed erosion occurs on a time scale spontaneously. However, channel migration in braided rivers is typically much faster than in meandering channels. In the present work it has been focused on the development of oblique flow due to the growth of sand bar developing sharp oblique angle in the braided systems and its impact on hydraulic and morphological parameters at the combined channel.

Several researchers adopted different methodologies and sources such as, Physical Modelling, Field observation, Satellite image, Numerical Modelling to explain the characteristics of the braided river scheme but the braided network appears with several difficulties; the system being characterized by numerous complicated features like- Strong Non-linearities, Unsteadiness, Time scales, Gravitational effects on sediment transport, Partially transporting cross sections, Secondary flows, etc. (Repetto, 2000).

All features related to the behavior of braided channel are very much incorporated with the oblique flow criteria. Channel bifurcations and development of bar generates oblique flow to the main channel which consecutively effects on bank protection works like the Jamuna river at Sirajganj district (Hard point) and so on. On the other aspects, avulsion or incision of new channel is one of the effects of oblique flow. It has been observed in this research work about the influence on hydraulic and morphological parameters of bank protection work due to oblique flow developed by braid bar.

3.2.2 Observations of Complex Phenomenon in Braided River System

The factors that govern the geometry and roughness of an alluvial river are numerous and inter-related. Their nature is such that it is not possible to isolate and study the role as an individual variable. Thus, if one attempts to evaluate the effect of increasing channel depth due to average velocity and additional related variables then not only will the velocity respond to change in depth, but also the form of bed roughness, the position and shape of alternate, middle and point bars, the shape of cross-section, the magnitude of sediment discharge and so on. The role of the variables on resistance and bed form had been discussed by Simons and Richardson (1962).

a) Non-Conformity with Linearity

The interactions between free responses of the system (due to an inherent instability of free surface turbulent flow over an erodible bed) and forced responses (induced by physical constraints, such as curvature, width variations, confluences) crucially affect the topographic behavior of the network.

b) Unsteadiness

In a Braided river system, there exhibit strong unsteadiness in flow field, sediment transport and scour depth formation. No equilibrium configuration exists rather a recursive process of formation and irregular of bed forms and morphological behavior are always observed.

c) Time Scale

Time scale of both bed and bank erosion are comparable. The full coupling between bed and planform evolution is another characteristics of the braided streams. Furthermore bank erosion induces a net effect on sediment transport.

d) Gravitational Effects on Sediment Transport

Sediment load with its gravitational properties mostly effect on the braided river systems actively. It is denoted as relevant factor for bar development and bed formations as well as scour depth determination in braided river morpho-dynamics (Ferdouse, 1978). In braided systems, channel migration is induced by the presence of both strong local deposition & scour and also at confluences accomplishing those effects have to be taken into account in detail.

e) Partially Transporting Cross Sections

Especially, only some branches in braided river system are simultaneously active. Furthermore, in a single channel, sediment transport may occur only in a limited part of the cross section but some partial sediment transport to the braided river system.

f) Secondary Current

Deposition and scour behavior are mostly incorporated with the development of secondary flows and bed deformation often developed by the centrifugal effect induced by curvature of streamlines of depth averaged flow and by inertial effects associated with flow adjustments to spatial variations of channel geometry. In the research, oblique flow through oblique channel has been flown along to left bank inward convex curvature and conveyed consecutive increase of inertia of oblique flow discharge at different formation of oblique flow angle.

g) Erosion

The various mechanisms of stream bank erosion generally fall into two main groups, bank scour and mass failure. In many cases of bank instability, both become evident. Sometimes with either scour or mass failure being dominant.

i) Bank Scour

Bank scour is the direct removal of bank materials by the physical action of flowing water and the sediment that it carries. As flow speed increases, the erosive power of flowing water also increases and scour may occur. Increases in flow speed can be the result of natural or human induced processes. Undercutting of the bank toe is an obvious sign of scour processes. Effective strategies for combating scour are generally aimed at reducing flow speed through vegetation and in some cases through strategic bank or channel works (Queensland Government, 2006).

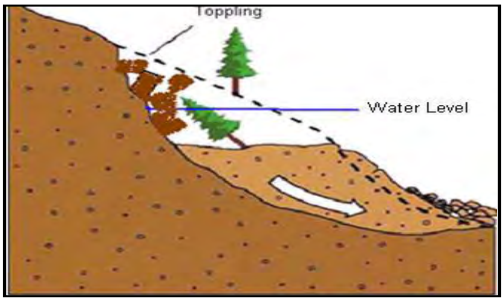


Figure 3.3: Process of Bank Scour and Mass Failure (Source: QG, 2006)

ii) Mass Failure

Mass failure describes the various mechanisms of bank erosion that result in sections of the bank sliding or toppling into the stream. Mass failure is sometimes described as collapse or slumping. Bar and near-vertical banks or areas of slumped bank materials are obvious signs of these processes.

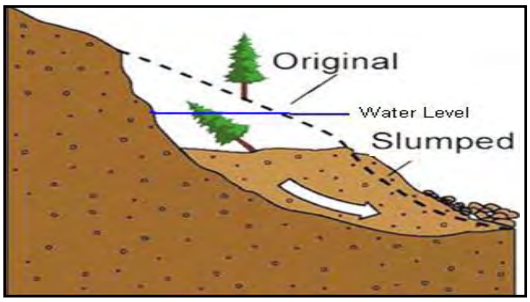


Figure 3.4: Slumping-Common type of Mass failure (Source: QG, 2006)

The causes of these types of failures are often difficult to determine but can include natural or collapse following undermining of the bank toe and slumping as a result of saturation after flooding are common examples of mass failure. Effective strategies for combating slumping or bank collapse are generally aimed at stabilizing the bank toe and restoring bank vegetation and human factors (Queensland Government, 2006).

3.3 Selection of Model Type

It is an urgent need to understand the river behavior (i.e. its fluvial process) to prevent the erosion. Riverbank erosion can be predicted through different approaches. The commonly exercised methods are: i) Physical Modelling ii) Empirical Modelling iii) Mathematical Modelling.

In this research, physical modelling has been selected for better understanding the behavior of the fluvial process of combined channel under action of oblique flow due to the following considerations.

- Identify the natural parameters those control the process.
- Ensure the range of governing parameters responsible for the river characteristics.
- Physical model integrates the appropriate equations those governing the processes without simplifying assumptions that have to be define for analytical or mathematical models.
- More suitable for the investigation of local flow configuration.
- Ability to visualize and observe the process close at hand.
- Use to verify (or extend) mathematical model.
- Test can be carried out under control conditions.
- Tests usually have a smaller time- scale (only a short time is needed).
- Extreme events can be simulated easily.

3.4 Theory of Physical Model

A physical model is a scaled representation of a hydraulic flow condition. Both the boundary conditions (channel bed, sidewalls), the upstream flow conditions and the flow field must be scaled in a appropriate manner. Physical hydraulic models are commonly used during design stages to optimize a structure and to ensure a safe operation of the structure. A hydraulic model may help the decision makers to visualize and to picture the flow field before selecting a suitable design (C. Hubert, 1999). Different types of physical model have been introduced to accomplish physical model. These are as follows:

a) Undistorted Model

When all the similarity requirements are fulfilled in a model or if a model is perfectly similar to its Prototype then the model is said to be undistorted or true scale model. In an undistorted model all the vertical lengths (including diameter of the bed material) and horizontal lengths are reduced with a constant scale factor and the slope ratio will be equal to unity. Results obtained from this type of model are quantitative and can be used successfully in the prototype.

b) Distorted Model

A model is said to be distorted if one or more similarity requirements are not fulfilled. A distorted model is in fact a compromise between a number of requirements and limitations. The rational approach will lead into the vicinity of the optimum point. But trial and error is only the way to find the best compromise.

In a distorted model vertical lengths and horizontal lengths of prototype are reduced to model with different scale factors and slope ratio deviates from unity. Results obtained from a distorted model are deviated from its prototype to some extend and does not represent to its prototype directly and that is why the results obtained from this type of model are qualitative. so profound knowledge, extensive experiences and fair judgments are essential to transfer data of distorted model to its prototype for use. To get precise result an undistorted model is expected but due to some physical and practical problems such as existing model facilities, precise and accuracy in measurements, fulfillment of hydraulic conditions, availability and characteristics of bed material etc. distortion (geometrical distortion, material distortion and the distortion of configuration) is allowed in some cases.

c) Fixed Bed Model

The fixed -bed model is designed with Froude's model law to hold strict dynamic similarity under the framework of rough turbulent flow. In this type of model, the similarity of boundary resistance should also be ensured.

d) Moveable Bed Model

The name moveable bed implies that in this type of model due attention should be paid to sediment transport, erosion, deposition, and bed forming processes. The design criteria of this type of model is almost similar to that of fixed model with a little exception. The exception is that in the moveable bed extensive attention should be paid to attain similarity in incipient motion and bed forming processes and thereby ensuring the bed load movement in the model.

In the present study, for the conveniences of the observation it has been selected in model as 1:50 scale relative to prototype that is denoted as undistorted model except scaling of bed material. Here, sand has been used as bed material to analyze sediment concentration and scour depth, so it has been considered as moveable bed model.

3.4.1 Theory of Model Scale and its Conformity

At first, type of model has to be needed fix either it is distorted or undistorted. Selection of model details has been done based on some literature showing that when all the similarity requirements are fulfilled in a model or if a model is perfectly similar to its prototype then the model is said to be undistorted. A model is also said to be undistorted model when all vertical lengths and horizontal lengths are reduced with a constant scale factor (Sharp, 1990).

The research has been carried out as a basic research so model is considered as undistorted except some distortion of bed materials like sand. The similarity of boundary resistance is ensured in a mobile bed model. Here, mobile bed has denoted that in this type of model proper attention is to be paid to sediment transport, erosion, deposition and bed-forming processes. The research objective is to be focused on river bed so the model bed has been selected as mobile.

Model scale has been selected based on the available facilities in the River Research Institute (RRI), Faridpur. This scaling is needed to convert model data into prototype. The model has been developed at a scale ratio of 1:50 (both for horizontal and vertical) to use the existing out shed model facilities of River Research Institute (RRI), Faridpur.

Horizontal Scale ratio model to prototype, $\frac{L_m}{L_p} = \frac{1}{50}$

Vertical Scale ratio model to prototype, $\frac{Y_m}{Y_p} = \frac{1}{50}$

3.4.2 Conversion of Gravitational Forces and Model Bed Slope

According to Froude model, it asserts that the primary force for accelerating fluid motion is gravity force and that all other forces such as fluid friction and surface tension, etc. can be neglected.

$F_{rm}=F_{rp}$

So, $\left[\frac{V}{(gL)^{\left(\frac{1}{2}\right)}}\right]_m = \left[\frac{V}{(gL)^{\left(\frac{1}{2}\right)}}\right]_p$ (3.1)

Hence, g = gravitational acceleration is constant over the surface of the earth so,

$\left[\frac{V}{(L)^{\left(\frac{1}{2}\right)}}\right]_m = \left[\frac{V}{(L)^{\left(\frac{1}{2}\right)}}\right]_p$ (3.2)

Then, $v_p = \frac{V_m}{\left(\frac{L_m}{L_p}\right)^{\left(\frac{1}{2}\right)}}$ (3.3)

Scales for discharge can be verified by transforming the Froudian requirements into different forms. Q is proportional to the product of velocity and area so,

$V \; \frac{Q}{L^2}$

Substituting in equation (3.1)

$$\frac{Q_p}{Q_m} = \left(\frac{L_p}{L_m}\right)^{\left(\frac{5}{2}\right)} \qquad (3.4)$$

Transformation to take account of time is made using, $V \ \frac{L}{T}$

So, $$\frac{T_p}{T_m} = \left(\frac{L_p}{L_m}\right)^{\left(\frac{1}{2}\right)} \qquad (3.5)$$

The regime theory is applicable for the equilibrium condition of a river. For a particular discharge these conditions are developed over a period of times as the width, depth and bed slope adjusted through movement of sediment until scour balances deposition and the bed becomes stable. Studies have indicated that width is proportional to $(\text{discharge})^{1/2}$, the depth is proportional to $(\text{discharge})^{1/3}$ and slope is inversely proportional to $(\text{discharge})^{1/6}$.

Now when a river is considered to be a model it follows:

$$\frac{L_m}{L_p} = \left(\frac{Q_m}{Q_p}\right)^{\left(\frac{1}{2}\right)} \qquad (3.6)$$

And, $$\frac{Y_m}{Y_p} = \left(\frac{Q_m}{Q_p}\right)^{\left(\frac{1}{3}\right)} \qquad (3.7)$$

Again, $$\frac{S_m}{S_p} = \frac{Y_m}{Y_p}\frac{L_p}{L_m} = \left(\frac{Q_m}{Q_p}\right)^{\left(\frac{1}{6}\right)} \qquad (3.8)$$

3.4.3 Selection of Bed Material and Bank Protection Type

The bed material for a physical model is selected by two criteria. The first criterion provides information on the magnitudes of the required model velocities than on the nature of the bed. The second criterion states that the model bed must be denser than water.

D_{50} = 0.168 mm has been selected for the model. Scaling of bed material is not possible in the existing model facilities of River Research Institute (RRI), Faridpur.

Revetments are usually used in many situations where riverbank is to be protected in its existing position with little work needed to reform or re-shape the bank line or profile (Rahman, 2012). Now at the time, the conventional way for using as bank protective material is stone boulders and geobag. In this research, revetment has been considered as bank protection work which has been protected by both stone boulders and geobag. It is a common engineering practice throughout the world to use stone boulder, loose stones or riprap, stone boulders etc as protective material and to hold river in place by protecting its bank against erosion (Froehlich, 2009).The behavior of launching apron is different for different materials (RRI,Bangladesh, 2010).

Now-a-days, geobag is being used as an alternative bank protective material as it is less costly than stone boulders, easily available, easy to handle and can be prepared quickly. Geobags are effective during the emergency protection works when the banks are under the threats of erosion but stone boulders cannot be constructed or placing of boulder is not possible (Bhuiyan, 2009). Stone boulder has been used as protective material in this work. Geobag has also been used as an alternative protective material to find its falling behavior as well as its efficiency as a bank protective material which is frequently being used in Bangladesh.

3.5 Design of Bank Protection Work

Holding a river in place by protecting its bank against erosion with a continuous covering of loose stones or riprap is a common engineering practice that is used throughout the world. Riveting a bank this way, the armour protection work needs to extend below the lowest bed level expected at the toe of the underwater slope as the streambed scours. The facing can be installed in two general ways: (1) by excavating the bank so that armour material can be placed directly on a prepared slope, or (2) by placing a sufficient quantity of loose stone along the top of the bank so that it will fall gradually and cover the slope as the bank recedes and undermines the stockpile. The first approach might be preferable, but construction is difficult or costly, especially when underwater excavation is needed. The second method has been used widely to stabilize the banks of both large and small alluvial streams by placing the rock supply on existing ground surfaces or in shallow excavations (Froehlich, 2009).

a) General Considerations for Falling Apron Design Practices

The fundamental idea behind placing a volume of protective material at the top of an eroding river bank is that it will be launched or deployed by itself without direct human control when the edge of the rock supply is eroded at its base, allowing the material to fall downward along the slope to form a continuous protective cover.

b) Apron Volume

Falling aprons formed from protective material riprap are often placed horizontally along the toes of embankments that are themselves protected from erosion by a layer of riprap as shown in Figure 3.5. Scour depth and silt factor introduce as two major parameters to determine apron volume of launching apron.

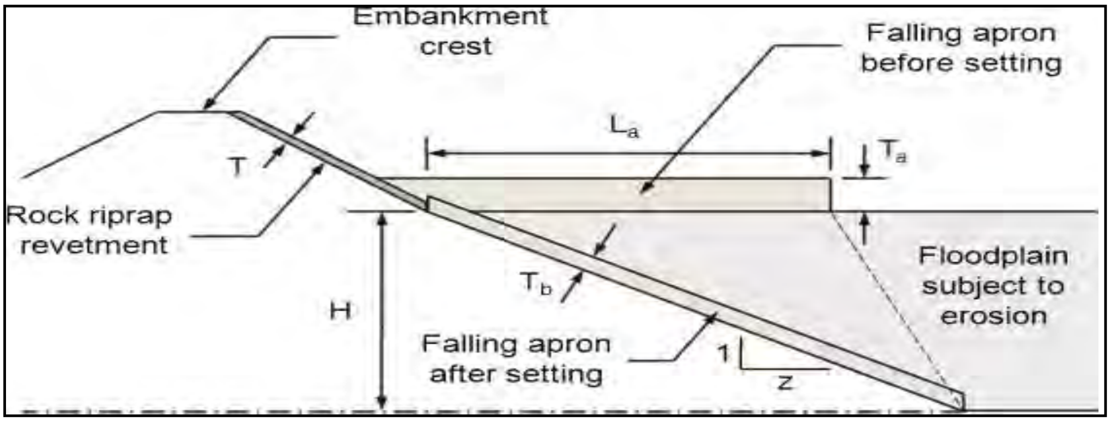


Figure 3.5: Design Consideration of Bank Protection Work (Source: Froehlich, 2009)

$R=.47\ x(Q_p/f)^{(1/3)}$; Here, R= Scour depth and $Q_p= Q_m\ x\ (S_y)^{2.5}$ here, S_y= Model scale, Silt factor, $f = 1.76\ x\ (d_{50})^{0.5}$

To estimate the material volume needed for the apron, the average thickness of bank coverage T_b is usually assumed to equal some multiple of the thickness T of the loose rock facing placed on the upper embankment. If an upper embankment does not exist, or if the upper revetment is made from a material other than what is used in the falling apron, then for design purposes T equals to the thickness of a protective cover that would be constructed on a prepared bank slope from the apron material. Based on this notion, the volume of material that would be needed per unit length of an apron to cover an eroding bank completely is given by, $V_b=T_b\ x\ H(1+z^2)^{0.5}$.

Where, H is the height of the bank that needs to be protected and z is the ratio of the horizontal distance to the vertical distance of the eroded underwater slope covered by the launched material.

c) Apron Shape and Thickness

Spring (1903) proposed that the apron thickness at the junction of the apron and the constructed slope be the same as that of the upper slope covering, with the apron thickness increasing towards the riverbed. In such a case the thickness of the river end of apron will be 2.25 times the thickness of the riprap on the slope. This idea was endorsed by Verhagen et al. (2003) who suggested that constructing an apron in the form of a wedge-shaped layer with more material near the river bank, rather than as a horizontal layer offer more protection at the beginning of the deployment process. Bell (1890), Spring (1903), and Gales (1938), all rely on a 2:1 (horizontal: vertical) underwater slope in their designs of falling aprons used to stabilize sand bed rivers in India. Richardson et al. (2001) suggested that for non-cohesive soil, falling aprons can be designed for underwater slopes of up to 2:1.

d) Effect of Bank Curvature

Depending on nature of channel a multiplying factor is commonly used for estimating the maximum natural scoured depth as 1.25, 1.5 and 1.75 for straight, moderate bend and severe bend respectively (BWDB, 1993). For this physical model test, especially due to oblique flow phenomenon to straight flow it has been assumed 1.75 as severe bend.

3.6 Methodology of the Physical Model Study

To observe impact of oblique flow in a braided river system a physical model study has been implemented to River Research Institute (RRI), Faridpur. A consecutive and successive number of steps have been followed to develop oblique flow phenomenon and its impact. These are precisely described as follows:

a) Site Selection

Proper location has been selected to River Research Institute (RRI), Faridpur incorporated with the availability of site. There have been developed two types of channel, one is main straight channel (60 m length) and another is oblique channel (70 m length). These two types of channel has been bounded with partially mobile boundary and remaining parts fixed boundary. Basically site selection has been confirmed with the conformity of different hydraulic and physical parameters.

b) Construction of Physical Model

Based on the requirement and available facilities, preliminary parameters of the experimental setups have been calculated for fixing model layout. According to the calculated parameters a detail layout of the model has been developed at field (RRI, Faridpur). Three angles have been selected as 20°, 40° and 60°.

c) Calibration of Physical Model

A design calculation has been done to determine hydraulic parameters of the physical model. According to the calculation, calibration of the physical model has been adopted to comply with design parameters. Physical model has been calibrated under earthen bank condition to observe proper situation of hydraulic parameters.

d) Selection of Design Parameters and Number of Model Run

Hydraulic and physical parameters have been selected after calibration of the study. There have been accomplished 21 (twenty one) set of physical model runs to observe different oblique flow conditions with different types of bank protective works.

e) Collection of Various Hydraulic Data

In a set of model run, there have been collected various hydraulic data such as velocity, water depth, scour depth, flow path, thalweg depth and its pattern etc.

f) Data Analysis

After collection of data, a proper and logical analysis has been done by graphical and mathematical solutions to observe its impact.

3.7 Summary

This chapter has been dealt with the essential theories based on oblique flow criterion in a braided river system and its observation for the development of a physical model. To dealt about this study, it has been found apparently that a few researchers have been carried out to observe and study related to this phenomenon. As such of that it has been considered in this research to observe consistently hydraulic and morphological behavior of a braided stream due to oblique flow. A methodology to carry out this physical model test and approaches have been briefed in this chapter.

CHAPTER FOUR
PHYSICAL MODEL SETUP

4.1 General

This chapter is consisted of the setup of physical model according to design parameters, process of the model run procedure, components of physical model facilities and finally measurement procedure of data for selected physical model run. From these predefined independent parameters and other parameters for the physical model has been selected and the model setup has been completed as per design criteria. Bank protection work has been designed from the calibration model run as of T1 to T3 (Table 5.1) and has been related model fixation at all.

4.2 Setup of the Physical Model

In the physical model, it has been observed that hydraulic and morphological parameters of bank protection work due to the effect of oblique flow in straight river bank. Flow angle of oblique channel has been formed by selecting the common point of angle in meeting point of the two channels (Main Channel and Oblique Channel). The oblique flow channel center line and the main channel center line has been designed and constructed in the field as 20^0, 40^0 and 60^0. The Oblique channel has been laid and constructed to the meeting point angles according to the design of model layout plan. Outer boundary of 20° as the right side of oblique channel and outer boundary 60° as left bank has been constructed first and in between boundary has been constructed temporary by brick which is wrapped by polyethylene material.

Physical model facilities of River Research Institute (RRI) have been accomplished with the model layout. For the investigation of discharge ratio of two channel, velocity, proper scour development and other hydraulic parameters with design value respective to the model facilities has been at first verified as calibration tests for different flow angle (20°, 40° and 60°) but conveying discharge ratio (Q_r)-1.4 at no protection work at straight right bank condition. Physical model calibration has been done in order to fix the water level in gauge point of weir, designed velocity distribution, efficiency of model run, operation of gate valve, depth of water, tail gate position etc. Now a design calculation table has shown in the following, from which the efficiency and other hydraulic parameters of the model has to be ensured as well as calibrated properly.

As a bank protective work of launching apron for right bank side of the combined channel, Stone boulder identified as scaled stone boulders has been used. Details analysis has been carried out to obtain the vulnerability of oblique flow angle with relative discharge of both channels. It has been observed for two types of bank protective materials such as stone boulders and geobag. Basically, it has been determined the hydraulic and morphological parameters of bank protection work due to oblique flow regarding to scour depth and distribution of flow velocity.

Geobag has been used as an alternative protective material for the maximum oblique flow angle as 60^0. The behavior of the protective work and launching apron, velocity, flow line, scour pattern has been observed and determined deliberately.

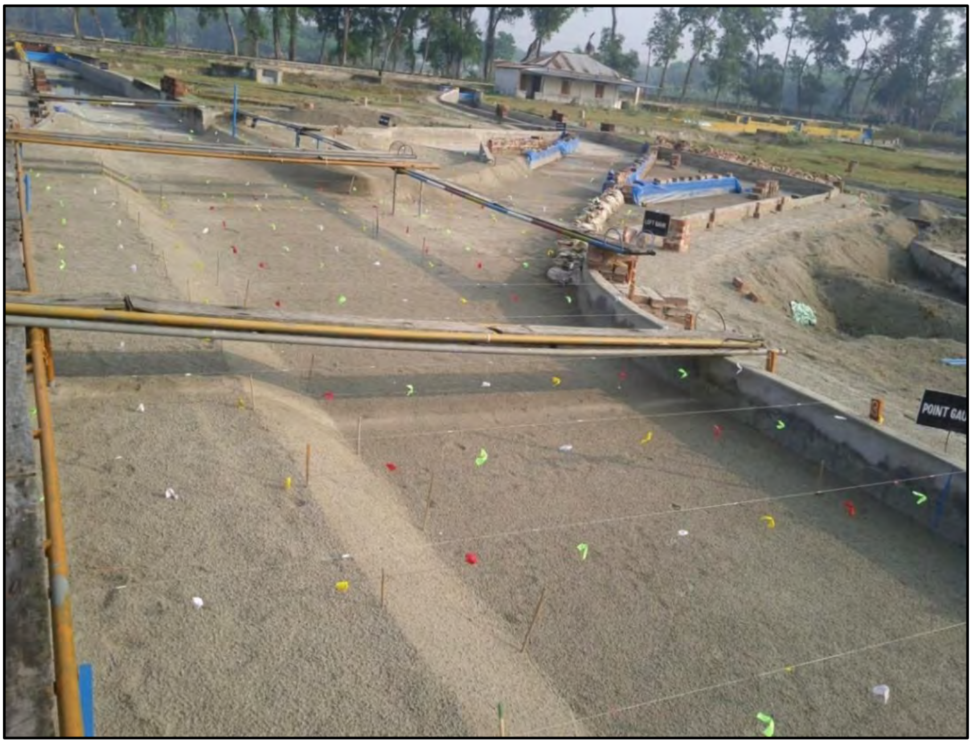


Figure 4.1: Plan of Study Area in Physical Model Bed

4.3 Different Components of the Physical Model

The physical model facility has been implemented at RRI, Faridpur in an open air space facilities. The main channel and oblique flow channel bearing length 60.00 m with 2.75 m (average) width and 80.00 m with 2.5 m (average) width respectively. Width of combined channel has been kept to 3.45m (average). Different components of the physical model, model construction picture and important pictures of experimental setup has been presented in detail at Appendix-A.

The physical model facility has comprised of two types of channel one straight and another oblique bifurcating by the sand bar. There have a periphery storage pools for water supply, weir, stilling basin, a re-circulating canal, measuring device such as, point gauges, tail gauges, etc. The different components of the model have been described in Figure 4.2.

a) Straight Channel

The straight channel with calibration basin has been constructed for main straight channel. The length of flume is about 60 m upto the discharge weir inclusive stilling basin which denoted as main channel. Main channel having a bottom width of 2.5m, top width of 3.00 m and channel height of 0.35 m at calibration section from where main channel discharge has been maintained.

b) Oblique Channel and Combined Channel

Oblique channel has been used as secondary channel having a length of 70 m upto discharge weir inclusive with stilling basin and other intermediate ancillary parts. At the calibration section, it is 0.3 m high and 2.5 m wide smoothened brick sidewalls. The two channels has met together and flown as a combined channel. Average top width of combined channel is 3.45 m at the downstream part fixed portion.

c) Water supply facility

The Supply of water is an essential part for the physical model facility. The pump house is located on the western side of storage pool. There are four centrifugal (each of 1.5 HP) electric water pump has been connected with the system. The total

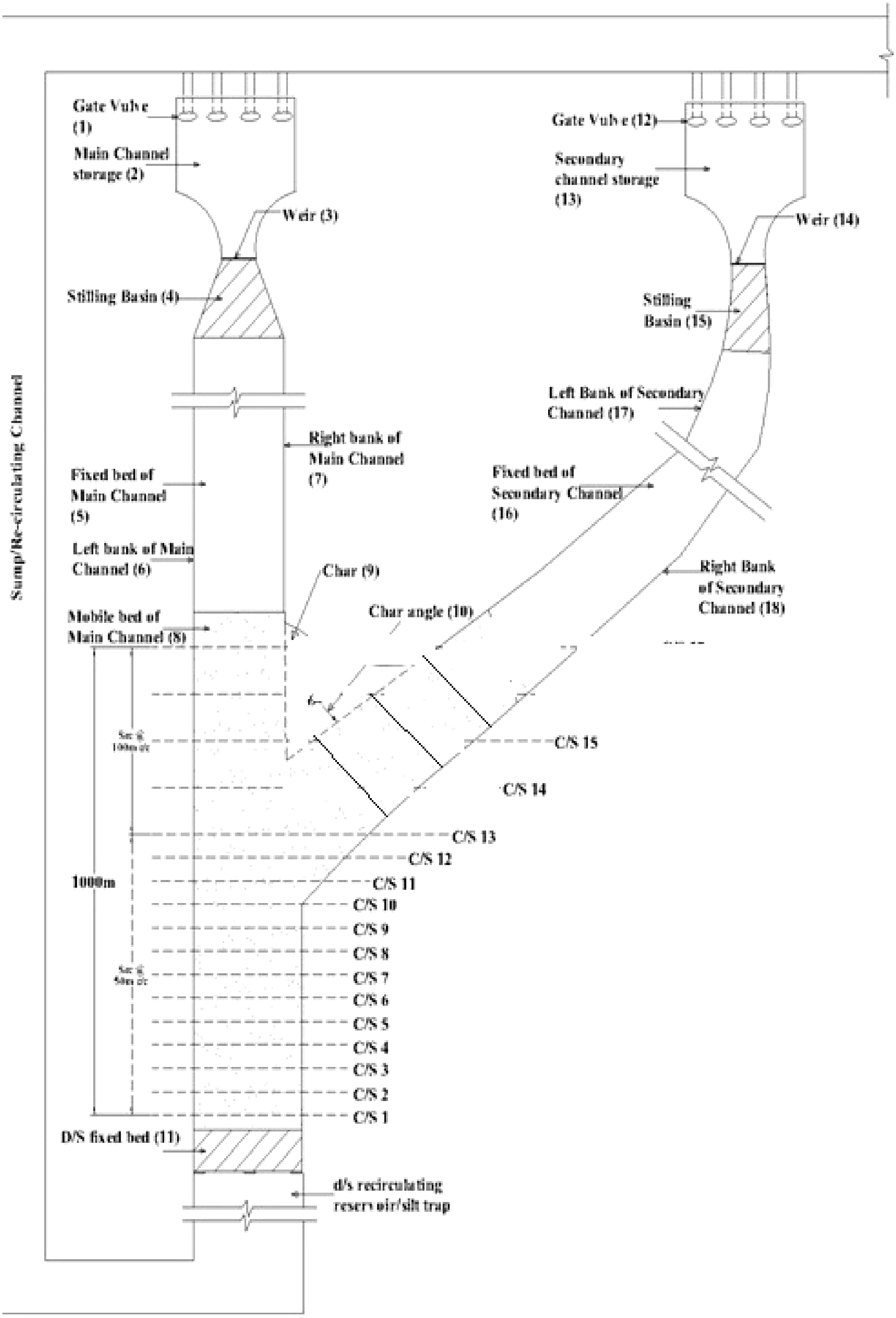


Figure 4.2: Physical Model Layout with Line Diagram

capacity of these pumps are 400 l/s. These pumps have been used to supply design discharge with seepage and other losses to storage pool.

d) Upstream Reservoir

The upstream reservoir is connected to the re-circulating tank from which water enters the storage pool of the weir. Water has been allowed to flow towards controlled gate valve to the storage pool when water level is sufficient for the required discharge checked by discharge gauge just at the intake of the individual channel like both main channel and oblique channel.

e) Downstream Reservoir

The purpose of this reservoir is to store water for delivering water to the re-circulating canal although there have some minor losses of water as evaporation, seepage loss, etc.

f) Discharge Weir

At the intake point of storage pool for both main channel and oblique channel a Rehbock weir has been installed for measuring the quantity of water i.e to allow the desired discharge and to observe the state flow (uniform flow). The stilling basin is connected with Rehbock weir (Figure 4.2). A calculation sheet has been done to determine the effective head of water above the crest of rehbock weir for the measurement of discharge of main and oblique channel respectively (Appendix-A).

g) Re-circulating Canal or Sump

The re-circulating canal is located on the last part of facility. It has connected the downstream reservoir with the upstream reservoir/sump and allows the water to fall back for re-supply. It is 100m long, 2 m wide and 2.0 m deep. It is capable for draining all the water supplied to the system. There are three drainage plugs connecting the sand bed and re-circulating canal. This plugs are can be used for drying up the bed.

h) Stilling Basin

When the water comes from weir that time it has conveyed much energy and it has to be reduced at a level by stilling basin or wall barrier with the depression of bed level between stilling basin and calibration flume so that it cannot create any hydraulic jump or wave induced flow in the model (Figure- 4.2).

i) Embankment

The physical model based research has been introduced to observe the effect on hydraulic and morphological parameters of bank protection work at 3.5 m wide embankment due to oblique flow as the behavior of braided channel.

j) Discharge Gauge and Reference Plate

There have been attached two discharge gauge one for main channel and another for oblique channel at the intake of rehbock weir. The point gauges is used for water level readings as the measurement of water surface slope for different zone. At the beginning of every measurement first the elevation of accompanying reference plate has been measured then water level has to be adjusted from calculation by adjusting water depth through point gauge. The point gauges are all manually operated equipment to which an adjustable screw is attached. With the movement of the screw the body of the point gauge slides up or down on a scale. Measurement is taken from the scale reading, corresponding to the zero marked on the point gauge body.

k) Strainer

Strainer has been provided at the end of downstream reservoir to free water from any kind of geobag or any other type of materials like leaves, paper, insects etc.

l) Fixed Bed

Fixed bed has been developed from end of stilling basin to the calibration point of both channel. A calibration flume has been marked at one third of the fixed bed to check discharge, water depth and velocity. Fixed bed is essential to control the flow as a uniform flow criteria not to create any complex flow phenomenon (Figure- 4.2).

4.4 Equipment Used in the Physical Model

The different equipments have been used in the experiment are presented below:

a) Measuring Lines

To indicate the layout plan of the physical model by the co-ordinate system, here (X,Y) ordinate system has been introduced relative to a assumed coordinate. The X-distance as measured from a peg to a particular vertical along a cross section. The Y distance is the accumulated distance upstream from the first transect in a study site. The Z-distance is the elevation of the channel bed at the X, Y-coordinate above or below the datum.

b) Velocity Meter

2D velocity meter and 3D Acoustic Doppler velocity meter have been used for velocity measurements. 2D velocity meter has been executed to measure velocity up to 250 cm/s.

Figure 4.3: 2D Velocity Meter

3D ADV meter of probe no. A1054F has been used in the research. The probe head includes one transmitter between two receivers. The remote sampling volume is located 5 cm from the tip of the transmitter. ADV system equipped with N receivers records simultaneously 4N values with each sample that is, for each receiver, a velocity component, signal strength value, a signal-to-noise (SNR) and a correlation value. The signal strength, SNR and correlation values are used primarily to determine the quality and accuracy of the velocity data.

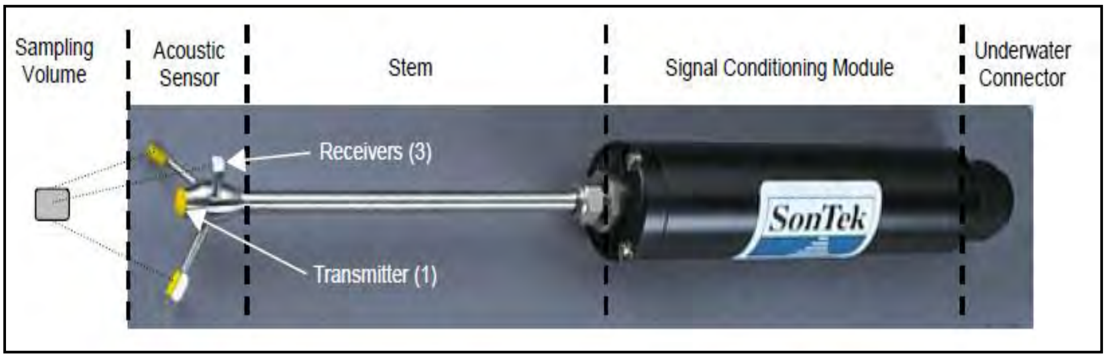


Figure 4.4: 3D Acoustic Doppler Velocity Meter (ADV)

Main features of the ADV meter are:

- Three-axis velocity measurement
- Sensor mounted on a 25cm stem
- High sampling rates — up to 50 Hz
- Small sampling volume — less than 0.1 cm^3
- High accuracy: 1% of measured range
- Large velocity range: 1 mm/s to 2.5 m/s
- Excellent low-flow performance
- No recalibration needed

Measuring Scale, measuring tape etc. have been used as some supporting materials for the experimental setup and collection of necessary data in the model.

4.5 Steps Undertaken during the Experimental Setup

Twenty one (21) numbers of experimental run has been carried out in the Physical Model with upstream and downstream fixed boundary and also with variable hydraulic conditions. Calibration of the model has been carried out for fixation of model boundary, discharge, scour velocity, flow condition with the calculated design conditions (Table 4.1). Thus the whole designed experimental procedure has been preceded in the physical model run.

a) Fixation of Reference Level

A fixed bench mark level (31m RL) has been denoted to have the elevation of model bed from wire which has been tied in reference peg for measurement of bathymetry by scale. The water level and bed level measurement has been taken with respect to a specific reference level.

b) Calibration of the Model

Calibration for Rehbock weir and sand feeding amount has been determined to ease the work for conducting experiments. Calibration test has been done to fix not only the water level but also discharge, design velocity of the calibration flume and at upstream weir for a fixed discharge, time scale for the dynamic equilibrium condition, upstream and downstream boundary condition.

c) Calibration of Rehbock Weirs

The discharge equation of a Rehbock weir is (ISO-1975, Dekker and van Voorthuizen, 1994) as follows:

$$Q_R = C_c^{0.67}(2g)^{0.5}\, b h_c^{1.5} \qquad (4.1)$$

$$\text{Here, } h_c = (h + h_k) = h + 0.0072 \qquad (4.2)$$

$$C_c = 0.602 + 0.083\,(h/p) \qquad (4.3)$$

Where,

Q_R = Discharge measured over the Rehbock weir.

C_c = Coefficient of discharge.

b = Measured width of the weir.

h_c =The effective piezometric head with respect to the level of the crest.

h = Measured head.

h_k= An experimentally determined quantity which compensate for the influence of surface tension and viscosity.

p = Apex height in meter.

Calibration chart for weir has been completed and for different discharges with the water depth in the storage pool. Discharge gauge has been fixed with zero reading according to the chart and adjusted if needed for each experimental setup.

d) Calibration of Sand Feeder

Calibration for volume of sand feeding has been done in order to supply the sediment corresponding to discharge so that for the control of fluvial behavior of the channel.

e) Calibration Section

Two calibration sections have been set up at main channel and oblique channel to check the discharge and velocity of the stream.

f) Discharge Measurement

The individual discharges of main channel and oblique channel has been measured with the respective Rehbock discharge measurement weirs. The water level at the crest of the weirs has been measured with discharge gauges, with an accuracy of 0.05 mm. The zeros of the point gauges are set by filling the two channels with water up to the crest level of the weirs, the point gauges are then being adjusted and the zero is fixed.

g) Preparation of Initial Bed

Fixed bed of the calibration flume has been provided before movable bed so that uniform flow can be obtained before it enters at mobile bed zone. Levels along each cross section have been calculated to maintain the bed slope with respect to bench mark. The initial bed has been prepared by existing sand facilities and each bed has to be prepared after consecutive three test run.

h) Design of Launching Apron and Geobag

Experimental setup for test run T1, T2 and T3 have been carried out and data has been analyzed to design the bank protection work such as Stone boulders and Geo bag. Again at unprotected condition scour depth for three test run have been found respectively at T1-5.5 m, T2-6.85 m, T3-10.60 m. Scour depth for test run T3 has been taken into consideration for the calculation (Das, 2014 and Alam, 2014).

Bank protection work done by stone boulder as protective material

Design Data: (Analyzed for Physical model setup)

Discharge in model, $Q_m = 0.360\ m^3/s$

Discharge in Prototype, $Q_p = Q_m \times (\text{Vertical Scale})^{2.5}$

$Q_p = 0.36 \times (50)^{2.5}$

$= 6363.96\ m^3/s$

Size of bed material, d_{50} $= 0.168$ mm

Table 4.1: Design Parameters of Physical Model setup

Particle Density, ρ_p - 2650 kg/m3; Water Density, ρ_w - 1000 kg/m3;

Relative Density - 2.65, Kinematic Viscosity - 1.2x10^{-6} m^2/s,

Dynamic viscosity - 1.2x10^{-3} kg-s/m^2

Description	Unit	Model		Prototype		Scale	
		OC[1]	MC[1]	OC[1]	MC[1]	OC[1]	MC[1]
Length, L	m	70	60	3500	3000	50	50
Width,T (Top) (calibration section)	m	2.50	3.0	125	150	50	50
Width, W (Bottom) (calibration section)	m	2.50	2.50	125	125	50	50
Water depth, h	m	0.20	0.20	10	10	50	50
Bed slope, S_f	-	0.00007	0.00005	0.00007	0.00005	1	1
Discharge, Q	m^3/s	0.21	0.15	3712.31	2651.65	17677	17677
Average velocity, V	m/s	0.42	0.27	2.97	1.93	7.07	7.07
Wetted perimeter, P	m	2.90	3.23	145.0	162.0	50	50
Cross-sectional area, A	m^2	0.50	0.55	1250	1375	50	50
Hydraulic depth, D= (A/T)	m	0.20	0.18	10.0	9.16	50	50
Hydraulic radius, R= (A/P)	m	0.172	0.169	8.62	8.49	50	50
Roughness height (K_s)	m	0.001	0.001	0.001	0.001	1	1
Cr. Velocity (Vanrign), V_{cr}	m/s	0.264	0.263	0.398	0.397	1.51	1.51
Chezy's rough. Coeffi., C_z	$m^{0.5}$/s	59.668	59.550	90.09	89.92	1.51	1.51
Med. particle diameter, d_{50}	m	.000168	.000168	.000168	.000168	1	1
Dim.less particle dia., D*	-	3.40	3.40	3.40	3.40	1	1
Cr. Shields parameter, θ_{cr}	-	0.05567	0.05567	0.05567	0.05567	1	1
Froude number, F_r	-	0.32295	0.21129	0.32295	0.21129	1	1
Shear velocity, u*	m/s	0.01088	0.00913	0.07694	0.06454	7.07	7.07
Critical shear velocity, $u*_{cr}$	m/s	0.01227	0.01227	0.01227	0.01227	-	-
Particle Reynolds No., R_e*	-	2.048	2.048	2.048	2.048	1	1
Reynolds number, R_e	-	72.269	46.225	25547	16340.5	353.5	353.5
Fall velocity, v_w	m/s	0.02090	0.02090	0.02090	0.02090	1	1
Shear velocity/Fall velocity (u*/ v_w)	-	0.52	0.43	3.68	3.04	7.07	7.07

1: OC- Oblique Channel ; MC- Main Channel

Highest water level = 14.963 m (RL)

Lowest water level/ Bed Level = 4.713 m (RL) [Average value]

Average velocity, V = 3.88 m/s

Calculation for Scour Depth:

Silt factor, $f = 1.76\ d_{50}^{0.5}$

Here, d_{50}= Size of bed material =0.168 mm

Now, Silt factor, $f= 1.76 \times (0.168)^{0.5} = 0.721$

According to Lacy's regime scour depth, $R = 0.47 \times (Q_p/f)^{0.33}$

Where, R = Scour depth (m)

$R = 0.47 \times (6363.96/0.721)^{0.33}$

= 9.42 m (RL)

Determine Maximum Scour Depth below Lowest Bed Level:

Consider, Multiplying factor, x= 1.75 (For Severe bend)

Depth of scour = Rx= 1.75 x 9.42 = 16.48 m (RL)

Maximum anticipated scouring bed level = (HFL- Rx)

= (14.963- 16.48) m (RL)

= -1.517 m (RL)

Depth of anticipated scour depth, D = (RX-y) = (16.48-10.25) = 6.23 m (RL)

Where, y = HFL- LWL ; Observed max. scour depth for test run T3 = 10.60 m (RL)

Design scour depth, D =1.5 times of 10.60 m = 15.90 m ≈15.00 m (RL)

Determination of Volume of Launching Apron and its length & Thickness:

Thickness of launching apron is calculated by different ways:

i) According to Inglish formula, T = 1.11 m

ii) According to Spring for Slope 3inch/mile and fine bed materials, T = 0.864 m

iii) According to Gales, For Q = 1.5 million to 2.5 million cusec, T = 1.290 m

Among the above calculation considering thickness of launching apron, T =1.11 m.

Launching slope of 1:2 and the volume of launching apron is calculated 46.00 m^3/m.

Length of Launching apron = 1.5 x D = 1.5 x 15 m = 22.5 m

Thickness = 1.9 x T = 1.9 x 1.11 m= 2.10 m

Design of Protection Work by Stone Boulder as Protective Material:

Maximum average velocity, V = 3.880 m/s =12.726 ft/s

From BWDB, Design Manual, volume - I (Page no-208, Table-3, case - II) grading specification has been selected as follows: (Grading of riprap)
a) 100% smaller than 30 inch b) At least 20% larger than 24 inch c) At least 50% larger than 20 inch d) At least 80% larger than 12 inch.

Design of Protection Work by Geobag as Protective Material:

All values with the design has been determined from model and JEMREMP manual. According to USACE equation based on incipient motion of geobag, we have considered a geobag size as 2.8 cm X 2.4 cm X 0.8 cm. After prototype conversion weight of the geobag has found 740 kg (1.4 m X 1.2 m X 0.4 m) , length of influence in model = 5.5 m (5 m at revetment and 0.5 m on straight portion). Literature and Manual represents that 126 kg geobag can sustain 4.2 m/s velocity (BWDB, 2010). Based on the incipient motion of this study maximum size of geobag (740 kg) size has been selected as an initial option for bank protection material. Then small geobag (250 kg) has been used as final protective material to observe its performance.

i) Measurement of Each Experimental Set-up

The following data has been obtained from each experimental setup:

- Bathymetry measurement before and after each run
- Flow Velocity, Surface velocity and its float
- Water surface slope
- Scour depth and its pattern

4.6 Summary

In this chapter, the detail procedure to set up the physical model in River Research Institute (RRI), Faridpur with open air facility has been briefed. The different components of the physical model has been elaborated in detail. Also the steps taken during the whole experimental period has been detailed out here. Based on the theoretical background and other related parameters, twenty-one (21) numbers of experiment have been observed in this physical model study.

CHAPTER FIVE

RESULTS AND DISCUSSIONS

5.1 General

The observation of the effect of oblique flow on the main channel and its bank protection work has been demonstrated in this chapter. An oblique flow normally develops when an inclined oblique flow channel meets with the main channel that affects the bank protection work. Thus oblique flow has influenced on hydraulic parameters of the main channel which is vulnerable due to the combined flow. The protection work is comprised with stone boulder and different sizes of geobag. Different hydraulic behavior due to the presence of oblique flow such as velocity distribution, scour depth profile, dominant velocity for scour, thalweg channel pattern, flow line of the channel have been observed, measured and analyzed under different oblique flow angle (Θ_o) and discharge ratio (Q_r) conditions. Oblique flow has influenced the hydraulic parameters with respect to both oblique flow angle and discharge ratio. It has been observed in the physical model that the bank protection work is vulnerable for the combination of different oblique flow angle and discharge ratio.

5.2 Physical Model Lay-out

The physical model which has been constructed in River Research Institute (RRI), Faridpur identifying with major different segment in the following graphical view (Figure 5.1). Here it has been shown that main channel (M.C) and oblique channel (O.C) has been merged together like a combined channel, at which there has been given emphasis on three zones such as meeting zone (CS-14 to CS-12), mid zone (CS-11 to CS-09), downstream zone (CS-08 to CS-06) of channel with respective cross-sections. on the other hand, cross-sections exclusive of those cross-sections have not been analyzed due to the influence of tailgate as CS-05 to CS-01 and upstream of the channel as CS-15 to CS-17. The whole model has been distributed among seventeen (17) cross-sections, but here, for the convenience of the analysis denoted cross-sections has been observed such as CS-14 to CS-06 at all.

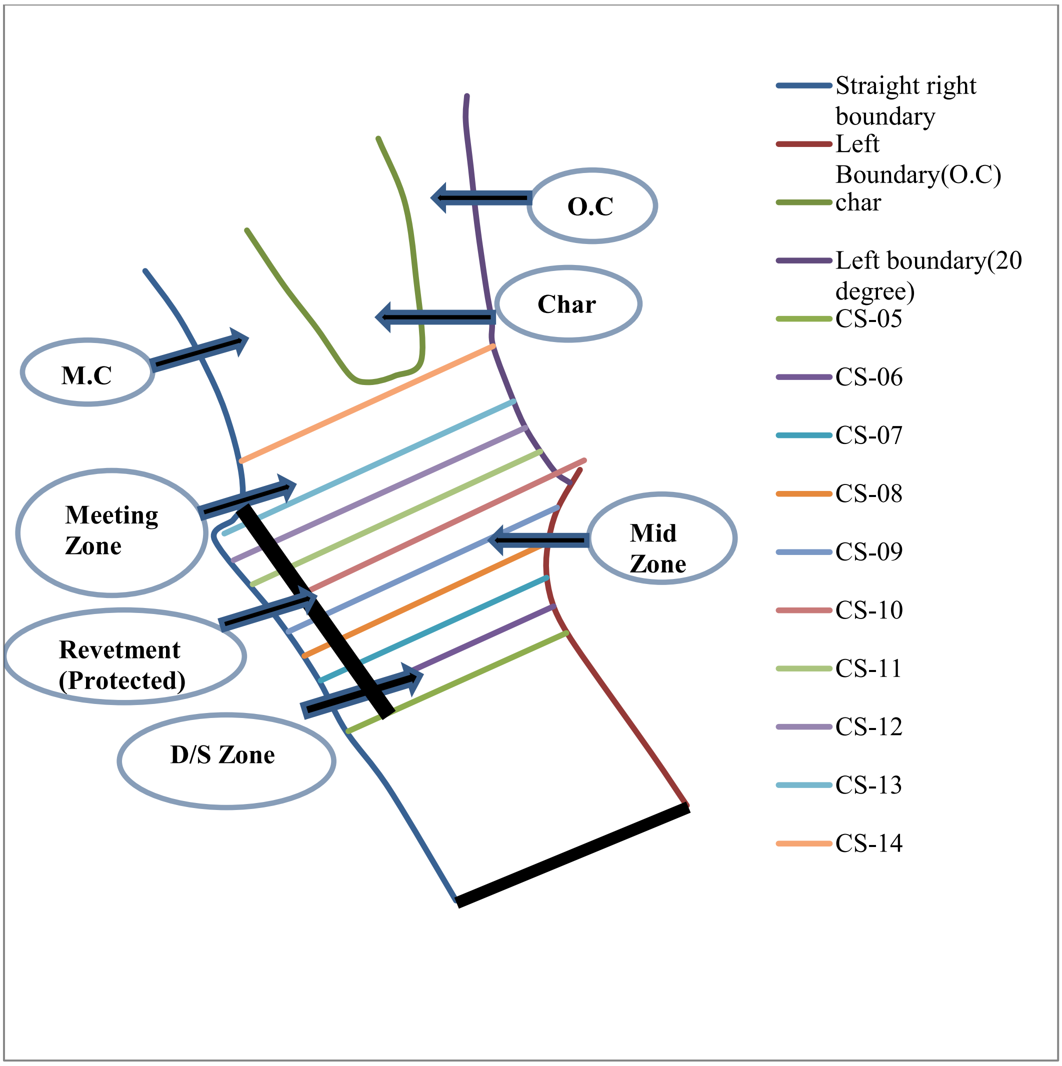


Figure 5.1: Different Zones of Combined Channel

5.3 Test Parameters

On account of a view to river bank protection work such as stone boulder and geo-bag have been used to protect stream flow. Based on those materials, several tests have been carried out as T1 to T20 and T0 which has been shown in the following table (Table 5.1). At first three (3) test runs as T1 to T3 have been done to calibrate the model for rational synchronization of design velocity and discharge with proper investigation at which right bank of the model has been arranged with no protective work as like earthen embankment. After analyzing these point of views, a series of investigation has been carried on at variable conditions of model parameters.

During these tests, different hydraulic parameters have been selected that are followed in the physical model setup. Basically, it has been emphasized on the flow phenomenon at the combined channel. So, three major cross-sections have been selected which belongs to the combined channel those are CS-13 for meeting zone, CS-11 (velocity distribution) / CS-10 (scour depth) for mid zone and CS-06 for downstream zone (Figure 5.2). Detail of test run are shown in the following table:

Table 5.1: Detail of Test Run in the Physical Model

Test		Bank Protection (Straight Bank)	C/S Provided	Q_m (litre/s)	Q_o (litre/s)	θ_o Degree	Q_r (Q_o:Q_m)
T1		Unprotected	Unprotected	150	210	20^0	1.4 : 1
T2				150	210	40^0	1.4 : 1
T3				150	210	60^0	1.4 : 1
T4	Set A	Stone boulder	C/S (14 to 5)	163	197	20^0	1.2 : 1
T5		Stone boulder	C/S (14 to 5)	150	210	20^0	1.4 : 1
T6		Stone boulder	C/S (14 to 5)	138	222	20^0	1.6 : 1
T7	Set B	Stone boulder	C/S (14 to 5)	163	197	40^0	1.2 : 1
T8		Stone boulder	C/S (14 to 5)	150	210	40^0	1.4 : 1
T9		Stone boulder	C/S (14 to 5)	138	222	40^0	1.6 : 1
T10	Set C	Stone boulder	C/S (14 to 5)	163	197	60^0	1.2 : 1
T11		Stone boulder	C/S (14 to 5)	150	210	60^0	1.4 : 1
T12		Stone boulder	C/S (14 to 5)	138	222	60^0	1.6 : 1
T13		Stone boulder	C/S (14 to 5)	Closed	360	60^0	Full
T14		Geobag (L-740kg)	C/S (12 to 5)	163	197	60^0	1.2 : 1
T15		Geobag (L-740kg)	C/S (12 to 5)	150	210	60^0	1.4 : 1
T16		Geobag (L-740kg)	C/S (12 to 5)	138	222	60^0	1.6 : 1
T17		Geobag (L-740kg)	C/S (13 to 7)	Closed	360	60^0	Full
T18		Geobag (S-250kg)	C/S (11 to 7)	163	197	60^0	1.2 : 1
T19		Geobag (S-250kg)	C/S (11 to 7)	150	210	60^0	1.4 : 1
T20		Geobag (S-250kg)	C/S (11 to 7)	138	222	60^0	1.6 : 1
T0		Stone boulder	C/S (14 to 5)	360	Closed	60^0	Full

5.4 Velocity Distribution at Combined Channel due to Oblique Flow

According to the Table 5.1, physical modelling has been performed depending upon some variables and looked upon the velocity distribution at combined channel due to oblique flow for the T4 to T20 and T0.

According to different conditions of the oblique flow angle and discharge ratio, twelve test runs has been grouped among different categories of arrangement. First three test runs have been continued for the calibration purpose as well as to observe oblique flow phenomenon for no protective work condition. Then comparison of study has been conducted by two factors, for each constant angle like 20^0, 40^0, 60^0 with variable discharge ratio 1.2, 1.4 and 1.6 were considered. Based on the bank protection material as stone boulder, 10 (Ten) test run have been carried out namely T4 to T13. In addition T0 test run has been performed to observe its behavior conveying only straight flow. For the purpose of analysis, these experiments have been distributed among three sets and three (3) experiments are grouped in each set.

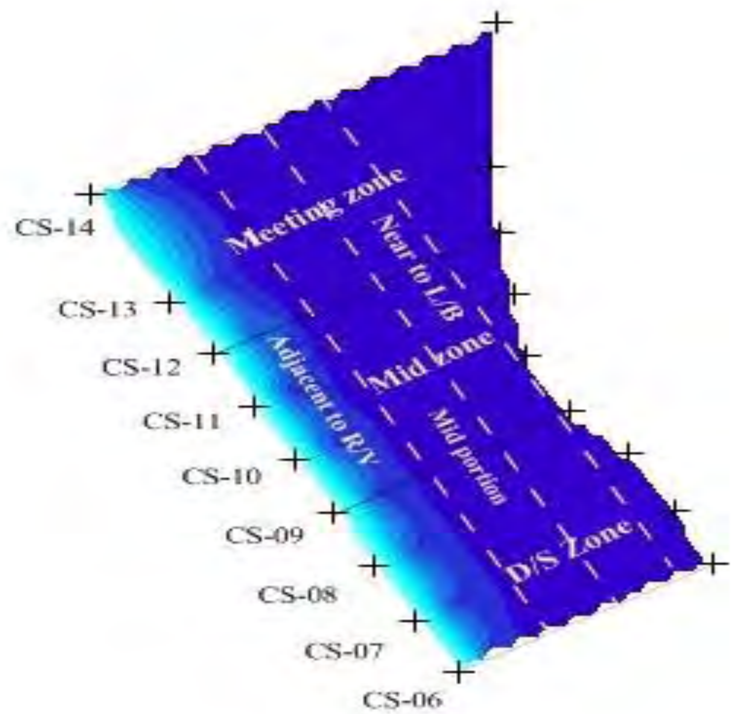


Figure 5.2: Zone Profiles of the Combined Channel

According to Figure 5.2, the whole combined channel has been differentiated among three major zone, these are a) Meeting zone: at where two dominating flows have met together, b) Mid zone: mid area of combined channel, and c) Downstream zone: forms where it acts as a single channel. At longitudinally, three major areas have been selected which signifies the major impact on combined channel, which are, a) adjacent to revetment b) mid portion of combined channel c) near to left bank (brick wall). In every test run, velocity has been observed at every 50 cm c/c spacing of specified points at each cross-section of the channel.

i) Observation from Test Run T0

According to Figure 5.6 (a) and (b), for the test run T0, whereas full discharge (Q) has to be flown at a single main channel no oblique channel has accompanied. Here, it has been found that a uniform range of velocity 3.15 to 3.64 m/s throughout the channel due to a steady discharge (Q) is being allowed without any oblique flow and secondary current.

ii) Observation from Test Run T4

According to Figure 5.3 (a) and (b), velocity has been gradually increased to downstream zone throughout the channel from 2.7 to 3.6 m/s although it is lower than T0. It has been observed that velocity distribution has influenced to the direction of oblique flow angle (θ_o). Also for the vulnerability of bank protection work, velocity has been increased consecutively adjacent to launching apron flowing towards downstream zone. Even though a high velocity zone has been developed at the downstream zone due to the recovery of stream.

iii) Observation from Test Run T5

According to Figure 5.3 (a) and (c), velocity has been moved increasingly towards downstream zone with its extent of area through out of the channel from 2.8 to 3.7 m/s just like T0 as maximum velocity range. It has been found here velocity has consequently enhanced than T4 and it's recovery zone forwarded to upstream from downstream zone. Thus there have been developed vulnerability adjacent to launching apron.

iv) Observation from Test Run T6

According to Figure 5.3 (d), It has been found in the test run that velocity has distributed uniformly somehow from 2.9 to 3.4 m/s throughout the combined channel but it has been slightly reduced from T4,T5 and moreover T0. Its extent of area of velocity distribution has been compared for highest oblique flow discharge with previous test run but attracted to left bank.

v) Observation from Test Run T7

According to Figure 5.4 (b), progression of oblique flow angle, velocity has increased towards downstream but attracting to left bank from 3.3 to 3.7 m/s as like T0. It has been observed that adjacent to launching apron velocity has been comparatively lower than mid portion velocity of the channel.

vi) Observation from Test Run T8

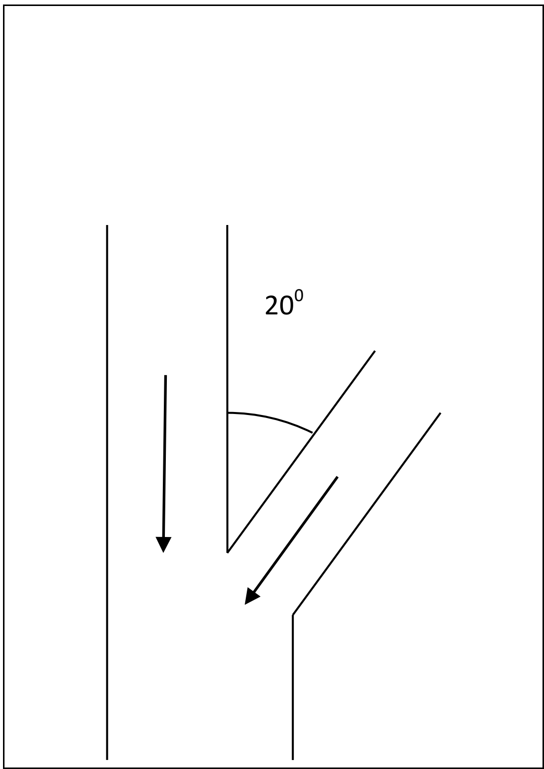
Now, according to the condition of Figure 5.4 (c), Then increasing with oblique flow discharge through oblique channel, velocity has gradually enhanced from 2.6 to 4.1 m/s towards downstream zone which is significantly more than T7 and T0. Velocity has been developed with its extent towards bank lines along to launching apron with its vulnerability. Here, it has been analyzed that recovery zone of stream at downstream zone has longitudinally protruded eventually to upstream zone. Basically, velocity distribution has intensified to the angle of oblique flow direction.

vii) Observation from Test Run T9

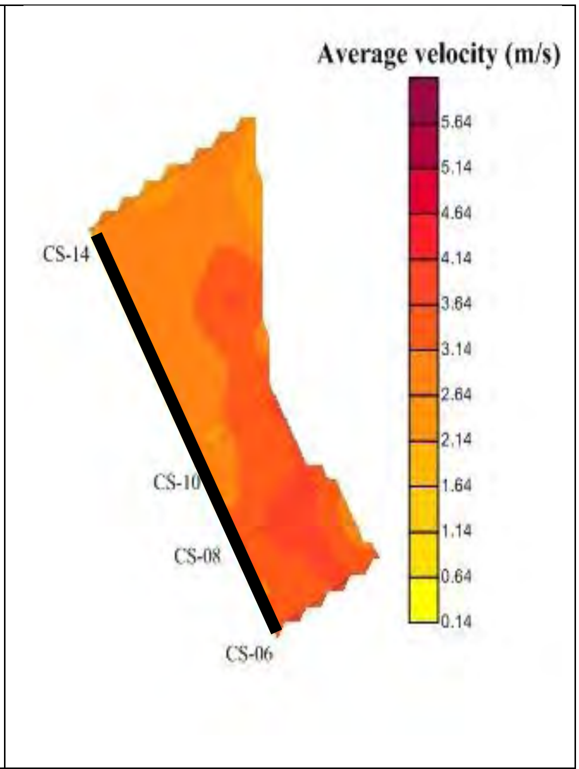
Now, according to the condition of Figure 5.4 (d), further increase of oblique flow discharge, velocity has been enhanced towards downstream zone from 2.6 to 4.5 m/s that is comparatively higher than T7, T8 and T0. It has been observed that velocity has been increased with its vulnerability at downstream zone and consecutively enhancing its extent of area adjacent to launching apron.

viii) Observation from Test Run T10

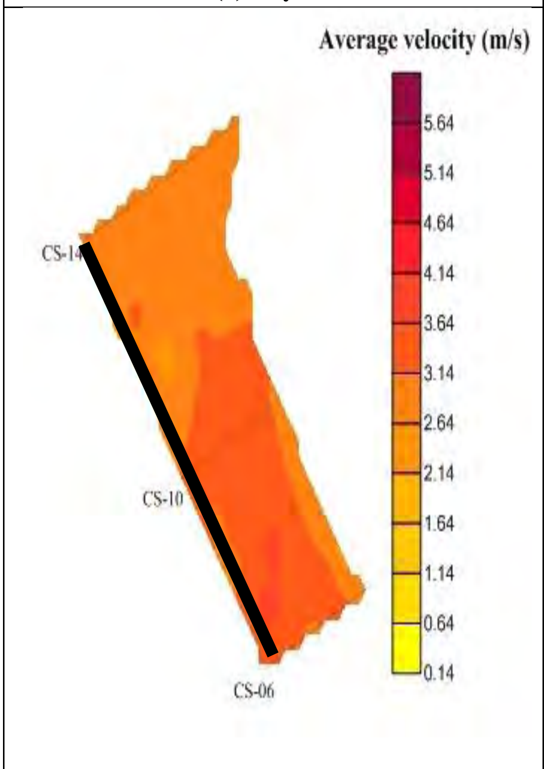
According to Figure 5.5 (b), here, in the experiment T10, oblique flow angle has been increased to 60^0 that inducing a trigger mode in velocity distribution towards



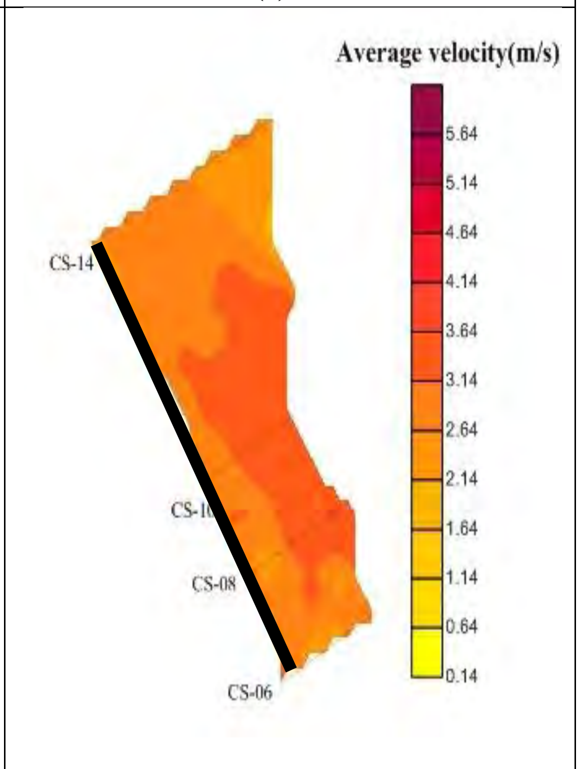
(a) Layout



(b) T4



(c) T5



(d) T6

Figure 5.3: Velocity Distribution for Variable Q_r at Fixed Θ_o:- 20^0

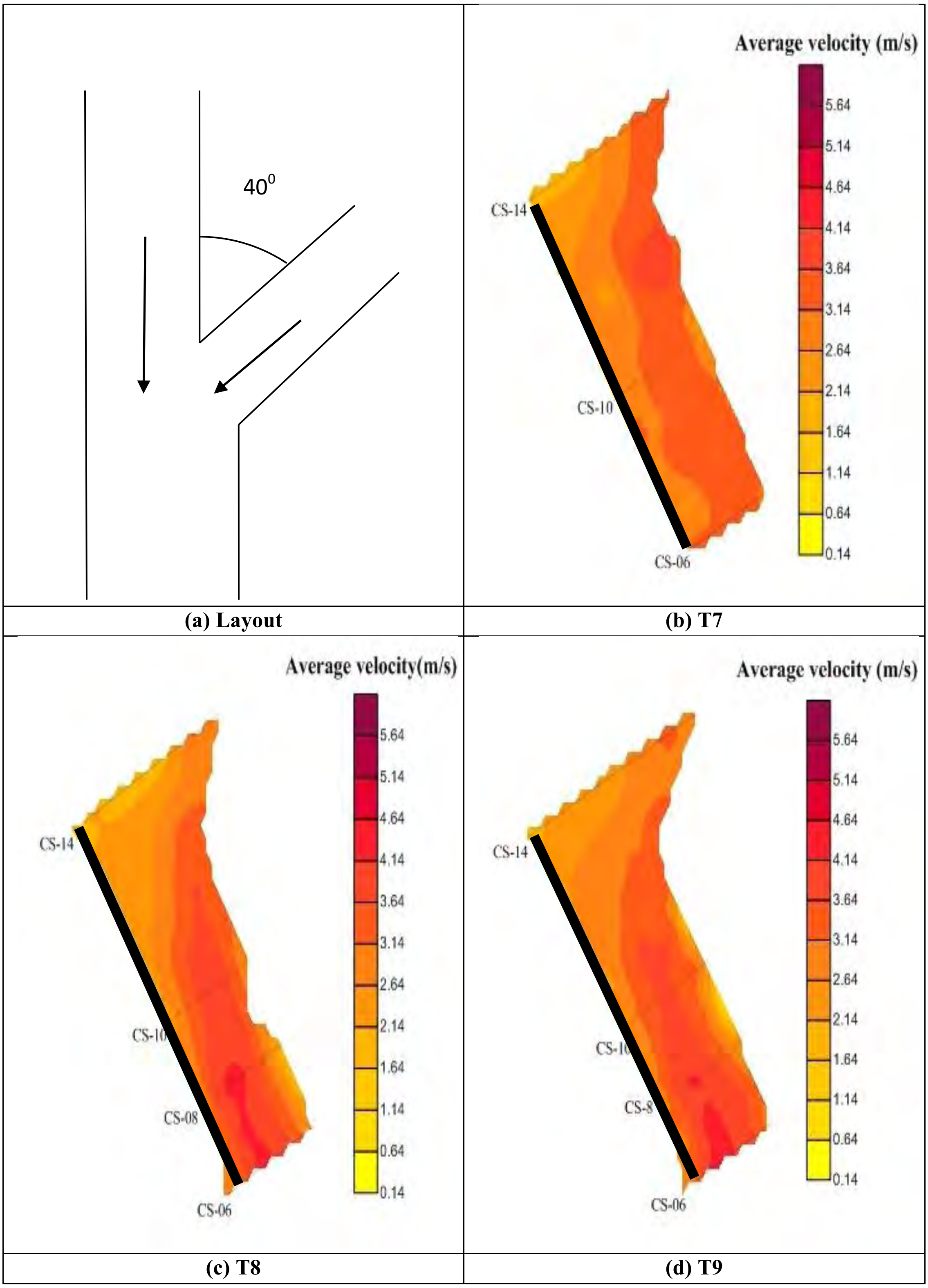


Figure 5.4: Velocity Distribution for Variable Q_r at Fixed Θ_o:- 40^0

downstream zone from 2.2 to 4.1 m/s. It has been observed that a specific velocity range as 3.2 to 3.6 m/s has dominated throughout the channel. Here, recovery zone has forwarded to more upstream than previous angle due to the sharp direction of oblique angle, bur separation zone has increased spontaneously at the left bank of combined channel.

ix) Observation from Test Run T11

Now according to Figure 5.5 (c), velocity has been also increased its intensity towards downstream zone with a range from 2.61 to above 4.6 m/s with the enhancement of oblique flow discharge. But, separation zone has been extended along left bank of combined channel which is more than T10 and T0. It has been observed that recovery zone has forwarded upstream with the advancement of oblique flow.

x) Observation from Test Run T12

But according to Figure 5.5 (d), velocity has been advanced increasingly towards downstream zone from 2.6 to above 4.6 m/s, but separation zone has been comparatively increased its extent of area along left bank of combined channel than T10, T11,T0. It has been found that vulnerability to bank protection work has gradually influenced with the increase of oblique flow discharge.

xi) Observation from Test Run T13

According to Figure 5.6 (d), velocity distribution has been concentrated from 3.4 to 5.3 m/s to the left bank of combined channel tending to revetment at meeting zone as CS-13 to CS-11. This location has been identified as separation zone for different oblique flow angle with different discharge ratio. But, for only oblique flow conveying full discharge, it has been behaved differently than previous test runs and increased vulnerability at left bank of combined channel at meeting zone. Here, exceptionally low velocity zone has been developed at downstream recovery zone.

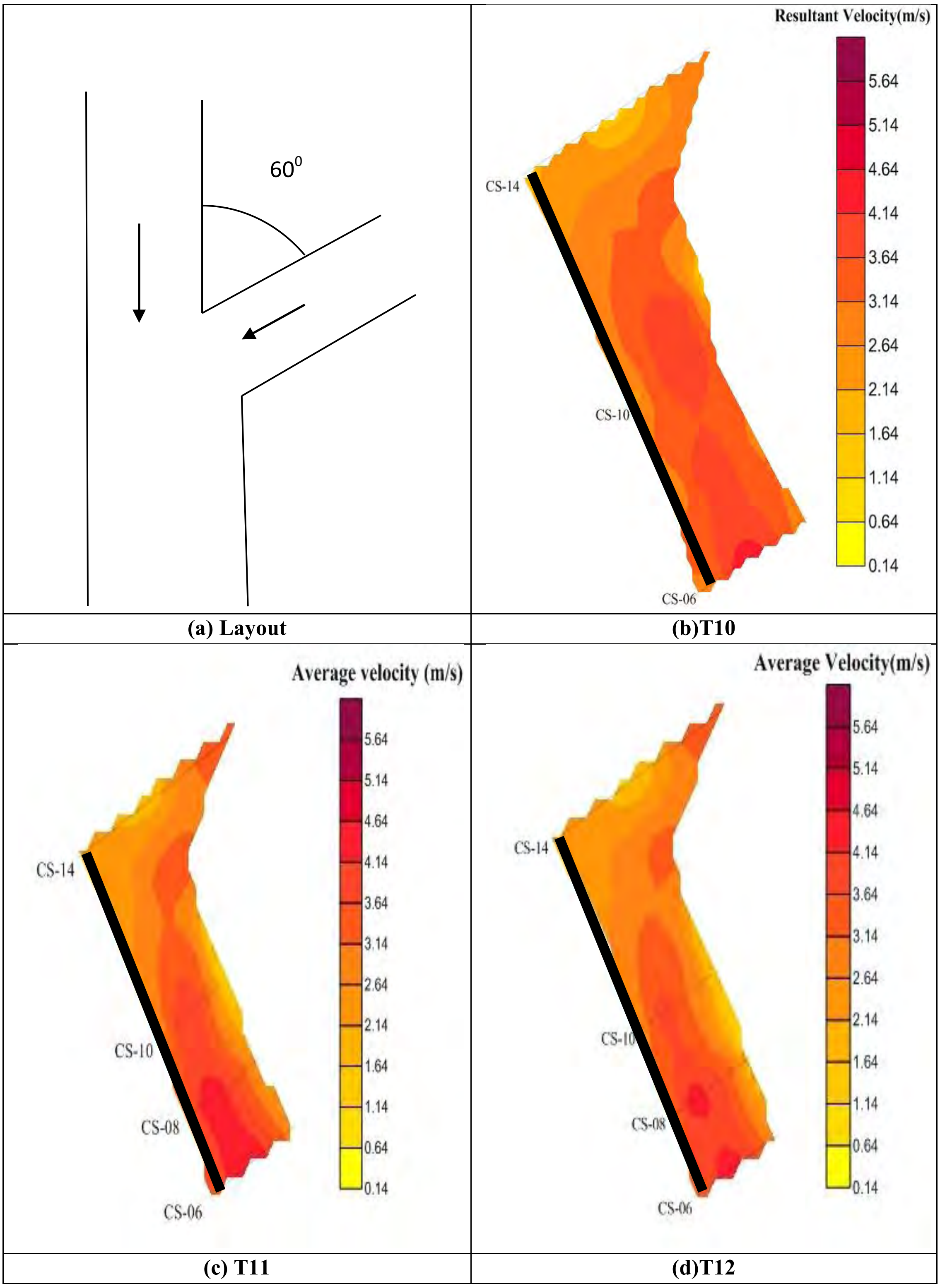


Figure 5.5: Velocity Distribution for Variable Q_r at Fixed Θ_o:- 60^0

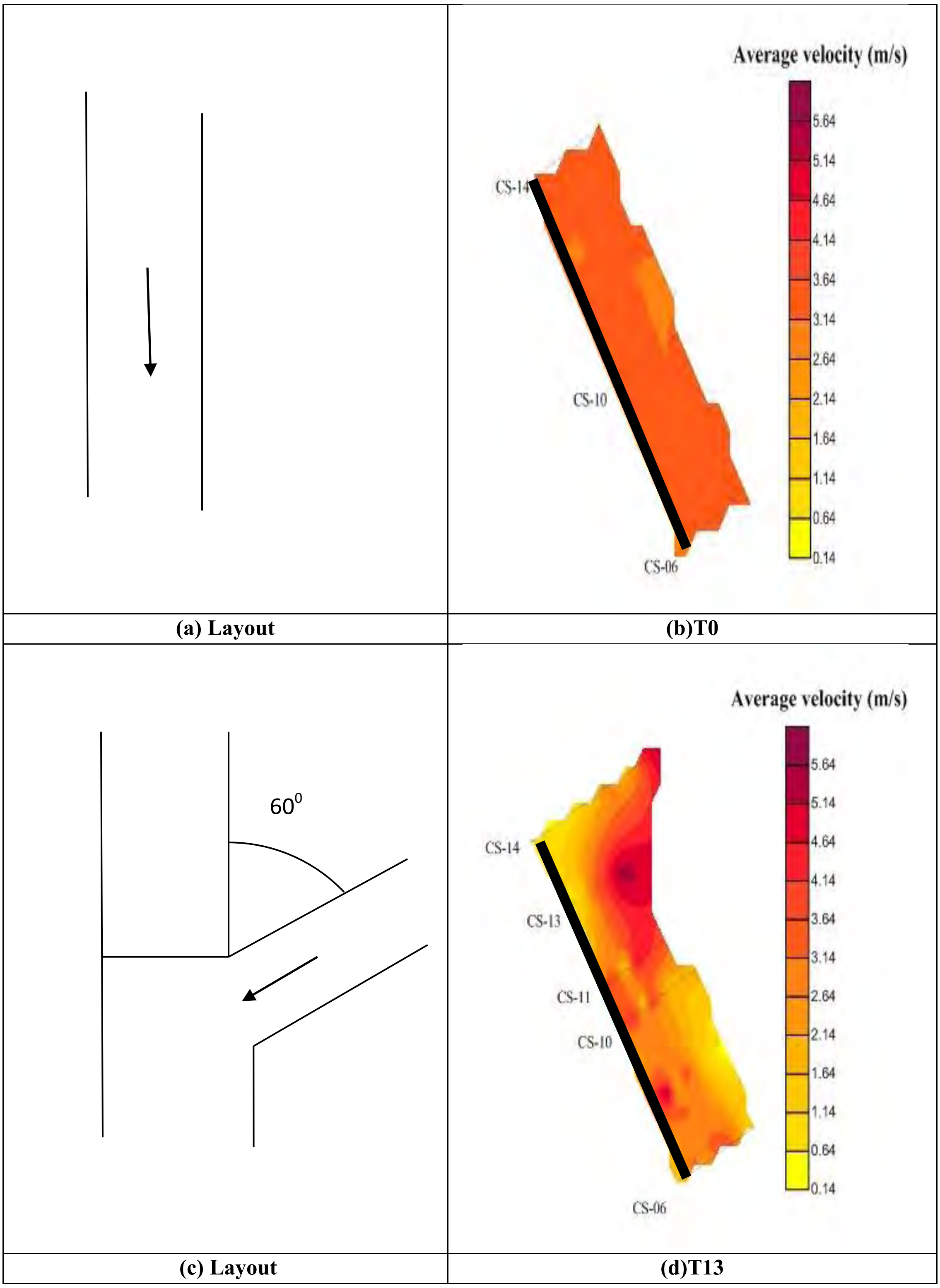


Figure 5.6: Velocity Distribution for Only Straight and Oblique Flow (Θ_o:-60^0) at Fixed Q:- Full Conditions

5.5 Comparison of Velocity Distribution among Different Test Run

In the physical model set-up, there have been arranged different test depending upon variable test parameters like oblique flow angle, discharge ratio, different types of bank material, flow condition etc. These above mentioned parameters are incorporated with each test run in the physical modelling. Now, velocity distribution has been compared for different discharge ratio at fixed oblique flow angle with stone boulder protection work.

5.5.1 Variable Discharge Ratio with Fixed Oblique Angle

According to this criterion, these scheduled test runs have been consolidated into three sets of arrangement. Here, comparison of study has been conducted for each constant angle as 20^0, 40^0, 60^0 with variable discharge ratio as 1.2, 1.4, 1.6. Based on the bank protection material such as stone boulder as launching apron along the right bank of the combined channel, there have been done 10 (ten) test run. For the conveniences, these experiments have been distributed among 3(three) sets and 3 (three) experiments are grouped in each set. The additional 1(one) test run has been conducted to only oblique flow condition with Q_r-1.6 and Θ_o-60^0. There have been preferred to analyze and show the details of comparison among those in the following graphical format and so that there have been selected three critical cross-sections from these each set of experiments, those are CS-13; CS-11; and CS-06 which are utmost responsible to behave a influential behavior of straight channel flows due to defined oblique flows . Here, at each cross-section it has been selected 3 major area signifying the major impact on combined channel, those are, a) adjacent to revetment b) mid portion of channel c) near to left bank (brick wall)

i) Variable Discharge Ratio (Q_r) with 20^0 Oblique Angle (Set-A)

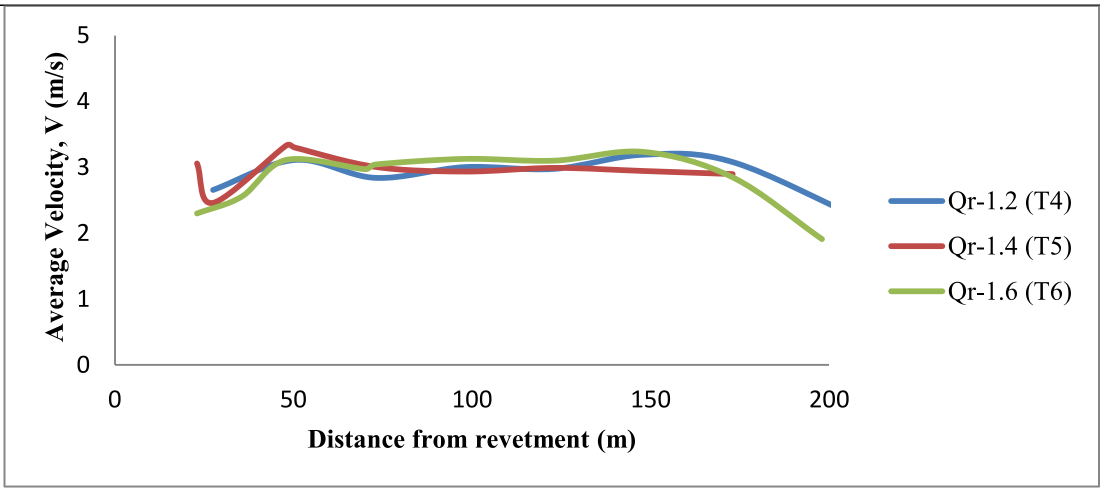
According to Figure 5.7 (a), in the meeting zone as CS-13, velocity has been varied into some certain criteria of places those are, adjacent to launching apron velocity increases at a certain peak level varying with discharge ratio but dominantly for median discharge ratio 1.4.Then it has been followed with a mild trend of variation except left bank due to side boundary impact and angular concentration of flow velocity field. Now from Figure 5.7 (b) and (c), at the mid zone and downstream zone, as CS-11 and CS-08 same behavior has shown except the mild reduction of velocity at left bank not as much as steep fall of velocity of CS-13.

According to Figure 5.8 (a) adjacent to the revetment, velocity has been enhanced longitudinally from meeting zone to downstream for all discharge ratio (Q_r) although for discharge ratio 1.2 velocity has been increased more rapidly. But from Figure 5.8 (b), velocity has been increased longitudinally upto starting of downstream zone as CS-08 then it has been reduced gradually towards downstream due to concentration of two stream creating two direction forces slow velocity zone. And from Figure 5.8 (c), for minimum and maximum discharge ratio, velocity has been increased as upto mid zone but for median discharge ratio as 1.4 it has been shown a reduction trend from upper mid zone due to complex co-ordination of oblique flow angle and discharge ratio.

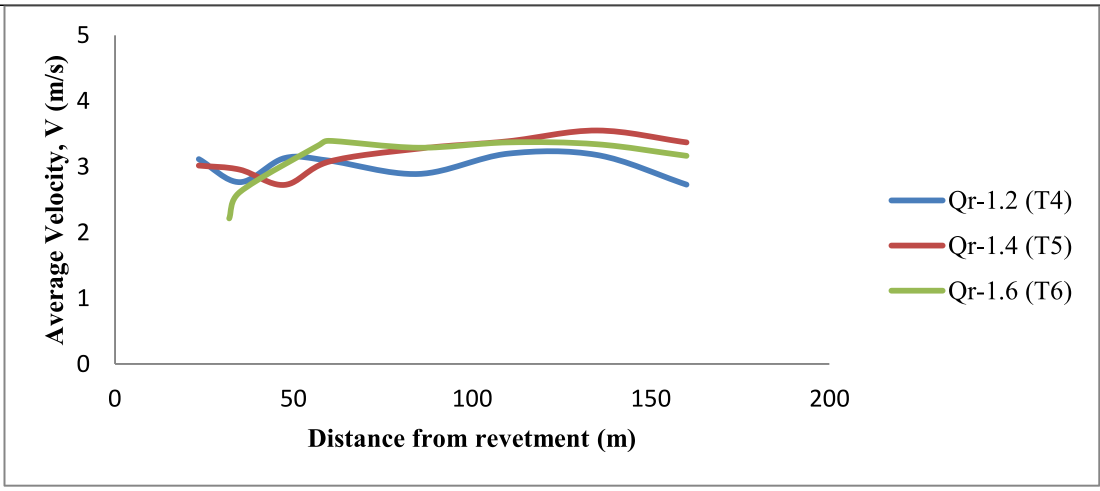
ii) Variable Discharge Ratio (Q_r) with 40^0 Oblique Angle (Set-B)

According to Figure 5.9 (a), in the meeting zone as CS-13, velocity has been increased transversely in overall section from revetment to left bank due to angular dominancy of flow with varying discharge ratio (Q_r). Now from Figure 5.9 (b) and (c), at the mid zone and downstream zone, as CS-11 and CS-08, almost same behavior has been observed except the mild reduction of velocity at left bank although in the downstream zone, reduction of velocity has been started from mid portion of the section varying with discharge ratio (Q_r).

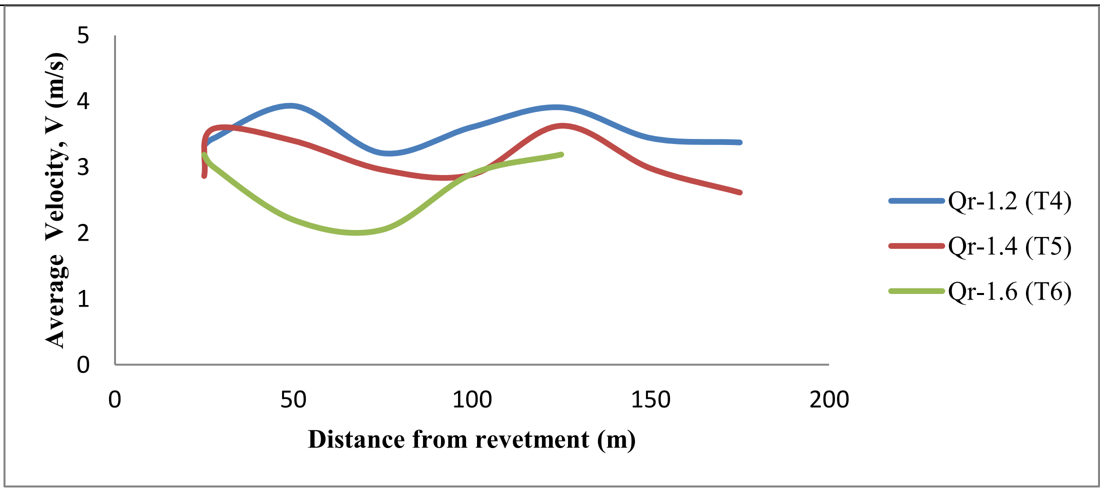
According to Figure 5.10 (a) adjacent to the revetment, velocity has been behaved as complex manner at longitudinally from meeting zone to downstream for maximum and minimum discharge ratio (Q_r). Although for median discharge ratio 1.4, velocity has been observed without any variation. But from Figure 5.10 (b), velocity has been increased longitudinally from meeting zone to downstream except some reduction has found at downstream zone for Q_r-1.2. And from Figure 5.8 (c), due to the more angular action of oblique flow angle as 40^0, velocity has been reduced gradually for varying discharge ratio (Q_r).



(a) CS-13: Meeting zone

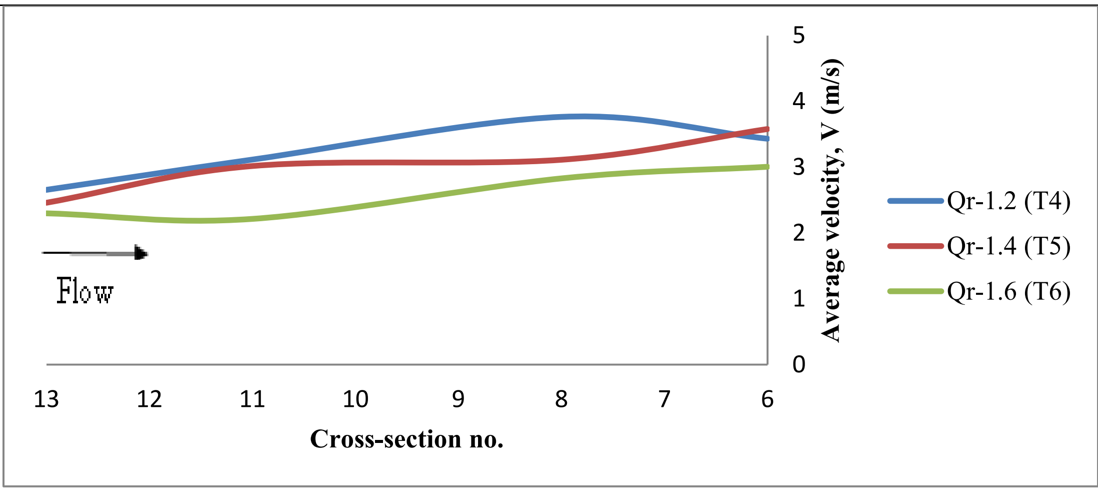


(b) CS-11: Mid zone

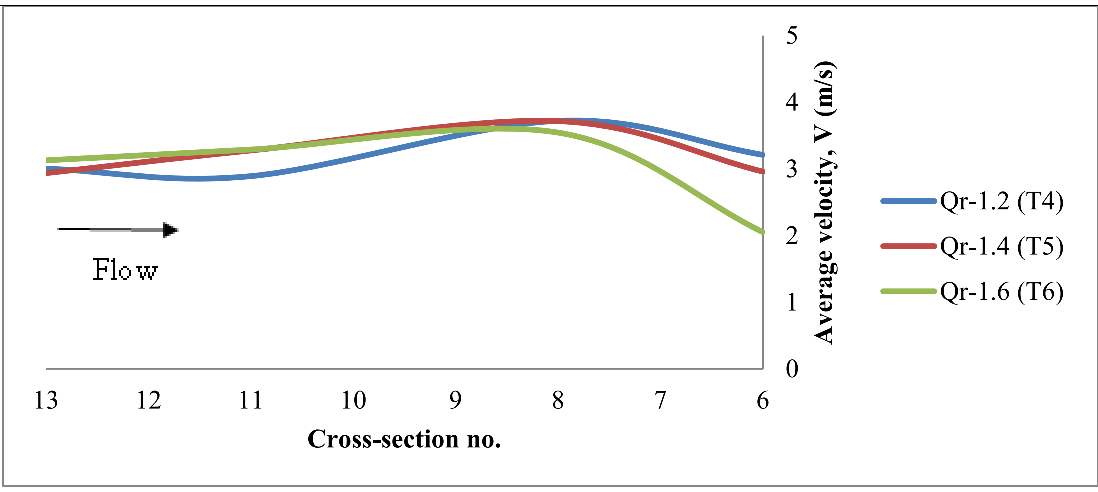


(c) CS-06: Downstream zone

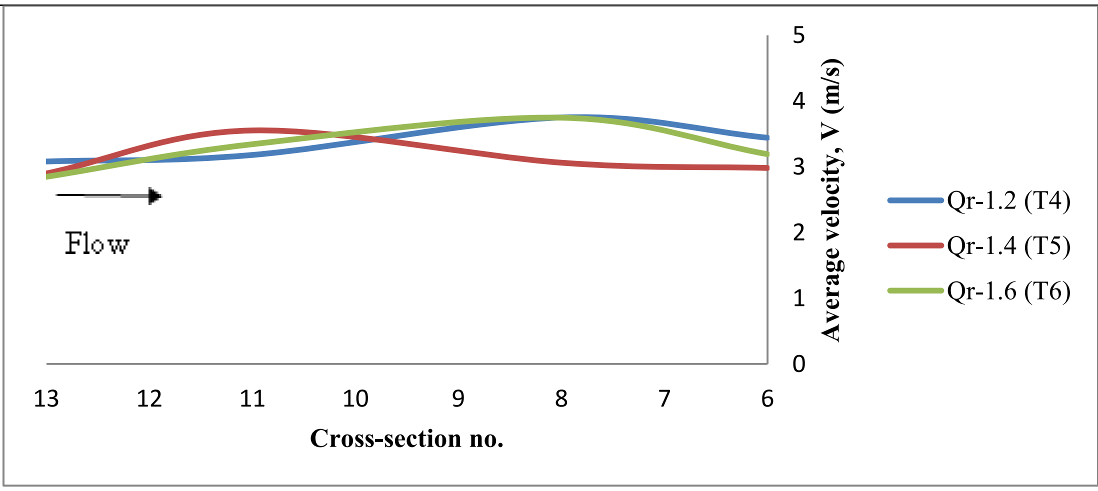
Figure 5.7: Comparison of Cross-Sectional Velocity for Variable Q_r at Fixed Θ_o:- 20^0



(a) Adjacent to revetment



(b) Mid portion of combined channel



(c) Near to left bank

Figure 5.8: Comparison of Longitudinal Velocity for Variable Q_r at Fixed Θ_o:- 20^0

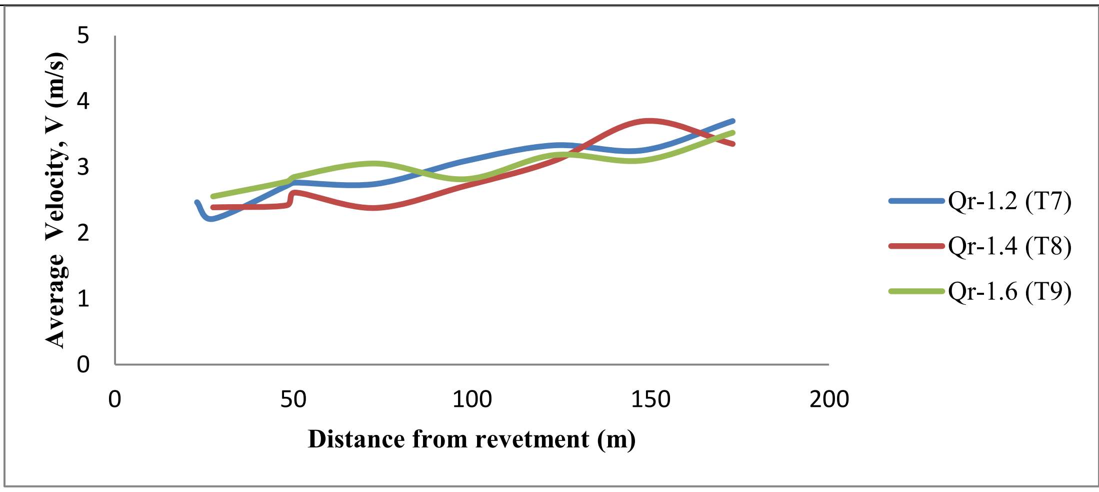
iii) Variable Discharge Ratio (Q_r) with 60^0 Oblique Angle (Set-C)

According to the Figure 5.11 (a), it has been determined that at the meeting zone, as CS-13 varying with discharge ratio resultant velocity has increased to the intake of oblique channel. Basically, due to constriction of flow and velocity distribution of main channel also morphological changes of main channel diverts flow to the oblique channel bifurcated by any char or sand bar. So, flow attracts to the oblique channel creating high attracting velocity. Far away from meeting zone, from Figure 5.11 (b) at the mid zone as CS-11, velocity has been increased towards mid portion of the section and then reduced to left bank consecutively respective to variation of discharge ratio (Q_r).Then from Figure 5.11 (c) at the downstream zone as CS-06 same behavior has been shown like mid zone. And it has been observed that at the left bank velocity has always been reduced due to the action of side boundary (Brick wall). But it has been physically observed that from meeting zone to downstream resultant velocity has been induced towards river bank protection work.

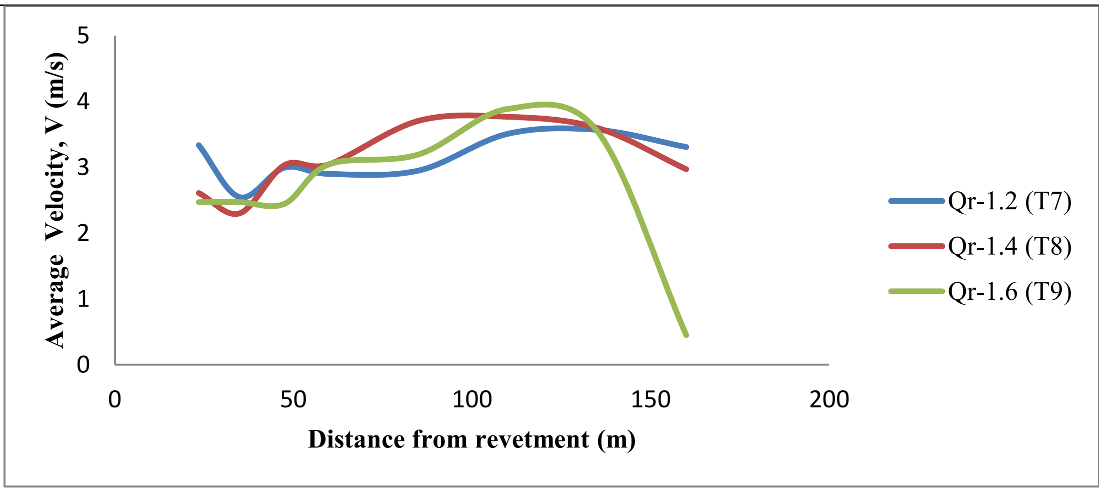
According to Figure 5.12 (a), adjacent to revetment velocity has been increased longitudinally upto downstream zone with increasing discharge ratio (Q_r), but its influence has been carried away to downstream due to power of stream as 1.4 and 1.6 affecting with its vulnerability at most downstream zone r than 1.2. But from Figure 5.12 (b), varying with discharge ratio (Q_r) velocity has been increased in the whole combined channel. And from Figure 5.12 (c), velocity has been reduced gradually at longitudinally with varying discharge ratio due to the sharp angle of influence and angular void zone and side boundary factor.

5.5.2 Variable Oblique Angle with Fixed Discharge Ratio

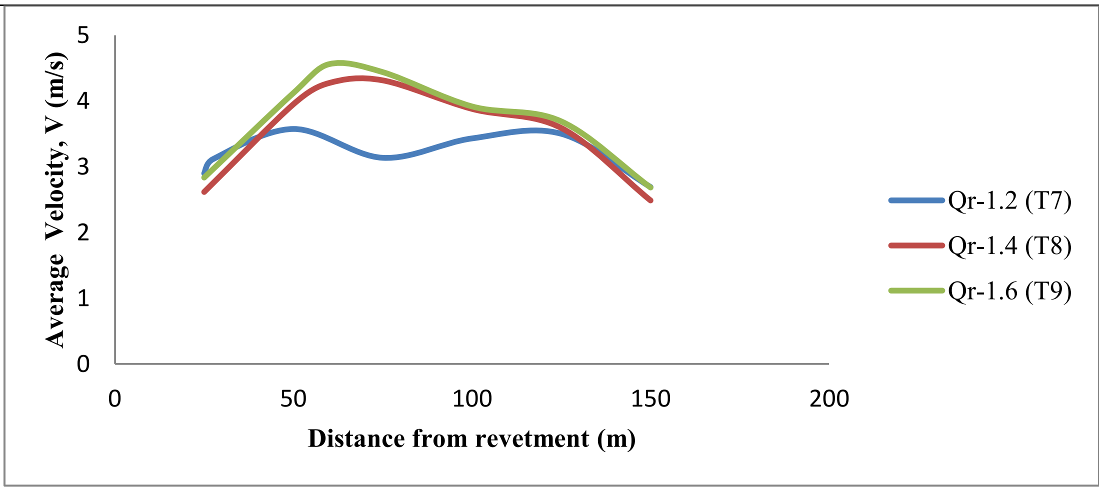
According to this condition, it has been consolidated these scheduled test runs into three sets of arrangement. Here, comparison of study has been conducted by two factors like each constant angle as 20^0, 40^0, 60^0 with variable discharge ratio as 1.2, 1.4, 1.6. Now the analysis has been comprised of varying angle with fixed discharge ratio as 1.2 ,1.4,1.6.



a) CS-13: Meeting zone

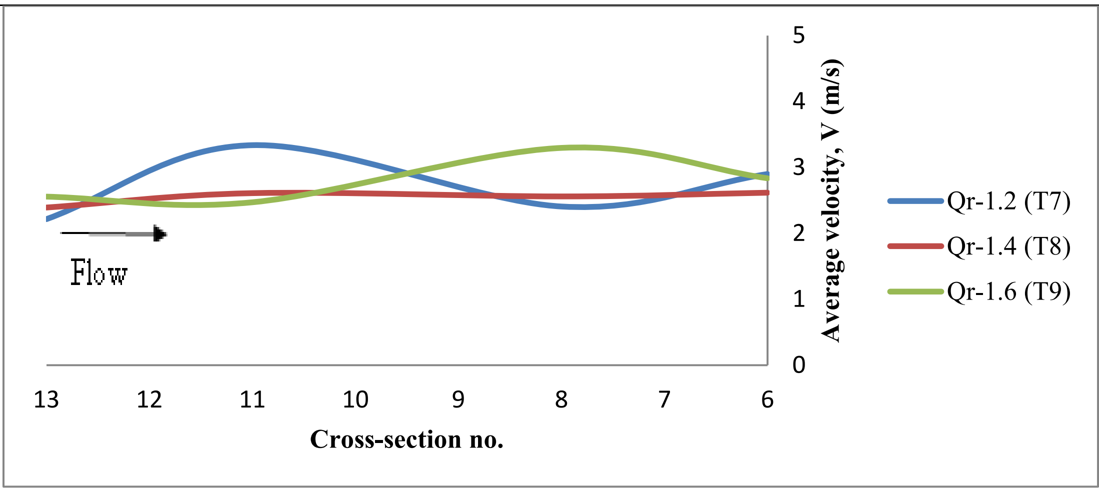


b) CS-11: Mid zone

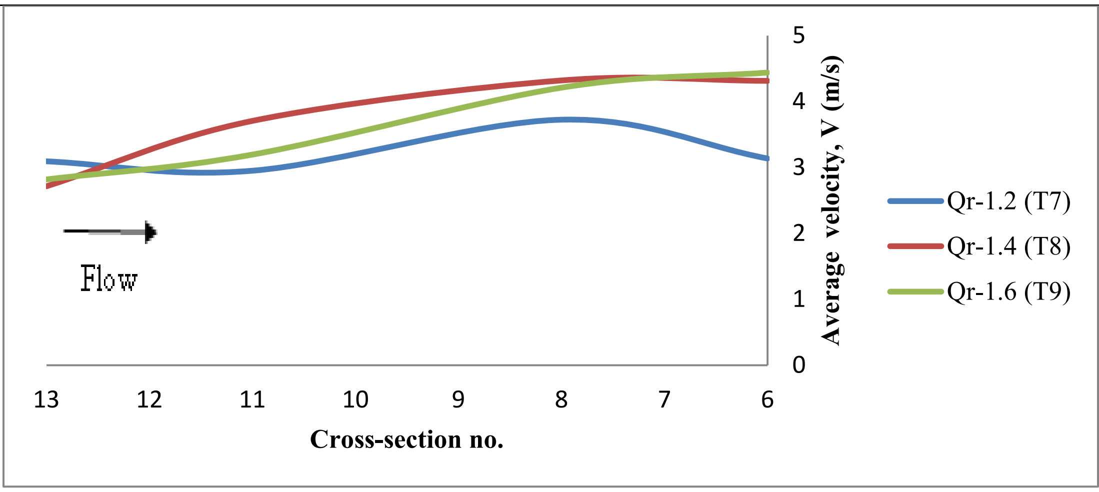


c) CS-06: Downstream zone

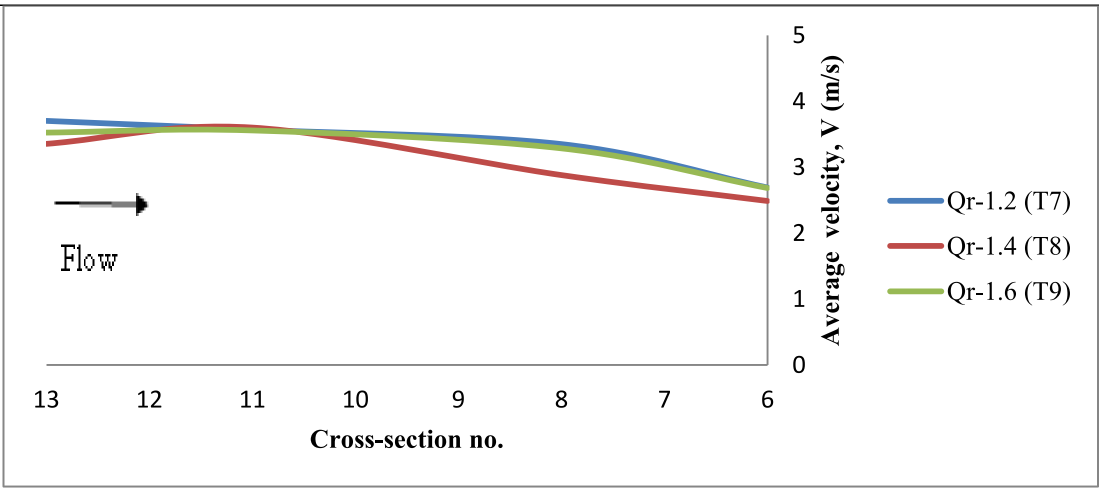
Figure 5.9: Comparison of Cross-sectional Velocity for Variable Q_r at Fixed Θ_o:- 40^0



(a) Adjacent to revetment

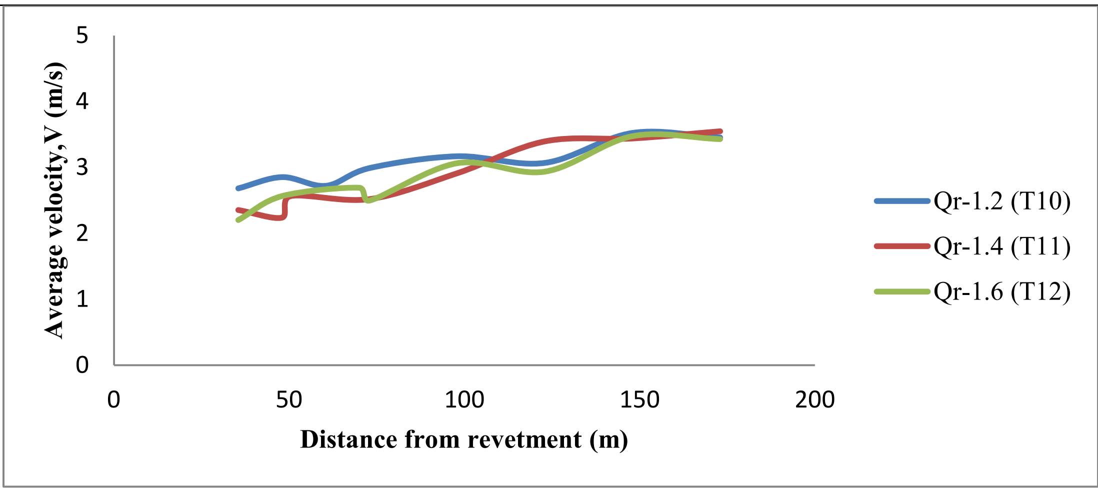


(b) Mid portion of combined channel

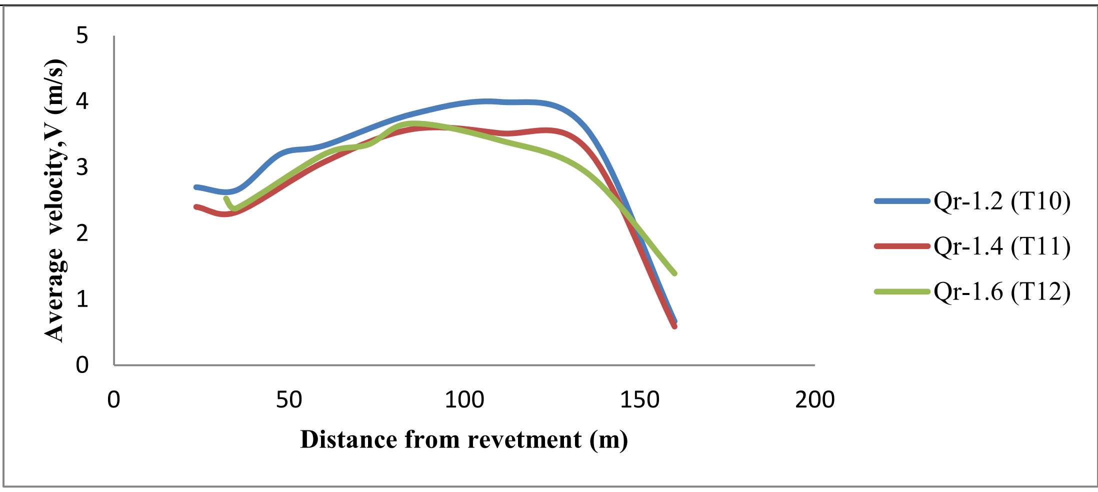


(c) Near to left bank

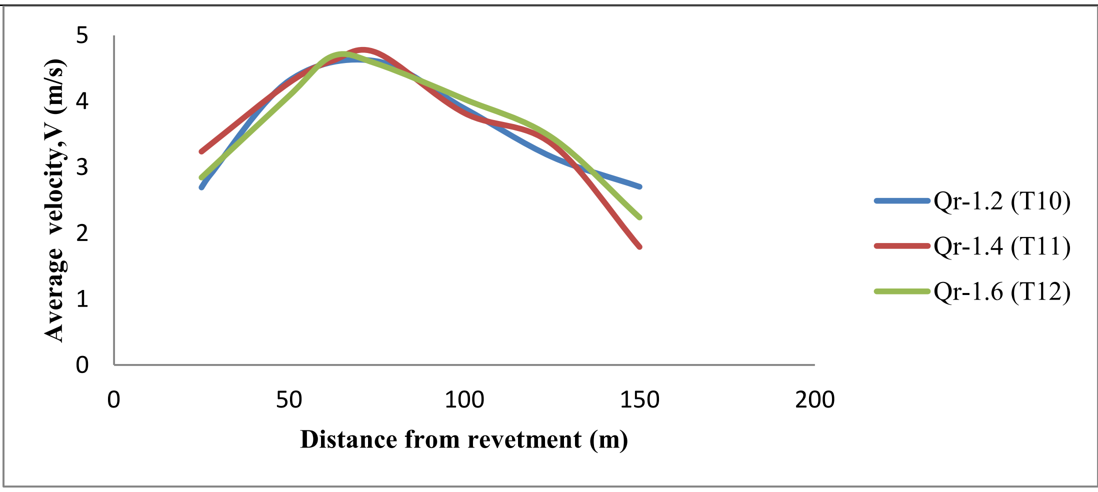
Figure 5.10: Comparison of longitudinal velocity for variable Q_r at Fixed Θ_o:- 40^0



a) CS-13: Meeting zone

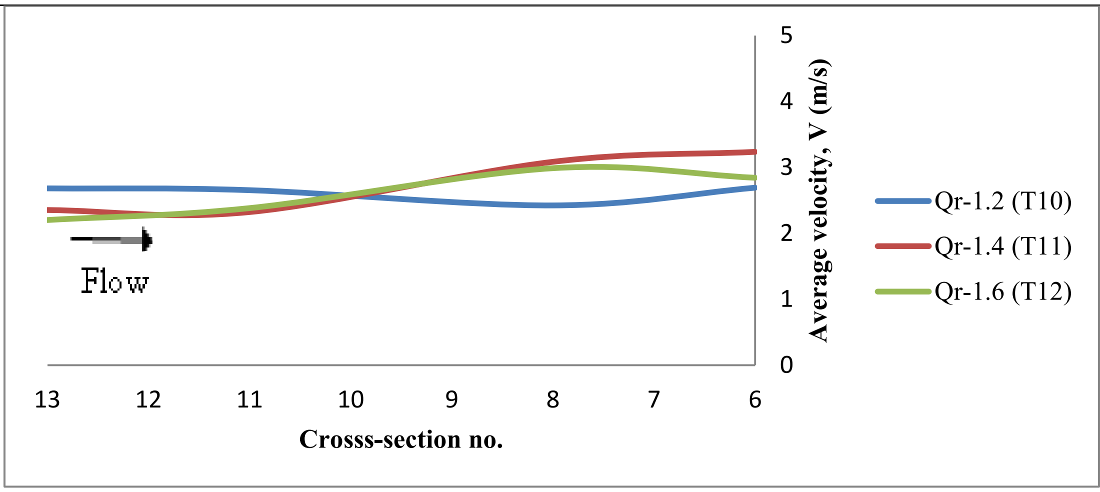


b) CS-11: Mid zone

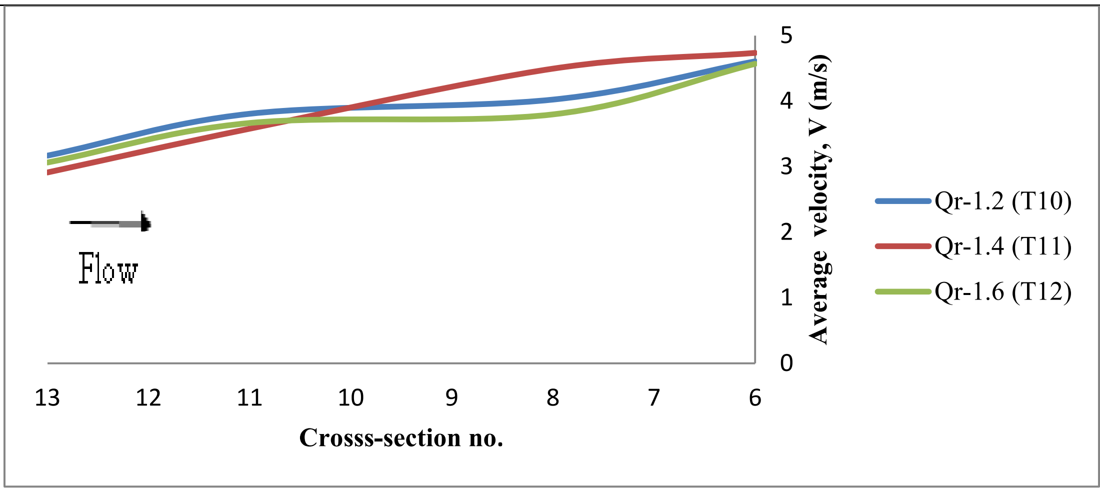


c) CS-06: Downstream zone

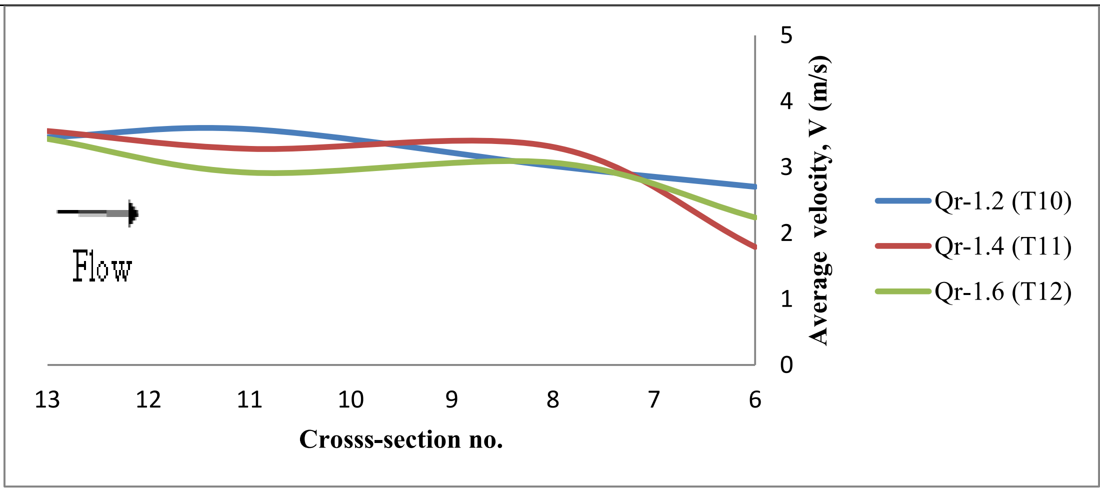
Figure 5.11: Comparison of Cross-sectional Velocity for Variable Q_r at Fixed Θ_o:-60^0



(a) Adjacent to revetment



(b) Mid portion of combined channel



(c) Near to left bank

Figure 5.12: Comparison of Longitudinal Velocity for Variable Q_r at Fixed Θ_o:- 60^0

i) Variation of Oblique Angle with Discharge Ratio-1.2

According to Figure 5.13 (a), in the meeting zone as CS-13,variation of oblique flow angle from 20^0 to 60^0, velocity has been intended to increase transversely from revetment to left bank. And from Figure 5.13 (b), at mid zone as CS-11, variation of oblique flow angle from 20^0 to 60^0, velocity has been retarded for a few adjacent to revetment likely to be at the top of launching apron then increasing steadily far away from mid portion of combined channel and near to left bank it has been shown a reduction trend. But from Figure 5.13 (c), at downstream zone as CS-06, velocity distribution has been developed transversely in a fluctuating behavior varying with oblique flow angle from 20^0 to 60^0.

According to Figure 5.14 (a), velocity distribution has been observed with steady increase adjacent to revetment portion with varying discharge ratio (Q_r). But from Figure 5.14 (b), at mid portion of the combined channel from meeting zone to downstream zone it has been behaved as fluctuating pattern of velocity distribution as rise and fall. And from Figure 5.14 (c), near to left bank, longitudinally velocity has been reduced steadily with varying oblique flow angle except 20^0 oblique angle.

ii) Variation of Oblique Angle with Discharge Ratio-1.4

According to Figure 5.15 (a), in the meeting zone as CS-13,variation of oblique flow angle from 20^0 to 60^0, velocity has intended to increase transversely from revetment to left bank. And from Figure 5.15 (b), at mid zone as CS-11, variation of oblique flow angle from 20^0 to 60^0 ,velocity has retarded for a few adjacent to revetment likely to be at the top of launching apron then increasing steadily far away from mid portion of combined channel and near too left bank it has shown a reduction trend. But from Figure 5.15 (c), at downstream zone as CS-08, velocity distribution has developed transversely adjacent to revetment zone then forwarding to left bank it has observed retardation effect of velocity with variation oblique flow angle from 20^0 to 60^0. Here it has clearly found that peak of velocity has gradually moved towards revetment flowing through downstream zone.

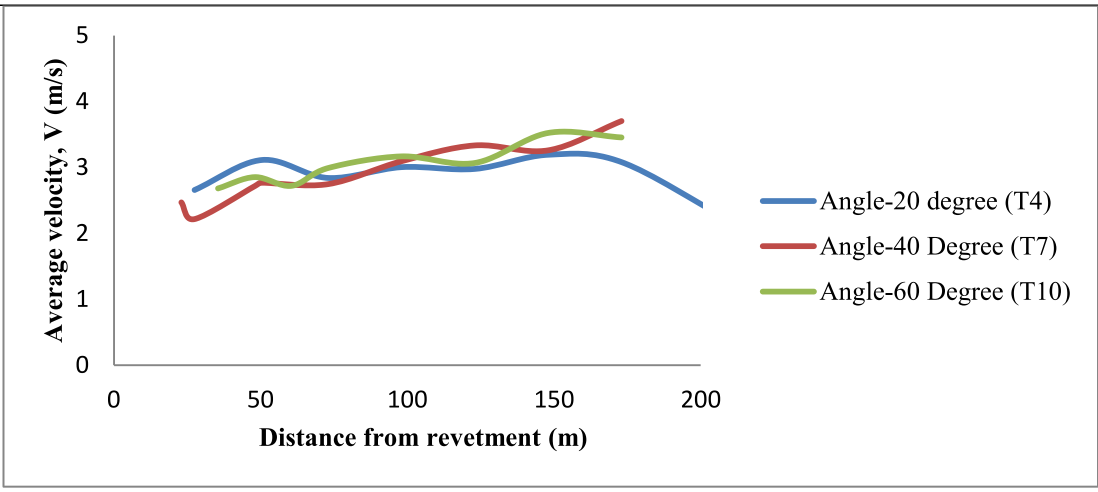
According to Figure 5.16 (a), velocity distribution has been observed with steady increase at longitudinally (meeting zone to downstream zone) adjacent to revetment portion, although 60^0 oblique flow angle shows high velocity. But from Figure 5.16

(b), at mid portion of the combined channel from meeting zone to downstream zone it has been behaved as increasing pattern of velocity distribution. And from Figure 5.16 (c), near to left bank, longitudinally velocity has been reduced steadily with varying oblique flow angle except 20^0 oblique angle which has been behaved as a flatter type continuing steady uniform velocity upto downstream zone due to sharpness of angle of influence.

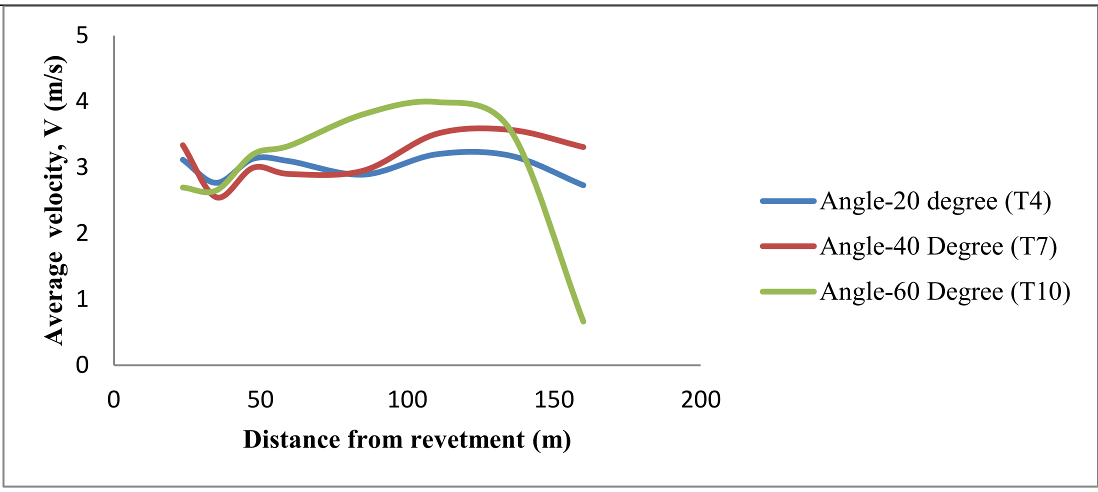
iii) Variation of Oblique Angle with Discharge Ratio-1.6

According to figure 5.17 (a), in the meeting zone as CS-13,variation of oblique flow angle from 20^0 to 60^0, velocity has been intended to increase transversely from revetment to left bank, although in 20^0 oblique flow angle velocity has been retarded due to the increase of stream power by creating concurrent flow to right bank . And from Figure 5.17 (b), at mid zone as CS-11, variation of oblique flow angle from 20^0 to 60^0, velocity has been increased steadily far away from revetment to mid portion of combined channel and near to left bank it has been shown as a reduction trend due to the attraction maximum stream power of oblique flow. But from Figure 5.17 (c), at downstream zone as CS-08, velocity distribution has been developed transversely adjacent to revetment zone then forwarding to left bank it has been observed with a retardation effect of velocity with variation oblique flow angle from 20^0 to 60^0. Here it has been clearly found that peak of velocity has gradually moved towards revetment flowing through downstream zone.

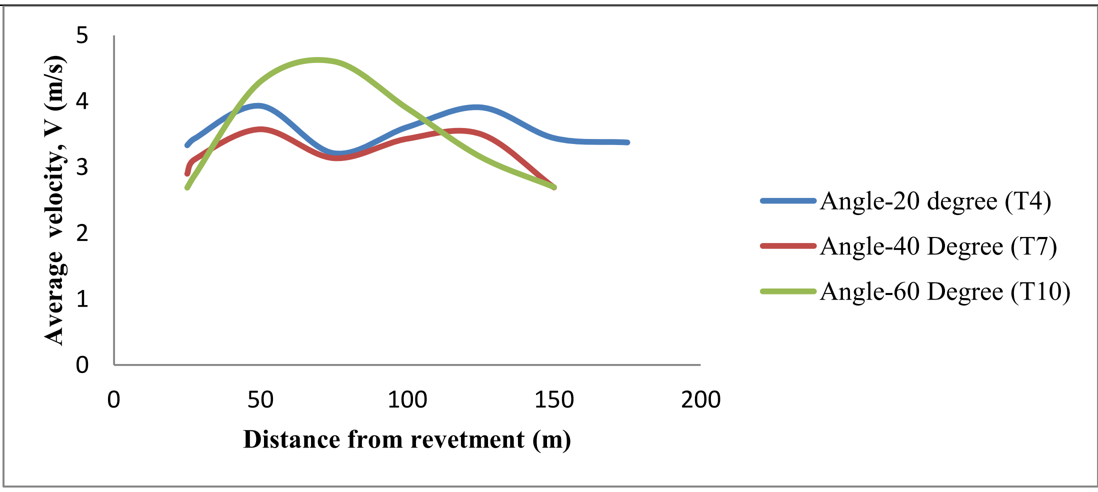
According to Figure 5.18 (a), velocity distribution has been observed with steady increase at longitudinally (meeting zone to downstream zone) adjacent to revetment portion. Although there have been observed shown high velocity for 60^0 and 40^0 oblique flow angle but for 20^0 oblique flow angle it has been shown reduction behavior at mid zone. But from Figure 5.18 (b), at mid portion of the combined channel from meeting zone to downstream zone it has been behaved as increasing pattern of velocity distribution but for 20^0 oblique flow angle it has been shown as reduction behavior at downstream zone. And from Figure 5.18 (c), near to left bank, longitudinal velocity has been reduced steadily with varying oblique flow angle except 20^0 oblique angle which shows as a flatter angle continuing steady increase of velocity upto mid zone due to smoothness of oblique angle.



(a) CS-13: Meeting zone

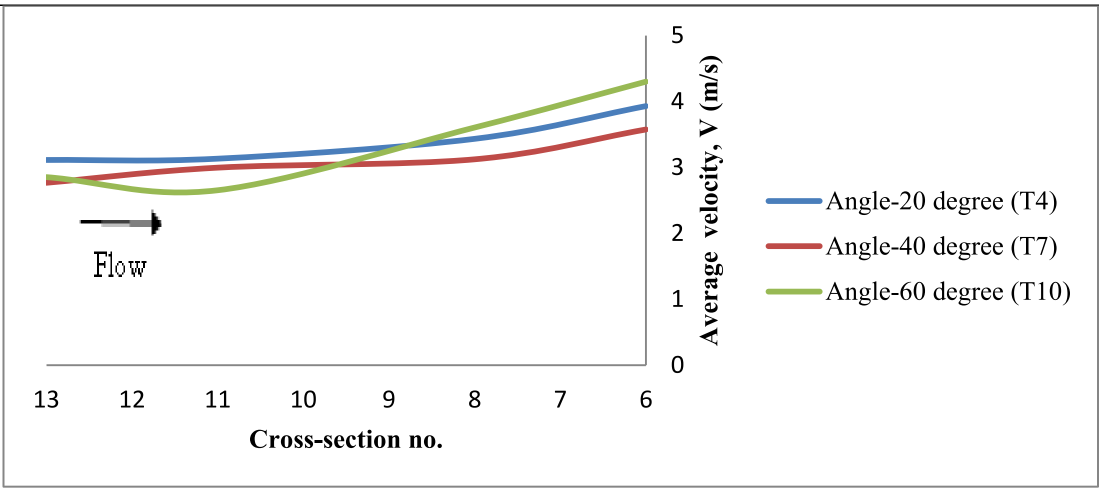


(b) CS-11: Mid zone

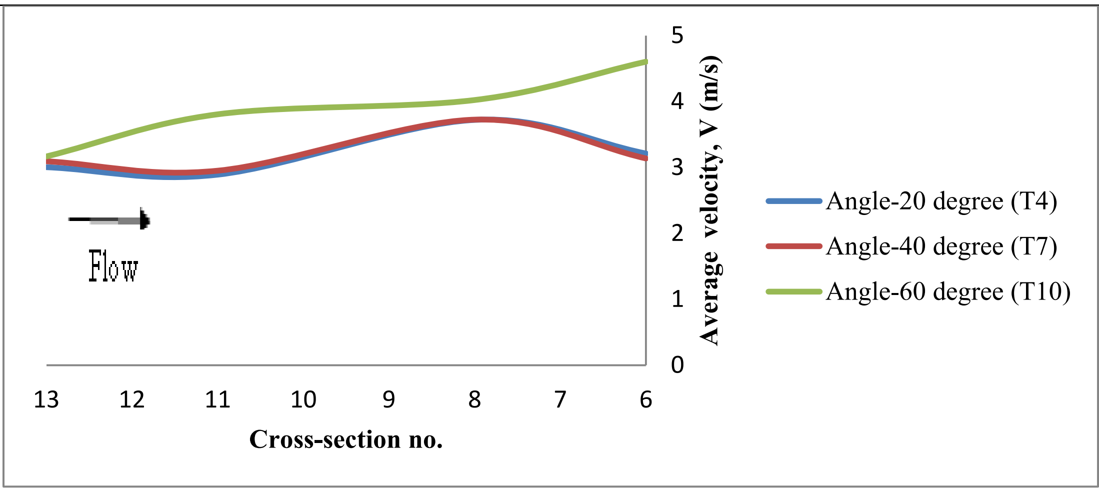


(c) CS-06 : Downstream zone

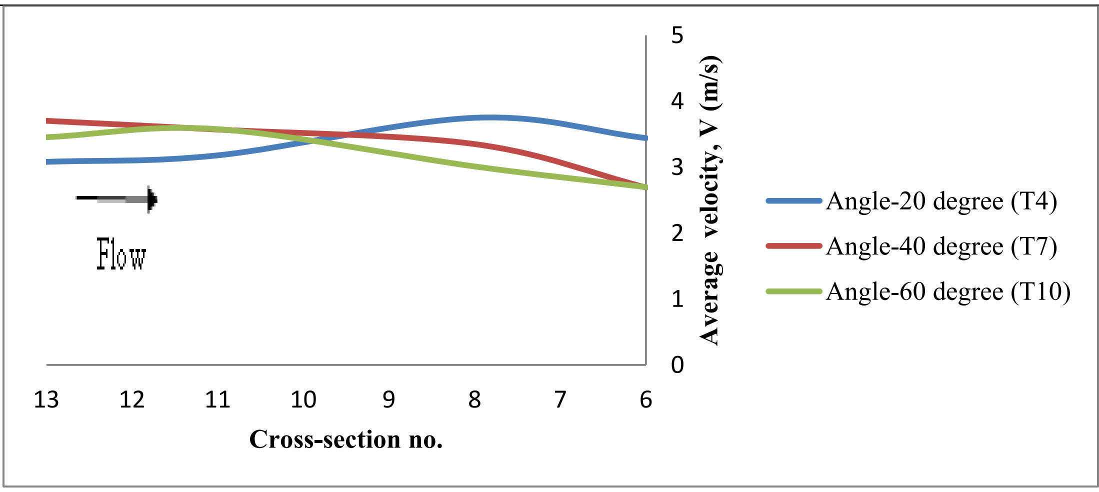
Figure 5.13: Comparison of Cross-sectional Velocity for Variable Θ_o at Fixed Q_r -1.2



(a) Adjacent to revetment

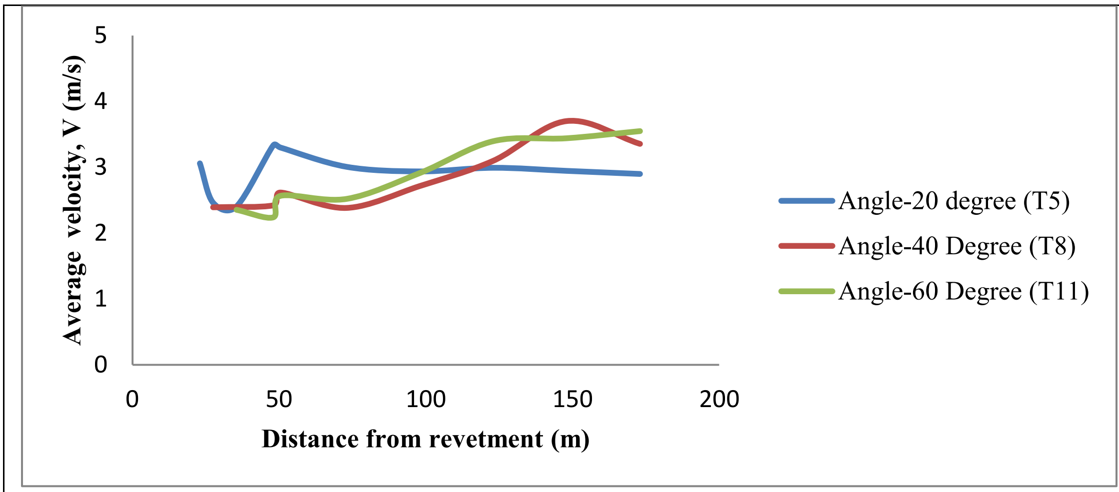


(b) Mid portion of the combined channel

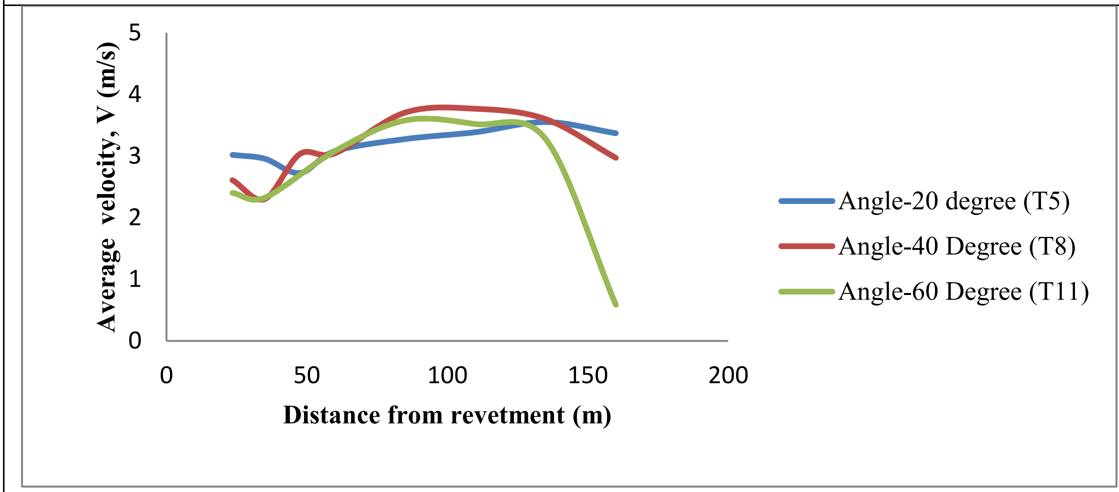


(c) Near to left bank

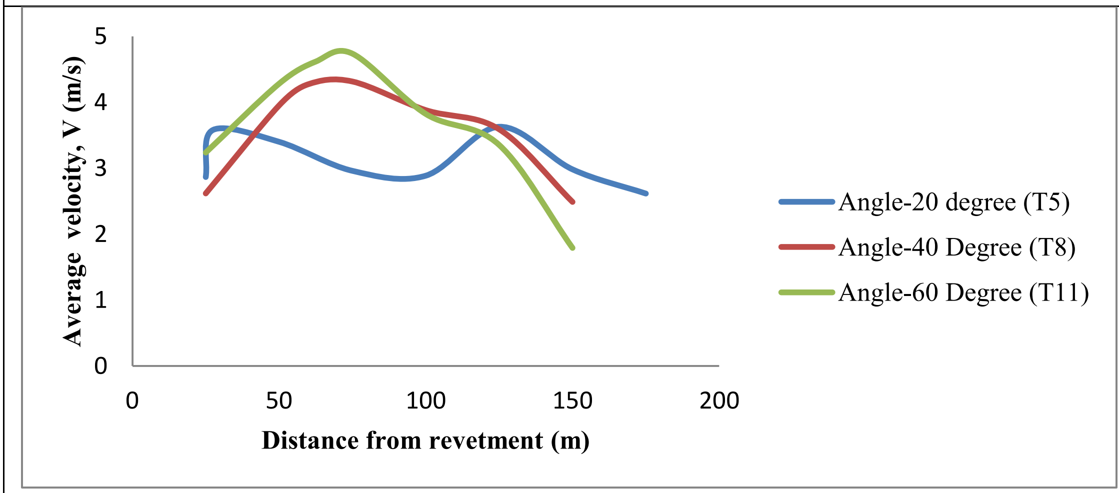
Figure 5.14: Comparison of Longitudinal Velocity for Variable Θ_o at Fixed Q_r -1.2



a) CS-13: Meeting zone

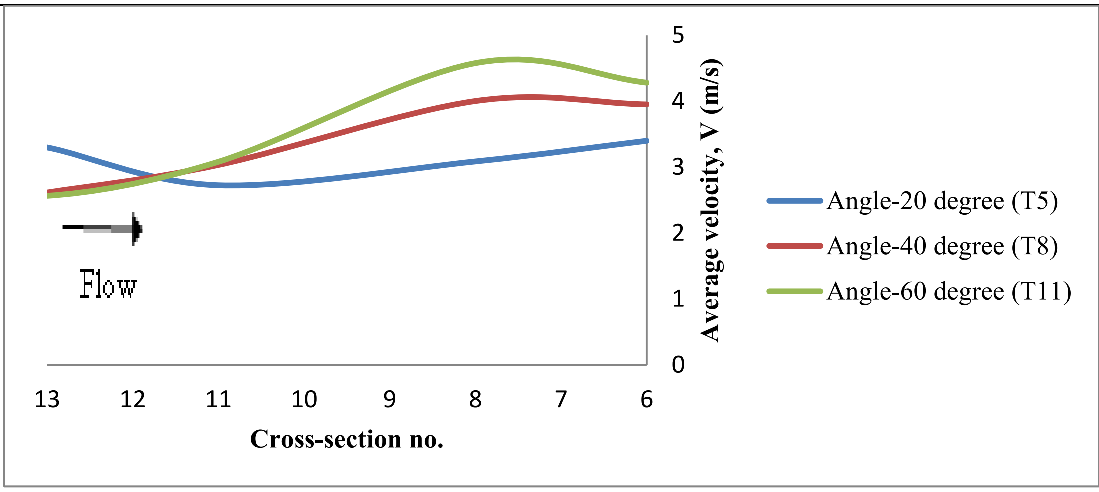


b) CS-11: Mid zone

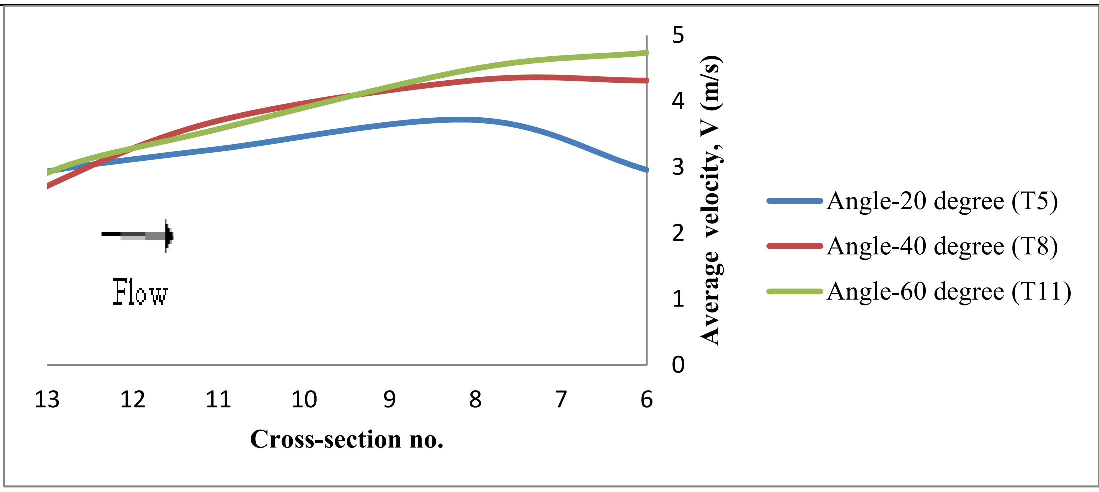


(c) CS-06 : Downstream zone

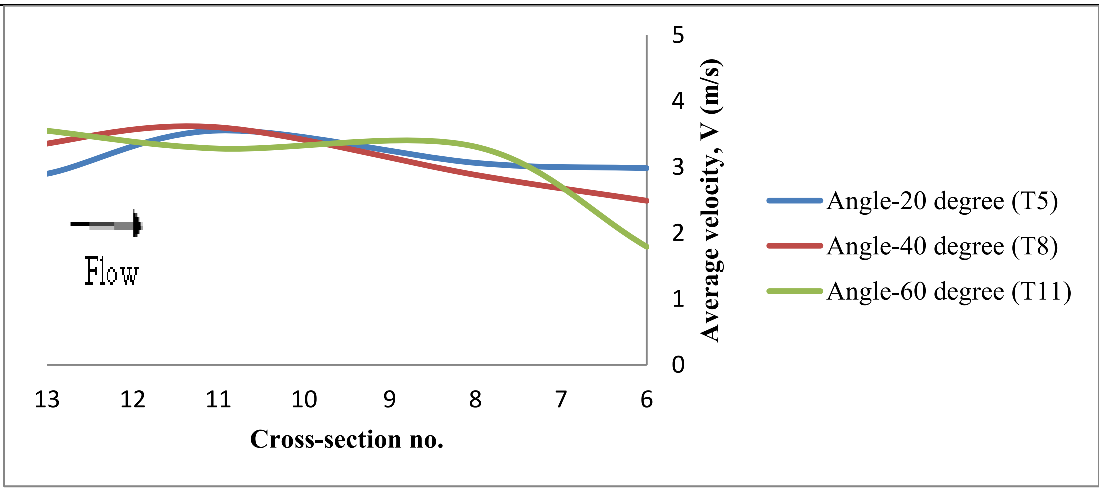
Figure 5.15: Comparison of Cross-sectional Velocity for Variable Θ_o at Fixed Q_r -1.4



(a) Adjacent to revetment

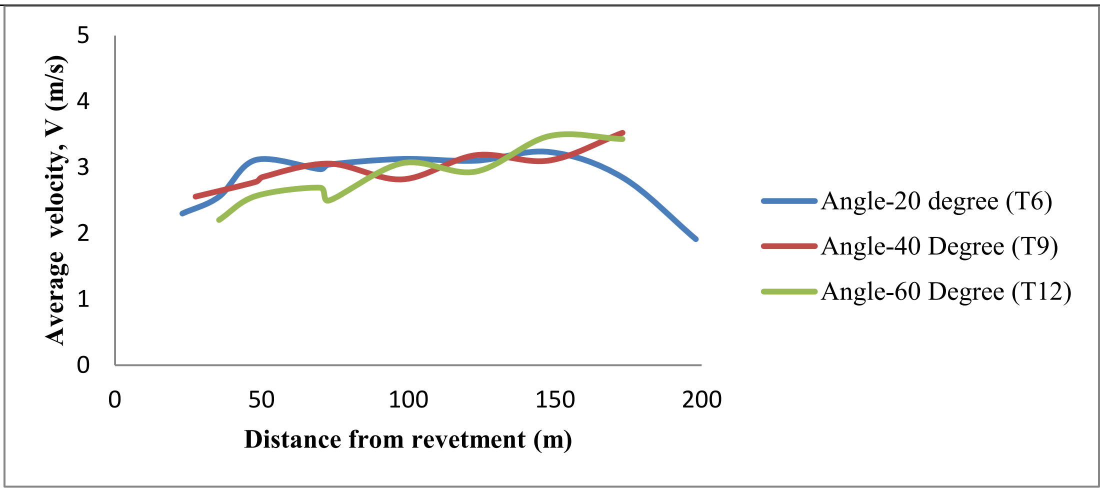


(b) Mid portion of combined channel

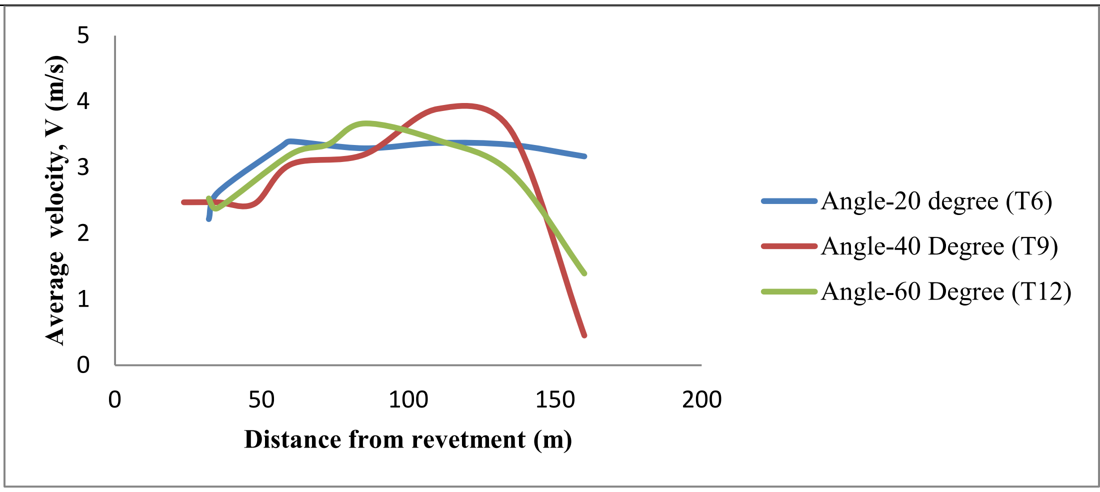


(c) Near to left bank

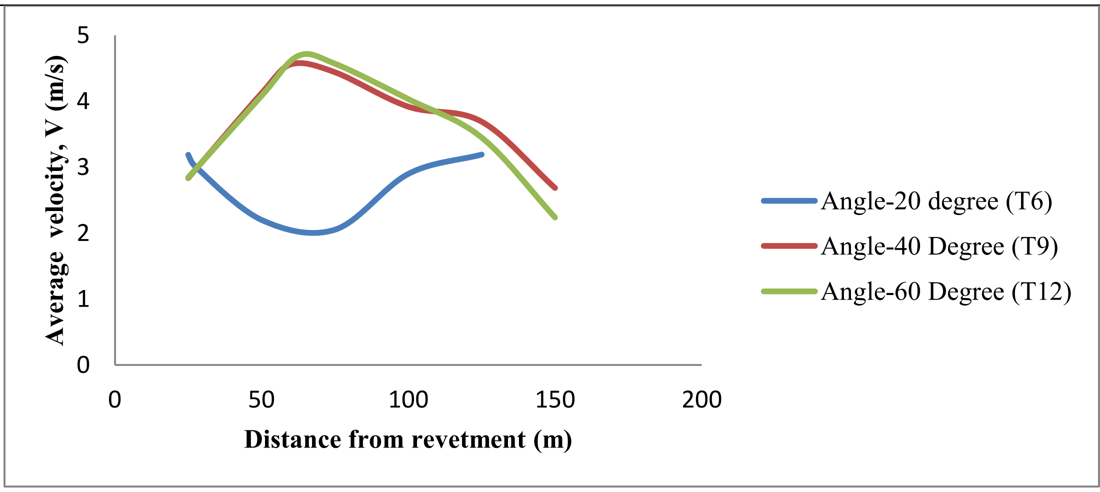
Figure 5.16: Comparison of Longitudinal Velocity for Variable Θ_o at Fixed Q_r -1.4



(a) **CS-13: Meeting zone**

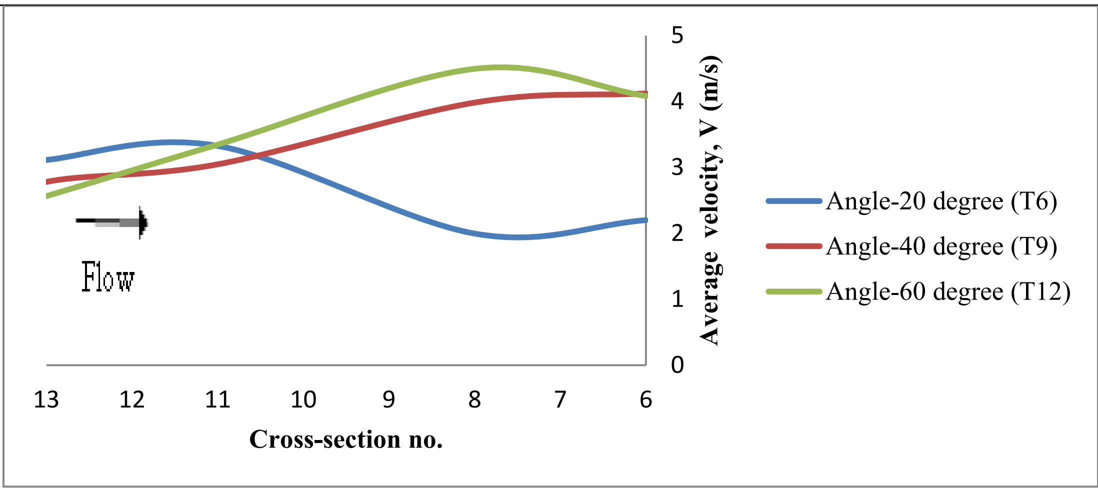


(b) CS-11: Mid zone

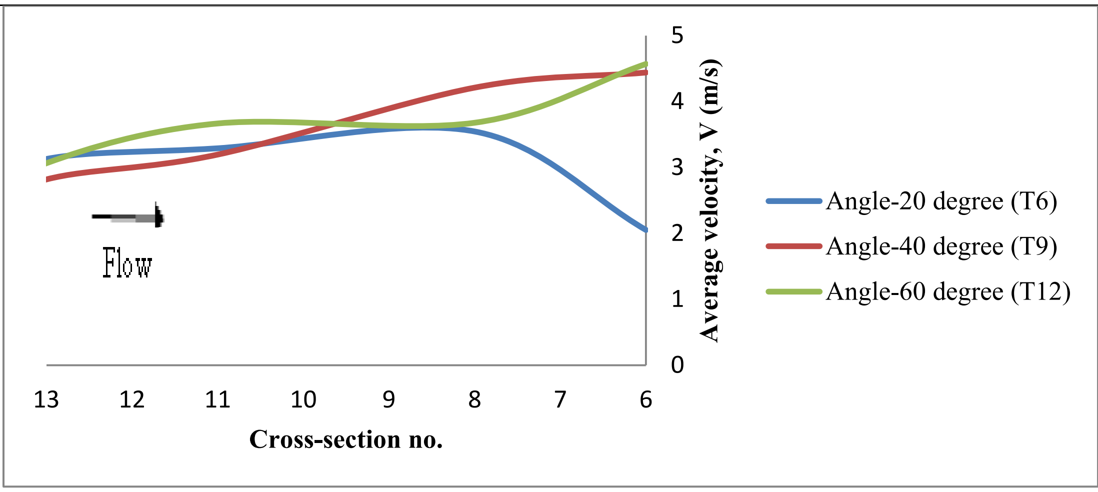


(c) CS-06 : Downstream zone

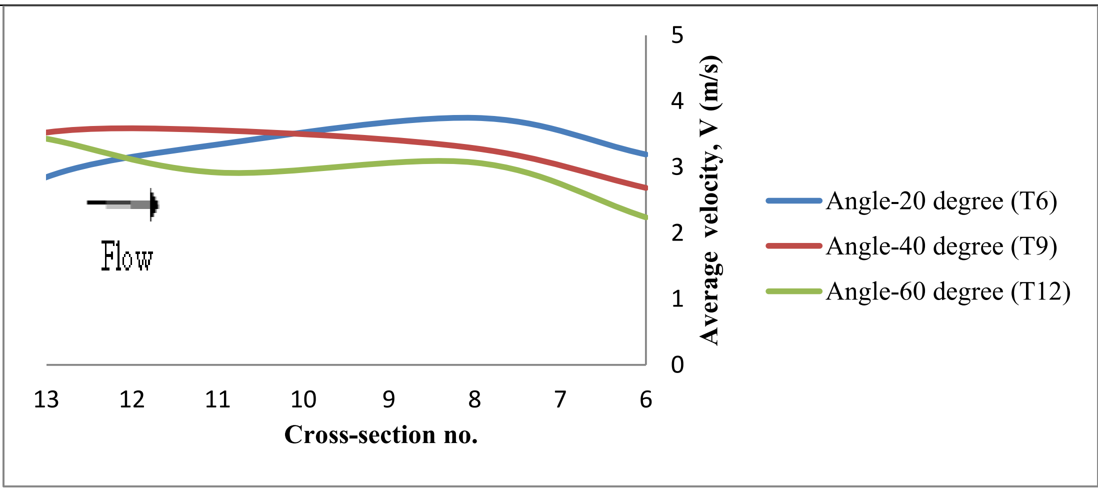
Figure 5.17: Comparison of Cross-sectional Velocity for Variable Θ_o at Fixed Q_r -1.6



(a) Adjacent to revetment



(b) Mid portion of combined channel



(c) Near to left bank

Figure 5.18: Comparison of Longitudinal Velocity for Variable Θ_o at Fixed Q_r -1.6

5.6 Scour Depth and Deposition at Combined Channel due to Oblique Flow

Scour depth denotes as a major hydraulic parameter of a channel. According to the Table 5.1, physical modelling has been done depending upon some variables and determined scour depth and deposition phenomenon at combined channel due to Oblique flow. On account of a view to river bank protection work such as stone boulder is used to protect the vulnerability of river flow. Based on that material, several tests have been carried out as from T4 to T13 and also T0. After that, several test have been done for different protective materials like geobag to observe the comparative efficiency of that material with stone boulder. According to Figure 5.2, the whole combined channel has been differentiated among three major zone, these are a) Meeting zone b) Mid zone c) Downstream zone, same as velocity distribution measurement criteria. At longitudinally, three major areas have been selected which signifies the major impact on combined channel, which are, a) adjacent to revetment b) mid portion of combined channel c) near to left bank (brick wall). In every test run, scour depth has been observed at every 50 cm c/c spacing of specified points at each cross-section of channel.

5.6.1 Variable Discharge Ratio (Q_r) with Fixed 20^0 Oblique Angle

Test parameters of the set-up are fixed with 20^0 oblique angle and variable discharge ratio (1.2,1.4,1.6). In the Physical model set-up, a designed initial bed has been prepared at where three set of run has been completed consecutively. So, here these three test run as discharge ratio of 1.2,1.4 and then finally 1.6 have been analyzed for constant 20^0 oblique angle as if it would be logical to determine relative scour depth. Now, According to Figure 5.19 (a) it has been shown as initial bed level and from Figure 5.19 (b), for discharge ratio (Q_r-1.2), maximum scour depth contour approx. 6.2 m has been found adjacent to left bank of CS-11 and its extent of elongation to the transverse direction with some specific area of the combined channel rather than longitudinal direction but it has been found quite little scour depth for T0 at the same place.

It has been found that here difference of Q_r of two channel is quite small, so, when straight flow of main channel has merged at meeting zone, supposed to disperse to combined channel width along with oblique flow stream and there have been induced a secondary flow pattern attracting to oblique flow angle which is nearly to left bank and thus creates no backflow influence of straight flow. And its scour pattern has been found slightly moved away from intake of oblique flow to mostly downstream zone and merely tends to area of launching apron but not significant. Here it has been observed that scour behavior and patterns does not progress uniformly throughout the channel and also some siltation occurs at the mouth of char/sand bar.

But in Figure 5.19 (c), deposition pattern has been extended towards upper mid zone from the nose of sand bar like delta formation as well as mouth of meeting zone of two channel. It is being analyzed that here difference of Q_r of two channel has been increased and oblique flow channel has been dominated with flow angle thus creating backflow force to straight flow at just meeting zone closely to mouth of sand bar. And Maximum dominated scour prone contour approx. 6.91 m has been elongated from CS-11 to CS-06 but its movement has been followed longitudinally compared more D/S action than Q_r-1.2. And finally the Q_r-1.6 has been allowed to convey through oblique channel, deposition pattern has been extended towards mid zone of combined channel from the mouth of meeting zone of two channel even as a whole cross-section.

Here from Figure 5.19 (d), it is important to analyze that no significant scour has been found for Q_r-1.6 although maximum scour is 6.96 m but it is not area specific rather location centric. It has been proved that scour depth with extent of area has increased with enhancing discharge ratio (Q_r) upto 1.4 but further increase, extent of scour has been reduced.

5.6.2 Variable Discharge Ratio (Q_r) with Fixed 40^0 Oblique Angle

Test parameters of the set-up has been fixed with 40^0 oblique angle and variable discharge ratio (1.2,1.4,1.6). Same procedure has been followed for initial bed as for 20^0 oblique angle. So, here these three test run as discharge ratio of 1.2,1.4 and then finally 1.6 has been consecutively analyzed for constant 40^0 oblique flow angle. Now, According to Figure 5.20 (b), here it has been observed that scour pattern has been cleared adjacent to launching apron and its vulnerability has dominated within CS-11 to CS- 08 due to the 40^0 oblique flow angle.

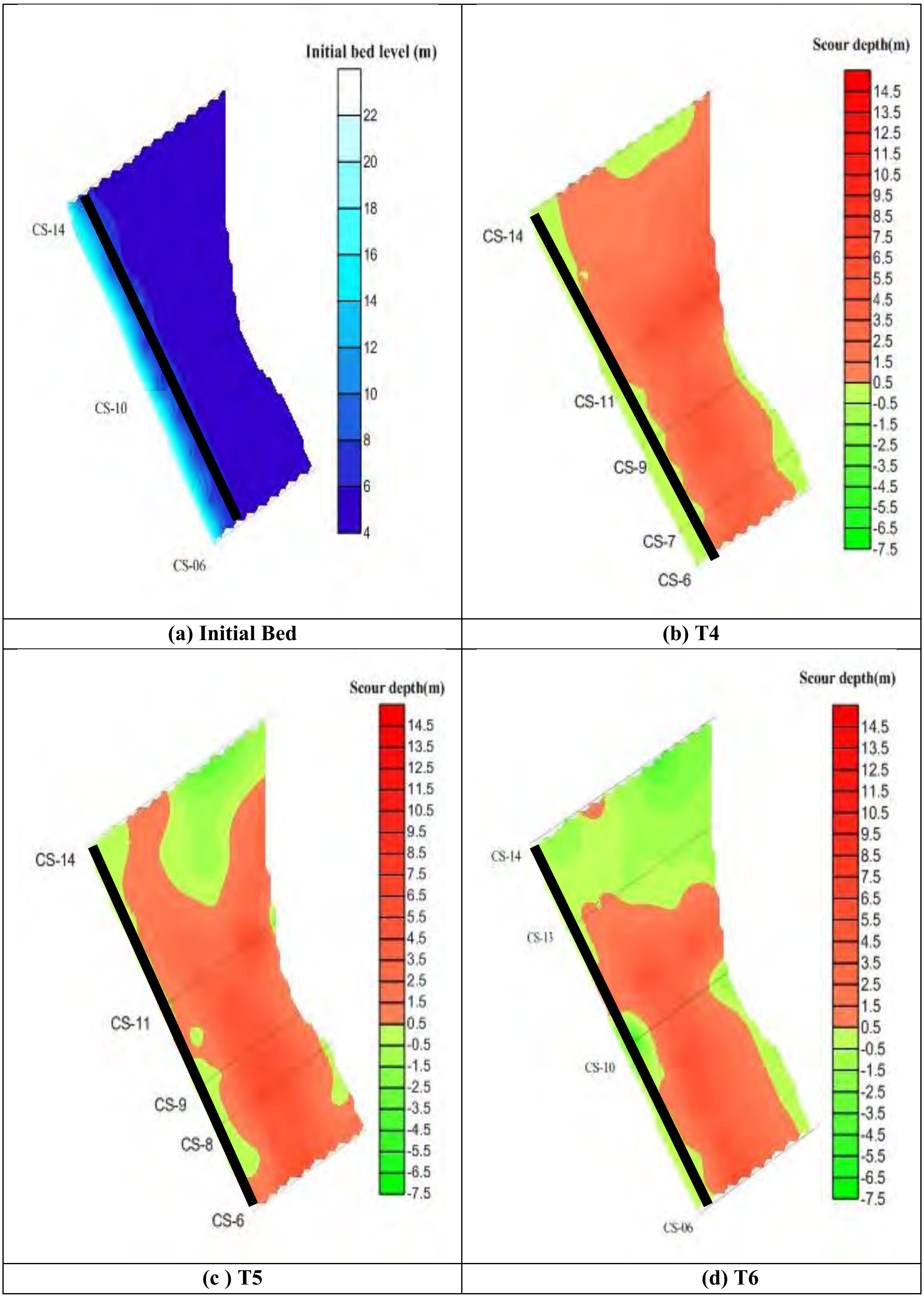
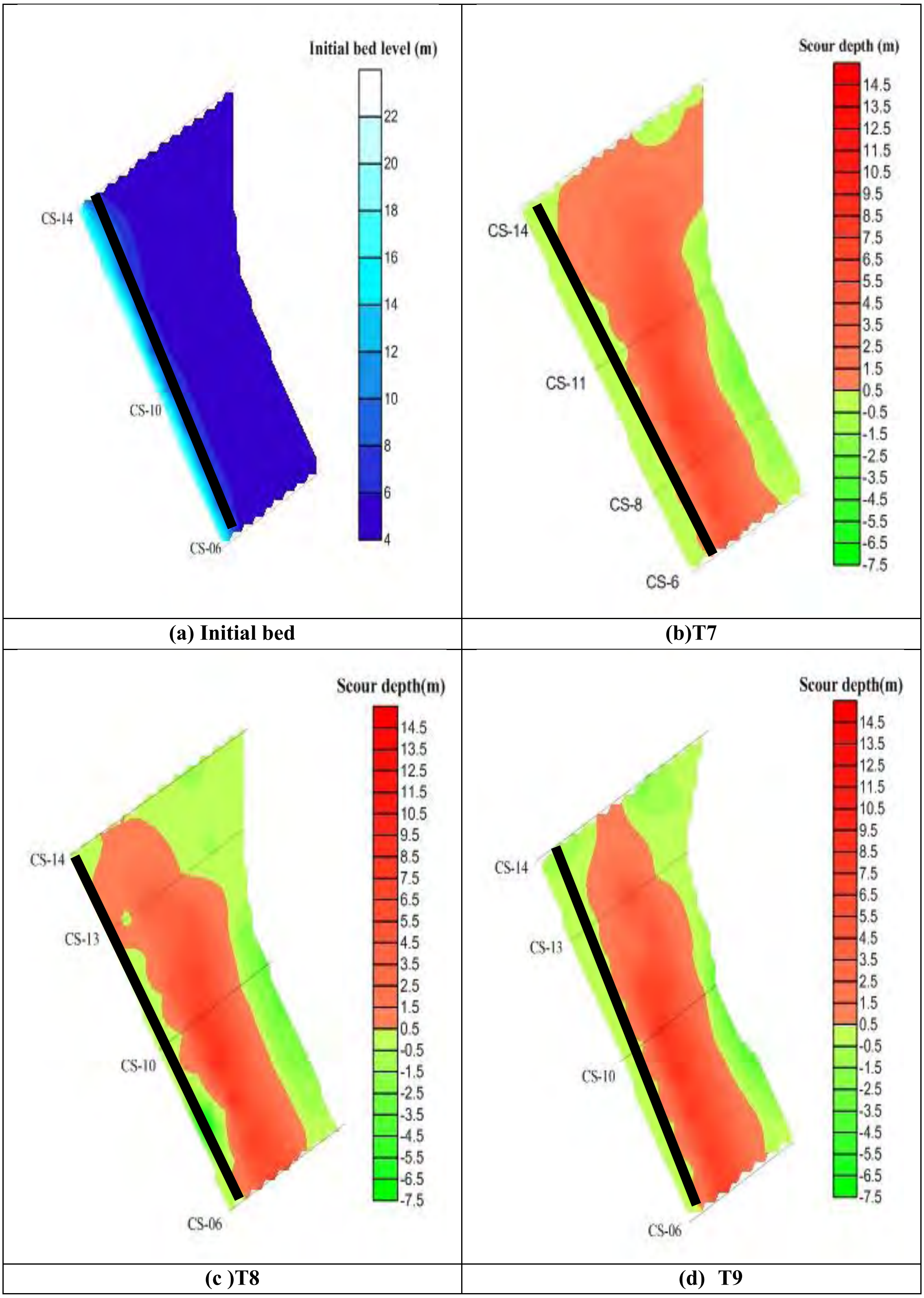


Figure 5.19: Scour Depth for Variable Q_r at Fixed Θ_o:- 20^0



(a) Initial bed **(b)T7**

(c)T8 **(d) T9**

Figure 5.20: Scour Depth for Variable Q_r at Fixed Θ_o:- 40^0

But from Figure 5.20 (c), scour pattern has been extended throughout the combined channel as well as adjacent to launching apron. And its vulnerability has been dominated within CS-11 to CS-07 with maximum scour contour. And from Figure 5.20 (d), scour pattern has been protruded longitudinally throughout the combined channel as well as adjacent to launching apron and its vulnerability has been dominated within CS-11 to CS-07 with maximum scour contour. So it has been logically found that spatially varying with discharge ratio scour depth pattern and contour has become almost same but their vulnerability has defined by the closest position of scour depth pattern with embedded launching apron at river bed.

5.6.3 Variable Discharge Ratio (Q_r) with Fixed 60^0 Oblique Angle

These test parameters have been selected with 60^0 oblique angle and variable discharge ratio (1.2, 1.4, 1.6). In the Physical model, a designed initial bed has been prepared at where three set of run has completed. So, here these three test run as discharge ratio of 1.2, 1.4 and then finally 1.6 has been analyzed for constant 60^0 oblique angle as if it would be logical to determine relative scour depth. Now, According to Figure 5.21 (a) it has been shown as initial bed value and from Figure 5.21 (b), here it has been observed that scour pattern has been cleared adjacent to launching apron and its vulnerability has dominated within CS-11 to CS-09 due to the 60^0 oblique flow angle with maximum scour contour. But from Figure 5.21 (c) scour pattern has been not extended throughout the combined channel as well as adjacent to launching apron and its vulnerability has dominated within CS-12 to CS-10 with maximum scour contour but not uniform scour depth path.

And from Figure 5.21 (d), scour pattern has been protruded longitudinally throughout the combined channel as well as adjacent to launching apron and its vulnerability has dominated within CS-12 to CS-10 with maximum scour contour and some deposition has been observed at the left bank due to the concurrence action of oblique flow angle at right bank. So It has been logically found that spatially varying with discharge ratio scour depth pattern and contour has become almost same but their vulnerability has defined by the closest position of scour depth pattern with embedded launching apron at river bed and deposition field has upgraded at left bank with uprising discharge ratio.

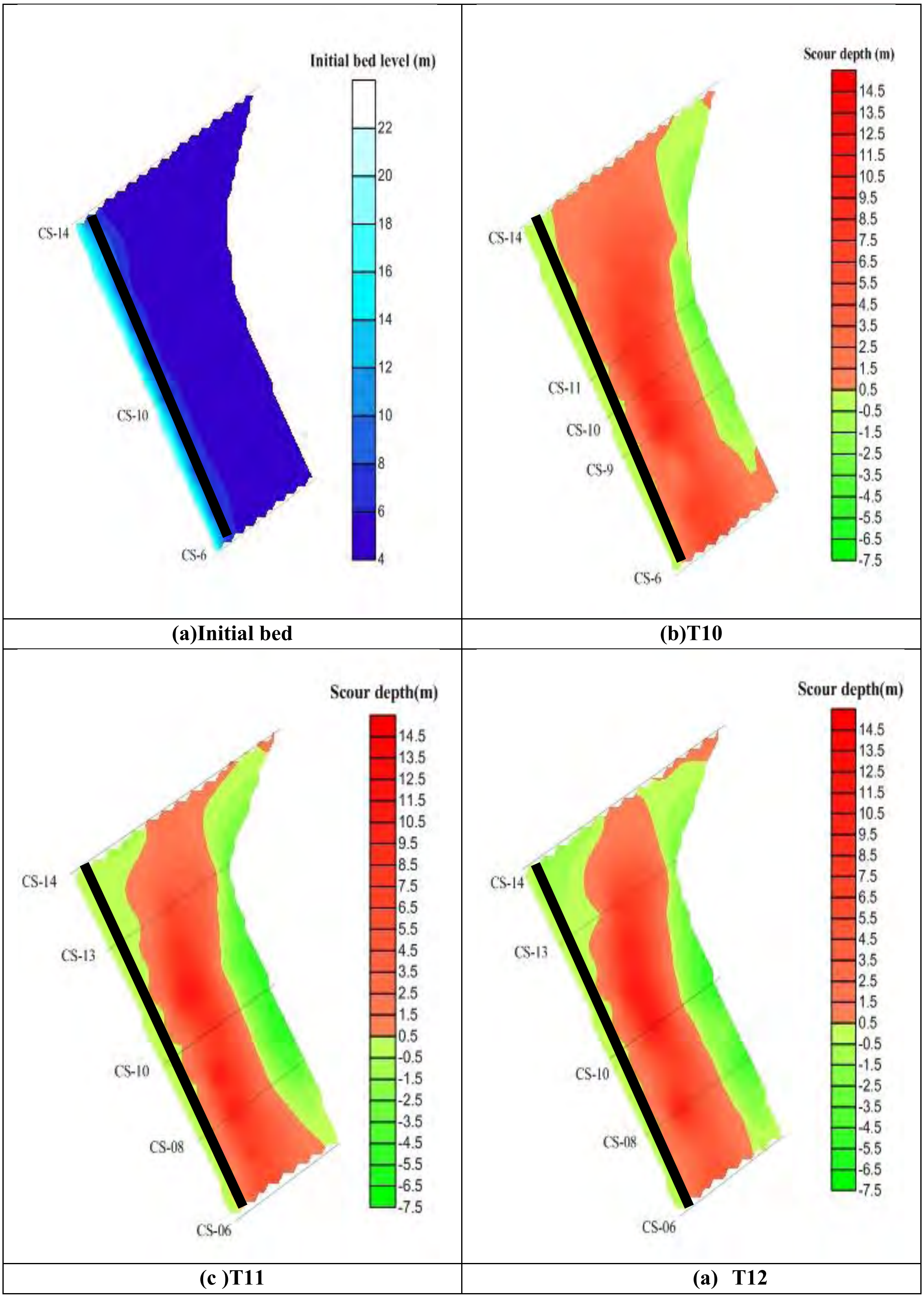


Figure 5.21 : Scour Depth for Variable Q_r at Fixed Θ_o:- 60^0

5.6.4 Observation between Only Straight and Only Oblique Flow Condition

According to Figure 5.22 (b), total discharge has been conveyed through the oblique flow channel where the main channel was not in operation. This is a critical condition where the flow towards the bank protection work at 60^0 oblique angle has concentrated the flow to the bank protection and produced a separate stream flow along right bank of the combined channel. The extent of siltation has been extended upto mid portion of the channel which is completely a different phenomenon. The scour depth has developed near to the bank protection work which was about 12.2 m adjacent to mid zone and gradually reducing its intensity towards downstream zone of the channel.

From the Figure 5.22 (d), it has been observed that no further vulnerable scour has been developed in the combined channel. No significant scour have been observed adjacent to revetment from meeting zone to downstream zone except some little local scour. A silted channel has been developed over all due to the no oblique flow phenomenon which has influenced and uniform flow pattern.

5.6.5 Variation of Oblique Angle (Θ_o) with Fixed Discharge Ratio-1.2

According to Figure 5.23 varying with oblique angle with fixed discharge ratio 1.2, firstly at figure 5.23 (a), from the meeting zone as CS-13, scour depth has been gradually increased toward mid portion and then reduction trend to left bank with increasing oblique angle which has been shown the maximum scour depth approx. 6.0 m at 60^0 oblique angle except some reduction of scour depth at 20^0 oblique flow angle. And from Figure 5.23 (b), at mid zone as CS-10 same as CS-13 but it has been observed near to maximum scour depth approx. 11.0 m at 60^0 oblique angle. But from Figure 5.23 (c), it has been found that scour depth for respective angle has shown less variation among together and same pattern as previous described, although it has been shown lower than mid zone as scour depth approx.7 m for 60^0 oblique angle. It has been specially observed that as soon as stream flow has passed to downstream zone developing more scour depth adjacent to revetment. According to Figure 5.24 (a), it has been observed with a steady increase its scour depth longitudinally upto downstream zone adjacent to revetment as for 20^0 oblique angle.

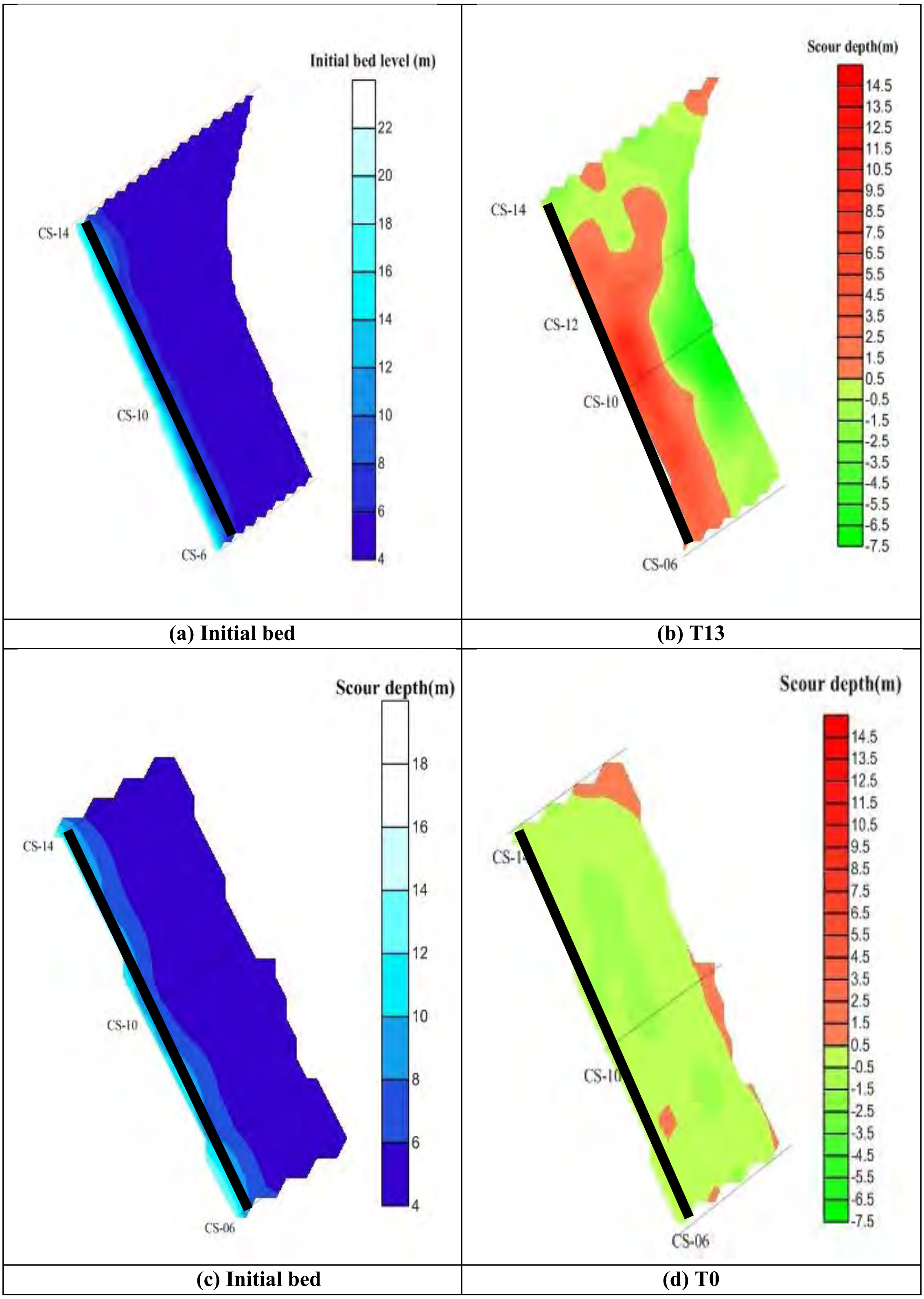
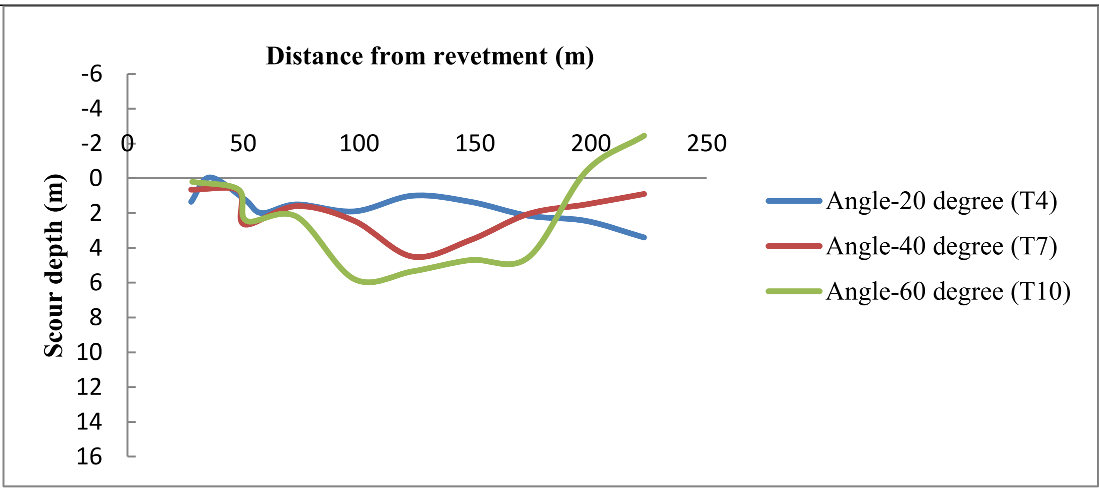


Figure 5.22: Scour Depth Variation Only Straight and Oblique Flow (Θ_o:- 60^0) at Fixed Q:- Full Conditions

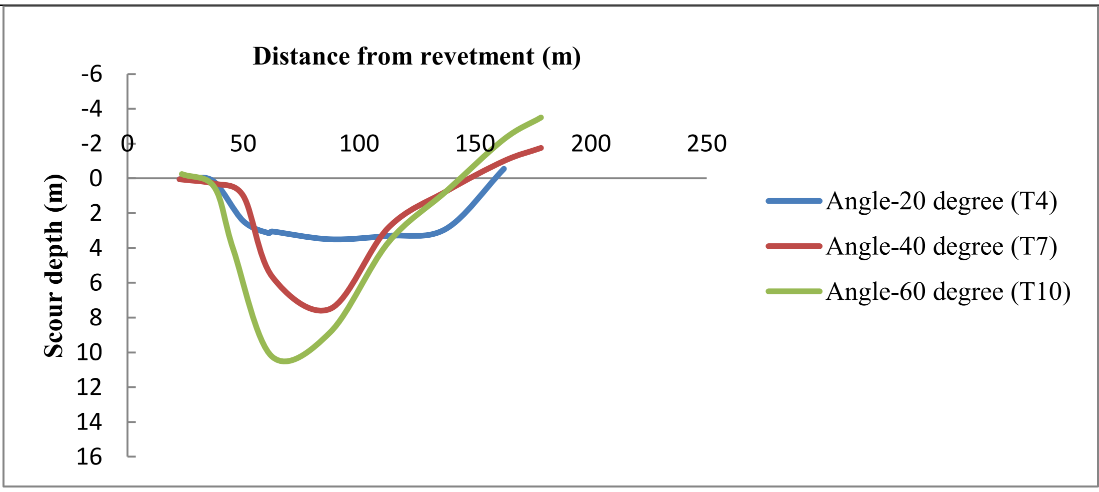
But for 40^0 oblique angle, it has been shown that upto CS-08 which defines scour tends to downstream and for 60^0 oblique angle, thus it has been shown that upto CS-10 indicating more scour forwarding to mid zone due to sharper oblique flow angle. But from Figure 5.24 (b), at mid portion of combined channel scour depth has been developed along same pattern up to CS-10 for varying oblique angle then it has been reduced steadily up to downstream, although higher scour depth has been found for 60^0 oblique flow angle. And then from Figure 5.24 (c), near to left bank for 20^0 oblique angle, scour depth has intensified to mid zone due to the concentration of flatter angle. But for 40^0 and 60^0 scour depth has been reduced, even siltation has been found respectively due to steeper angle tends to oblique flow with straight flow, which has been created a stagnant zone along left bank and contemporary for side wall boundaries also.

5.6.6 Variation of Oblique Angle (Θ_o) with Fixed Discharge ratio- 1.4

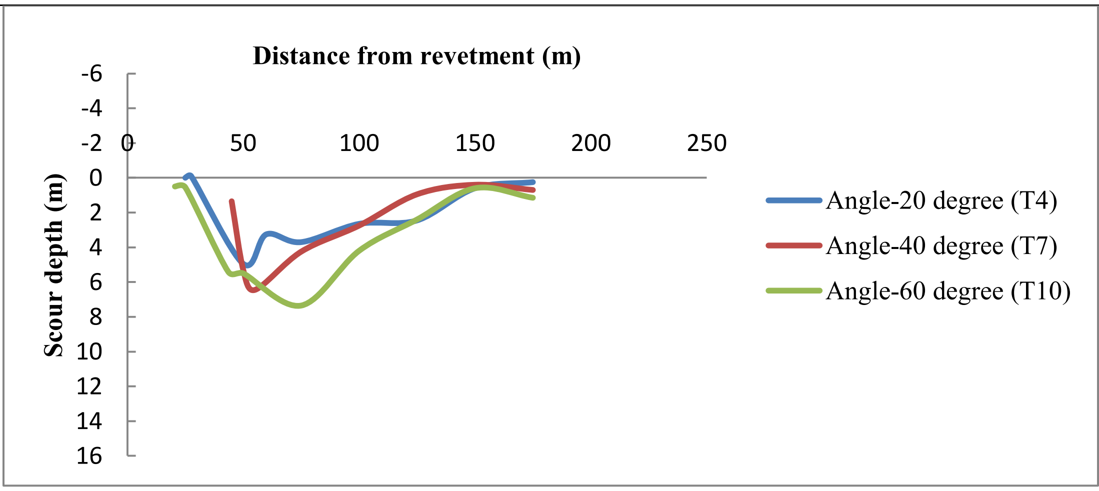
According to Figure 5.25 varying with oblique angle with fixed discharge ratio 1.4, firstly at Figure 5.25 (a), from the meeting zone as CS-13, scour depth has been gradually increased toward mid portion and then reducing trend to left bank with increasing oblique flow angle which has been measured as the maximum scour depth approx. 7 m at 60^0 oblique angle but for 20^0 oblique flow angle there have been observed small scour depth at over all section of CS-13, even frequent siltation has been found at mid portion and then near to left bank a small scour has been determined. And from Figure 5.25 (b) ,at mid zone as CS-10 same as CS-13 but it has been shown the maximum scour depth approx. 14.8 m at 60^0 oblique angle and siltation has found near to left bank for each oblique flow angle. But from Figure 5.25 (c), at downstream zone, it has been found that scour depth for respective angle has been shown with less variation among together and same pattern as previous described, although it has been measured lower than mid zone as scour depth approximate 7 m for 60^0 oblique angle. It has been specially observed that as soon as stream flow has been passed to downstream zone then scour depth has found adjacent to revetment.



(a) CS-13: Meeting zone

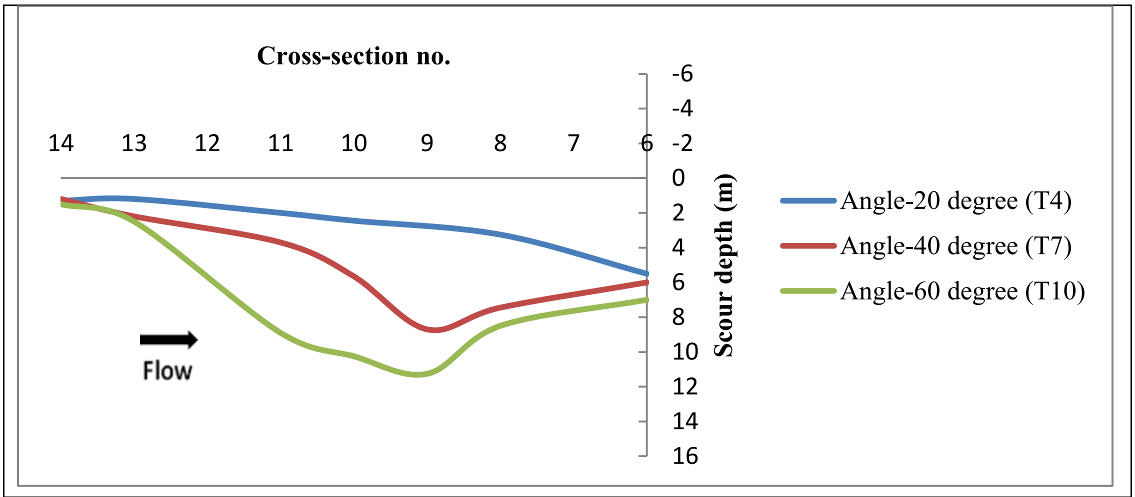


(b) CS-10: Mid zone

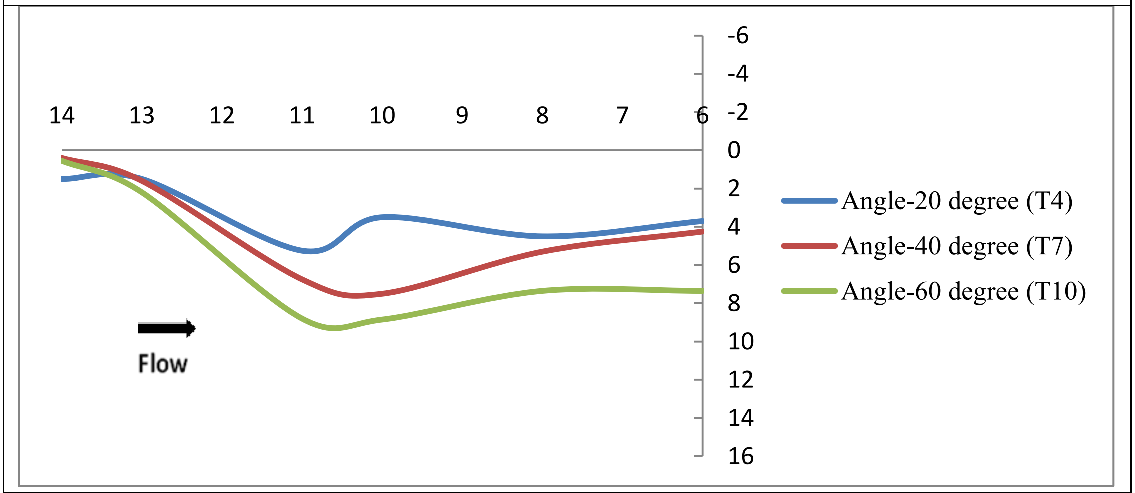


(c) CS-06: Downstream zone

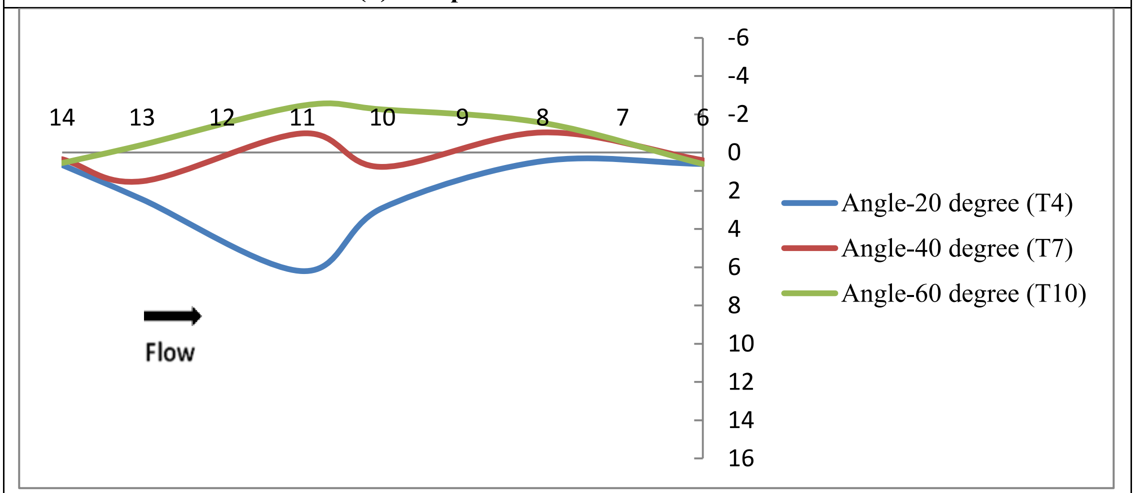
Figure 5.23: Comparison of Cross-sectional Scour Depth for Variable Θ_o at Fixed Q_r:- 1.2



(a) Adjacent to revetment



(b) Mid portion of combined channel



(c) Near to left bank

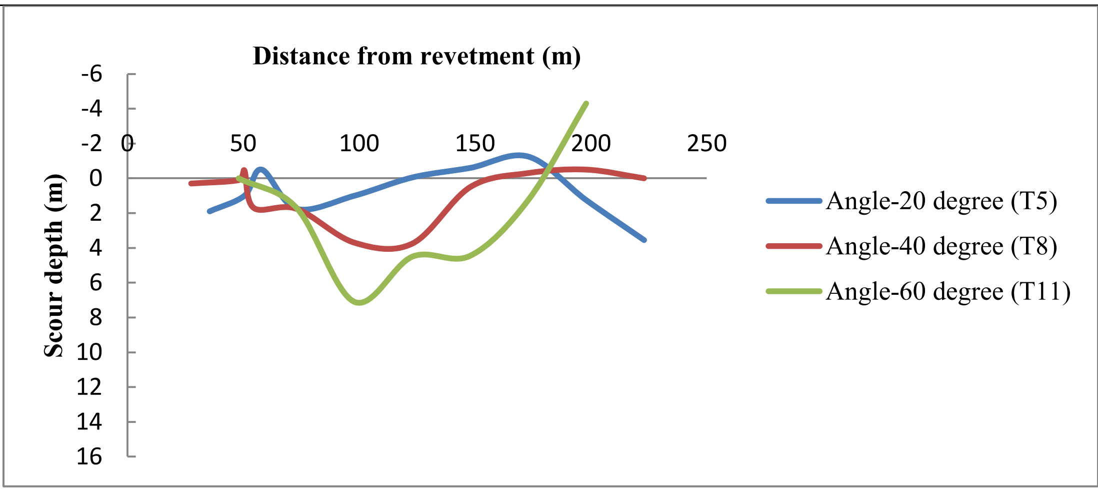
Figure 5.24: Comparison of Longitudinal Scour Depth for Variable Θ_o at Fixed Q_r:-1.2

According to Figure 5.26 (a), Here it has been observed that adjacent to revetment longitudinally varying with oblique angle, for 20^0 angle it has been shown steady increase its scour depth up to downstream zone but for 40^0 angle it has been shown up to CS-08 defining scour tends to upstream and for 60^0 angle, thus it has been shown up to CS-11 defining more forwarding to mid zone due to more sharper oblique angle.

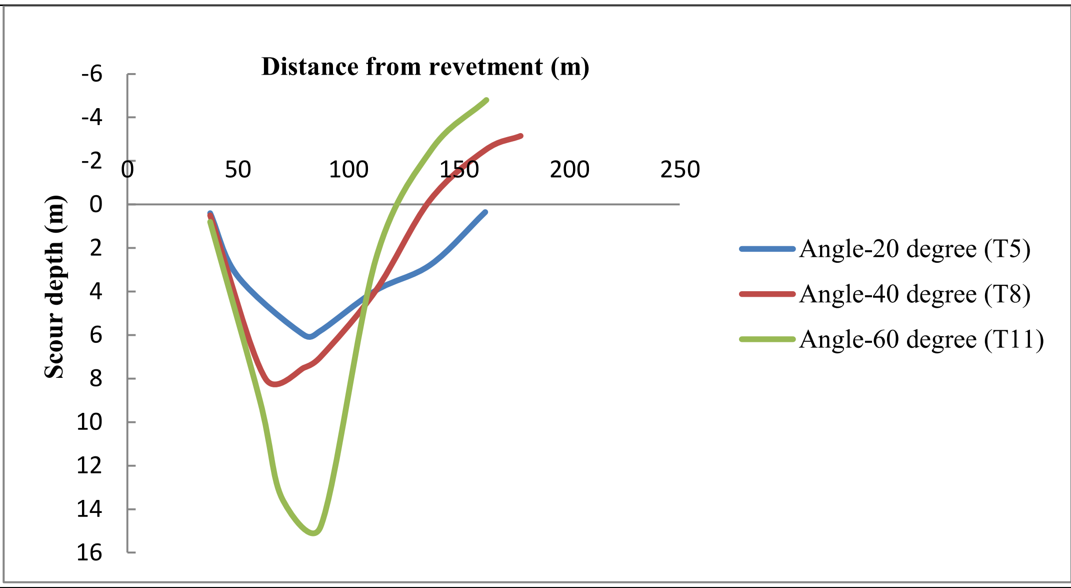
But from Figure 5.26 (b), at mid portion of combined channel, scour depth has been developed along same pattern up to approximate CS-10 for varying oblique angle then it has been reduced steadily up to downstream, although higher scour depth has been found for 60^0 oblique angle. And from Figure 5.26 (c), then near to left bank scour depth increases up to mid zone as CS-10 for 20^0oblique angle due to the concentration of smoother angle. But for 40^0 and 60^0 oblique angle, scour depth has been reduced at a level even siltation has found frequently due to steeper angle tends to normal flow with straight flow which has created a stagnant zone along left bank and contemporary for side wall boundaries also.

5.6.7 Variation of Oblique Angle (Θ_o) with Fixed Discharge Ratio-1.6

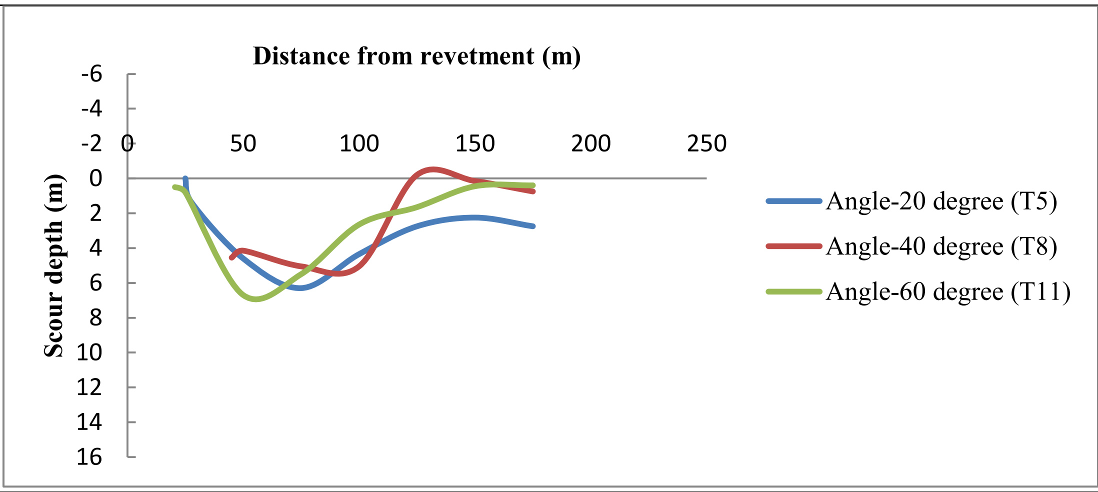
According to Figure 5.27 (a), from the meeting zone as CS-13, scour depth has been gradually increased toward mid portion and then reducing trend to left bank with increasing oblique flow angle which has shown the maximum scour depth approximate 8.5 m at 60^0 oblique angle . And from Figure 5.27 (b), at mid zone as CS-10 same as CS-13 but it has been shown the maximum scour depth approximately 15.9 m at 60^0 oblique angle. But from Figure 5.27 (c), at downstream zone, it has been found that scour depth for respective angle is tentatively same and same pattern as previous described condition, although it has been shown lower than mid zone. It has been specially observed that as soon as stream flow has passed to downstream zone then scour depth found adjacent to revetment.



(a) CS-13: Meeting zone



(b) CS-10: Mid zone



(c) CS-06: Downstream zone

Figure 5.25: Comparison of Cross-sectional Scour Depth for Variable Θ_o at Fixed Q_r:-1.4

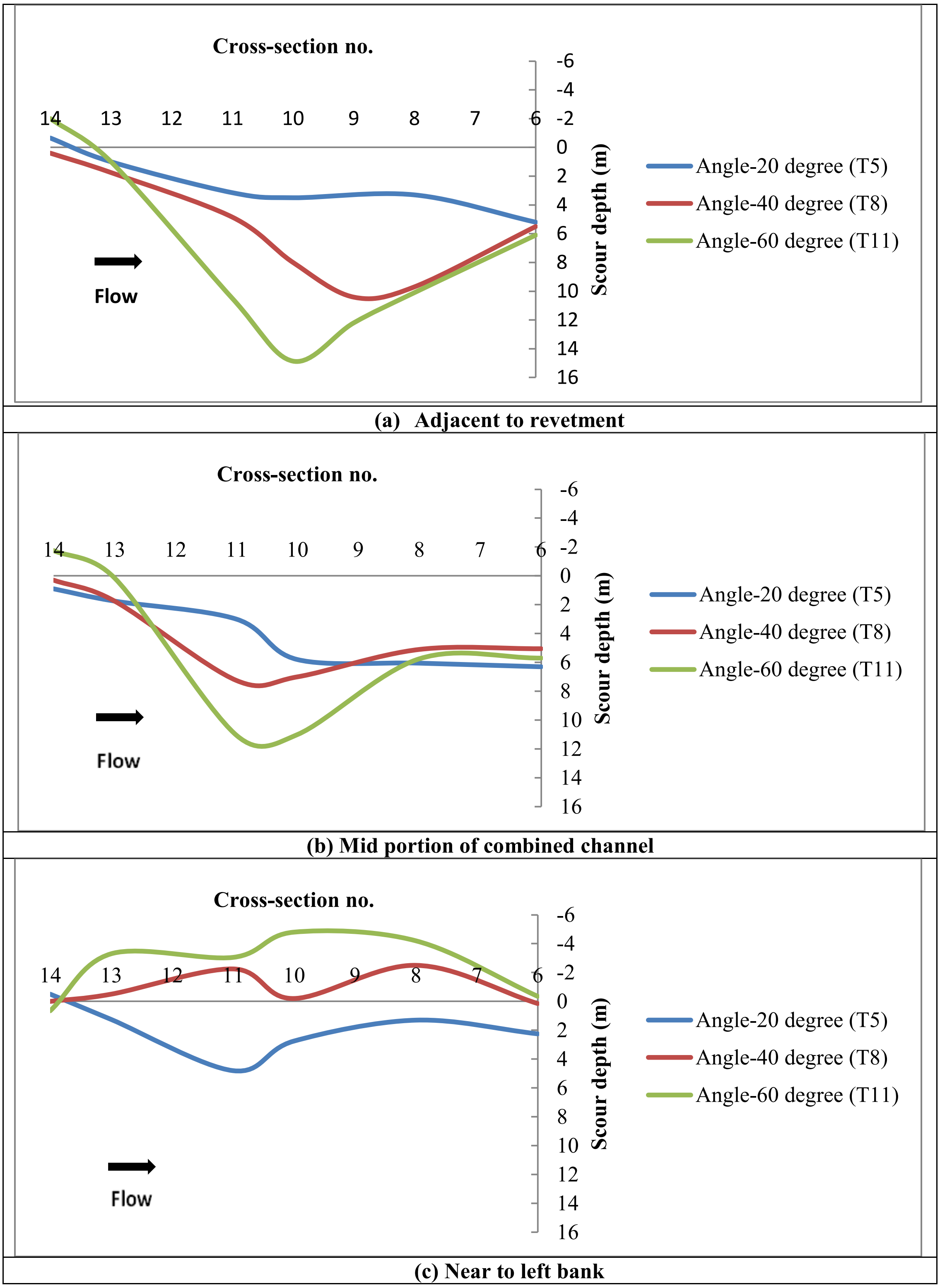


Figure 5.26: Comparison of Longitudinal Scour Depth for Variable Θ_o at Fixed Q_r:-1.4

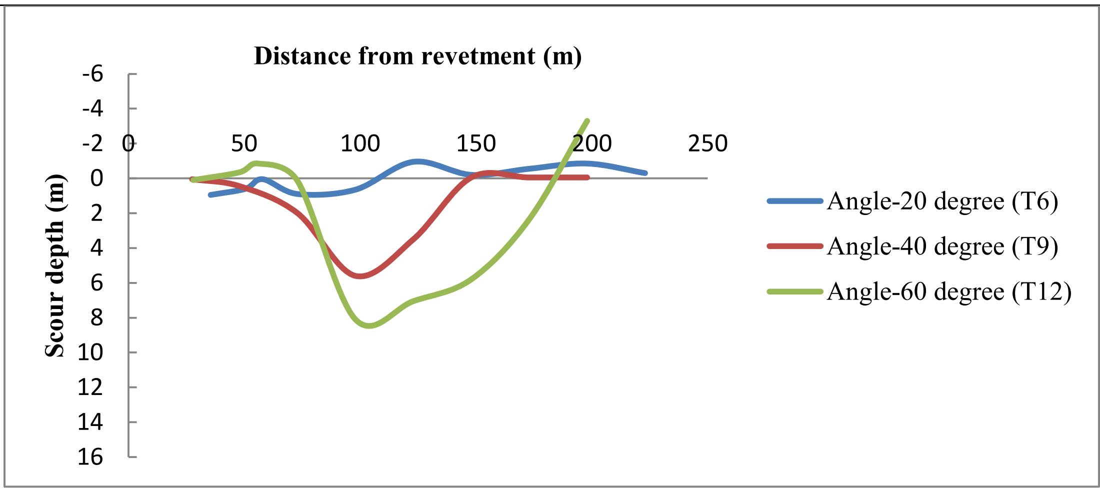
According to Figure 5.28 (a), here it has been observed that adjacent to revetment longitudinally varying with oblique angle, for 20^0, it has been shown that steady increase its scour depth upto downstream zone but for 40^0, it has been shown up to CS-10 enhancing scour tends to mid zone except reduction towards downstream and for 60^0, thus scour depth has been increased up to CS-11 defines more forwarding to mid zone due to more sharper oblique flow angle. But from Figure 5.28 (b), at mid portion of combined channel scour depth has been developed along same pattern up to approximate CS-10 for varying oblique flow angle then it has been reduced steadily up to downstream, although higher scour depth has been found for 60^0 oblique flow angle. And from Figure 5.28 (c), for 20^0 oblique flow angle near to left bank, scour depth has been increased up to mid zone as CS-11 due to the concentration of flatter oblique flow angle. But for 40^0 and 60^0 oblique angle, scour depth has been reduced even siltation has been found frequently due to steeper angle tends to normal flow with straight flow which has created a stagnant zone along left bank and contemporary for side wall boundaries also.

5.7 Thalweg Channel Pattern

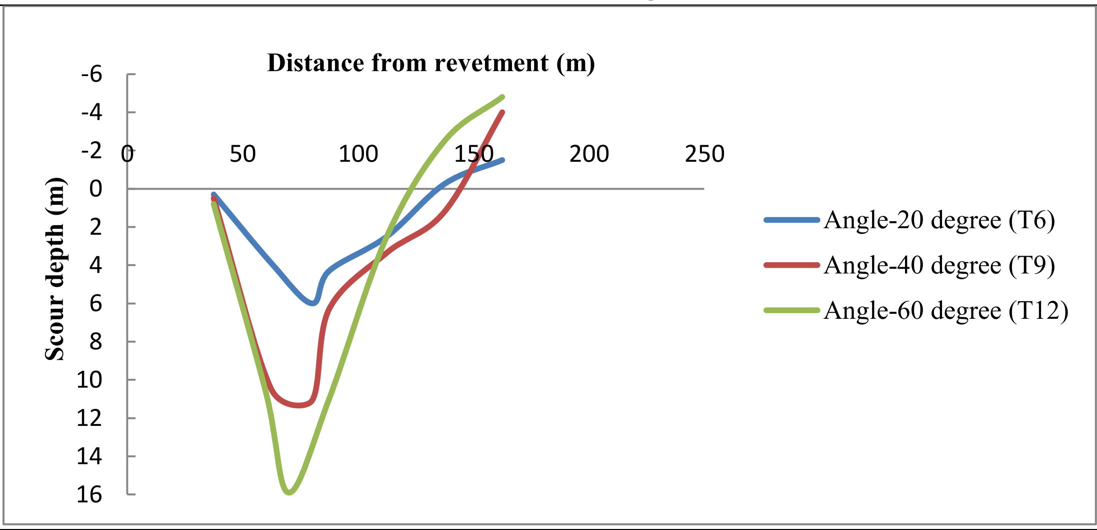
Thalweg channel has been defined as the deepest channel formation. Oblique flow has attracted to the channel with increasing its intensity to scour. Not only that, flow field of combined channel has attracted to the thalweg channel whether it has found mostly adjacent to revetment. Now, here it has been observed the impact of discharge ratio (Q_r) with oblique angle (Θ_o) under oblique flow as well as investigated the vulnerability of bank protection work using stone boulder as bank protective materials.

5.7.1 Variable Discharge Ratio (Q_r) with Different Oblique Angle (Θ_o)

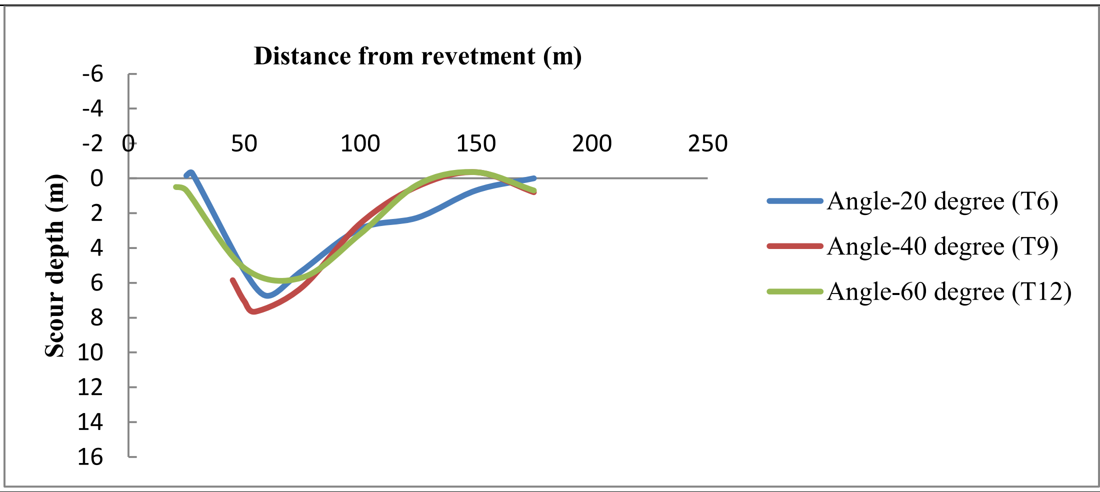
According to Figure 5.29, for 20^0 oblique angle increasing with discharge ratio, deepest channel formation has been observed from meeting zone to downstream zone considerably from CS-11 as mid zone, it has attracted adjacent to the bank protection work at right bank as far as approximate 50-75 m from revetment going through upstream to downstream, but maximum stream power of oblique flow shows maximum intrusion to the bank protection work.



(a) CS-13: Meeting zone



(b) CS-10 : Mid zone



(c) CS-06 : Downstream zone

Figure 5.27: Comparison of Cross-sectional Scour Depth for Variable Θ_o at Fixed Q_r:- 1.6

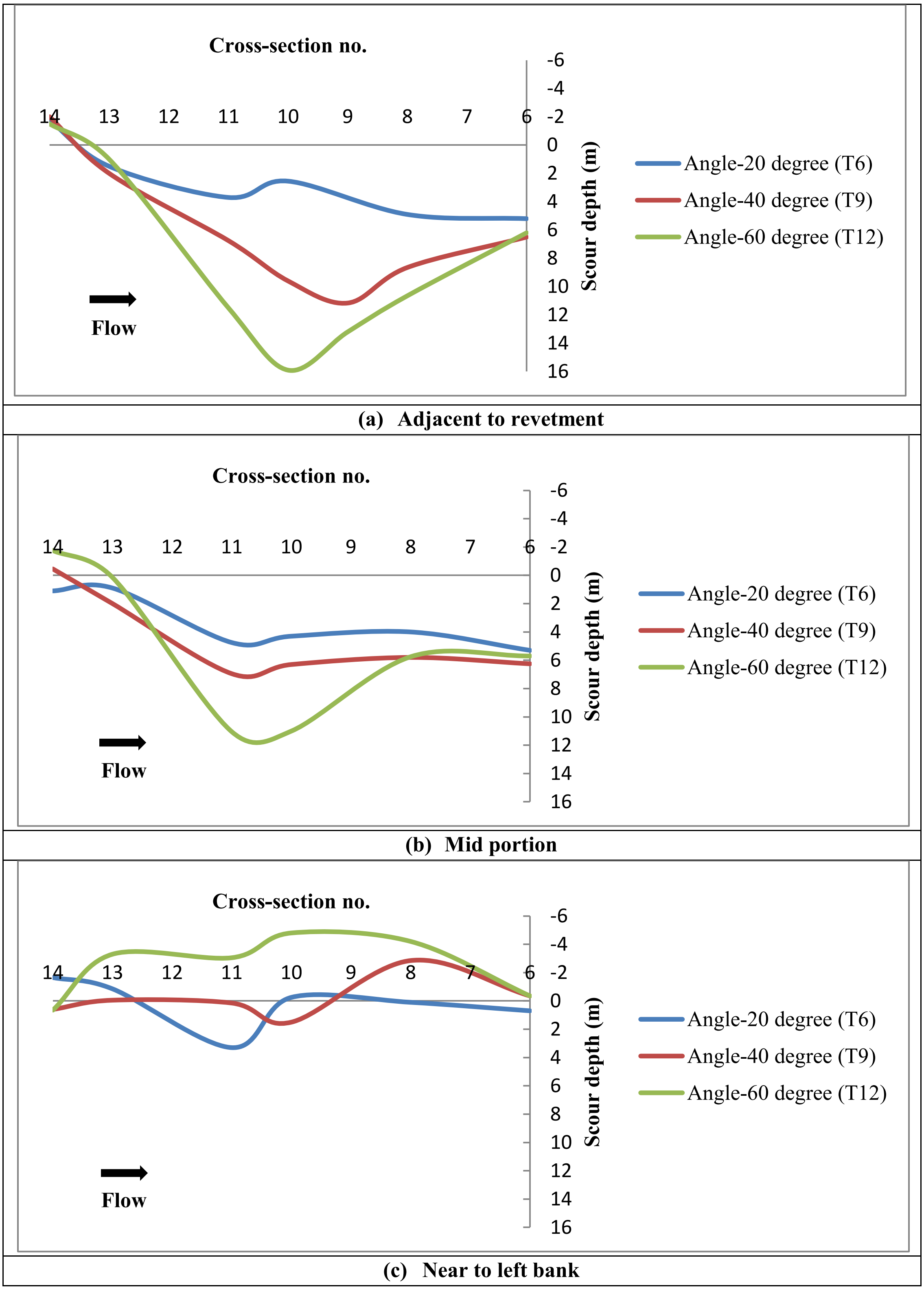


Figure 5.28: Comparison of Longitudinal Scour Depth for Variable Θ_o at Fixed Q_r:-1.6

As the increment of oblique angle as 40^0 and then 60^0, it has been observed critically that variation of discharge ratio with angular variation influences very much creating the deepest scour hole from the most upstream position which is almost adjacent to the revetment rather than any smother angle. It has been found that at any oblique angle maximum discharge ratio 1.6 as maximum oblique stream power has influenced to make deepest scour hole adjacent to revetment but increment of oblique angle deepest scour channel has shown its vulnerability forwarding to the meeting zone. So it has been decided most sharp angle (60^0) with maximum oblique stream power (1.6) is the most critical consideration for the bank protection work.

5.7.2 Variable Oblique Angle (Θ_o) with Different Discharge Ratio (Q_r)

From figure 5.30, increasing with oblique flow angle for consecutive fixed discharge ratio (Q_r), it has been observed that intrusion of deepest scour channel has been developed adjacent to bank protection work from the meeting zone to downstream zone with its vulnerability.

5.7.3 Comparison between Only Straight and Only Oblique Flow Condition

According to the figure 5.31, it has been observed that without any oblique flow as like as straight main channel flow with full discharge that not belongs to braided properties, then deepest scour channel has been developed far away from revetment although at downstream zone it tends to move adjacent to revetment due to the model limitations (influence of tail gate). But when the main channel has to be closed and full discharge has off taken through the oblique channel as a oblique flow with maximum oblique angle, it has been shown maximum encroachment to the bank protection work from the meeting zone to downstream as well as drastically.

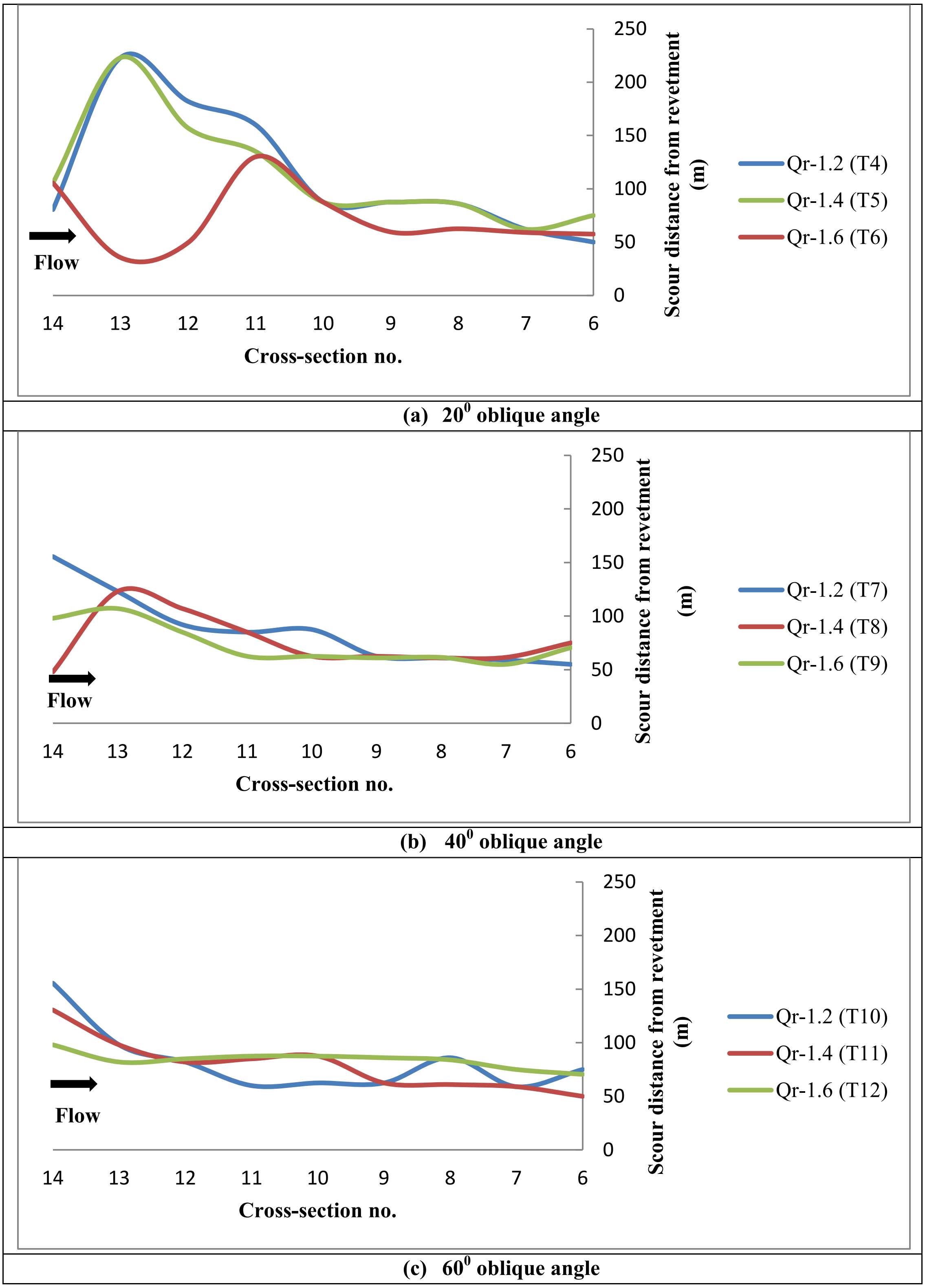
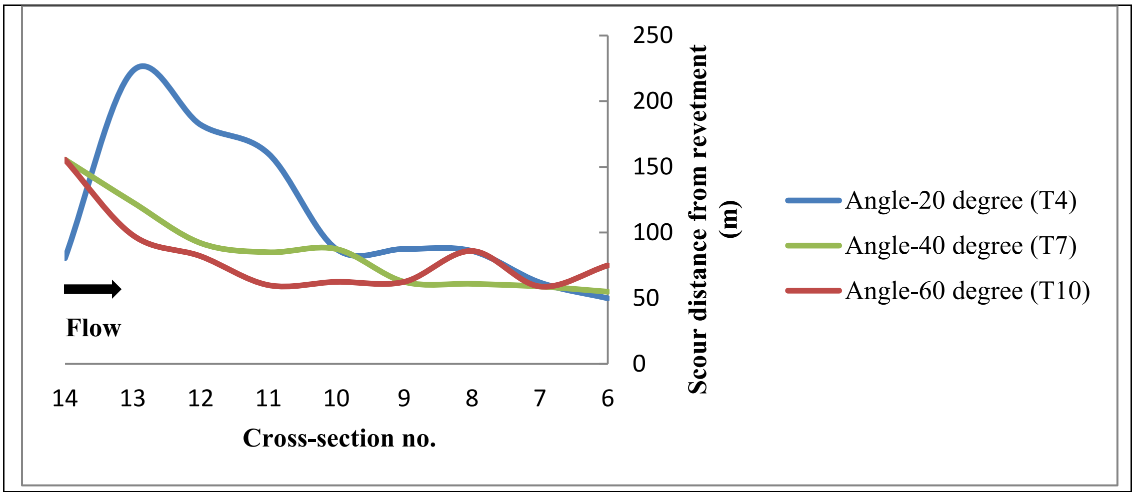
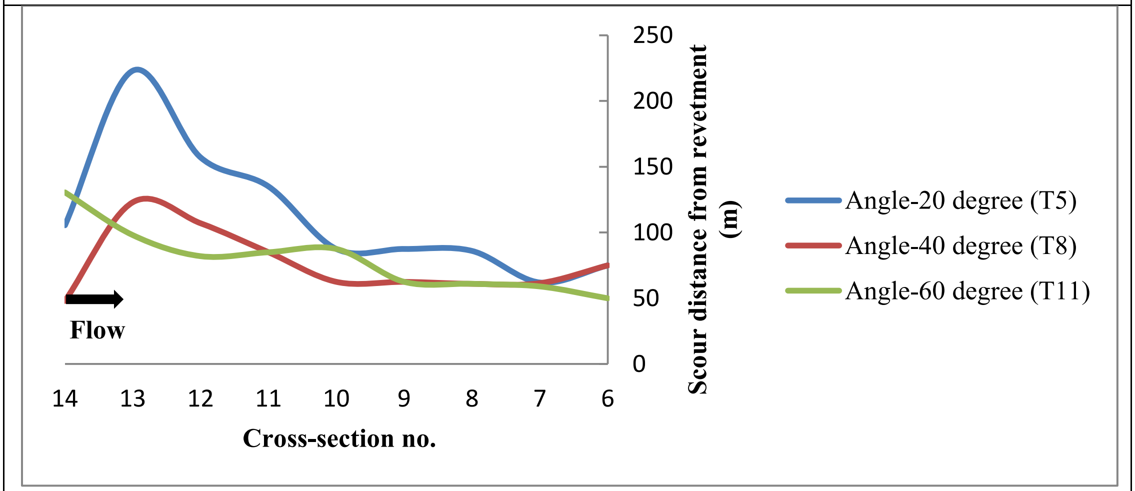


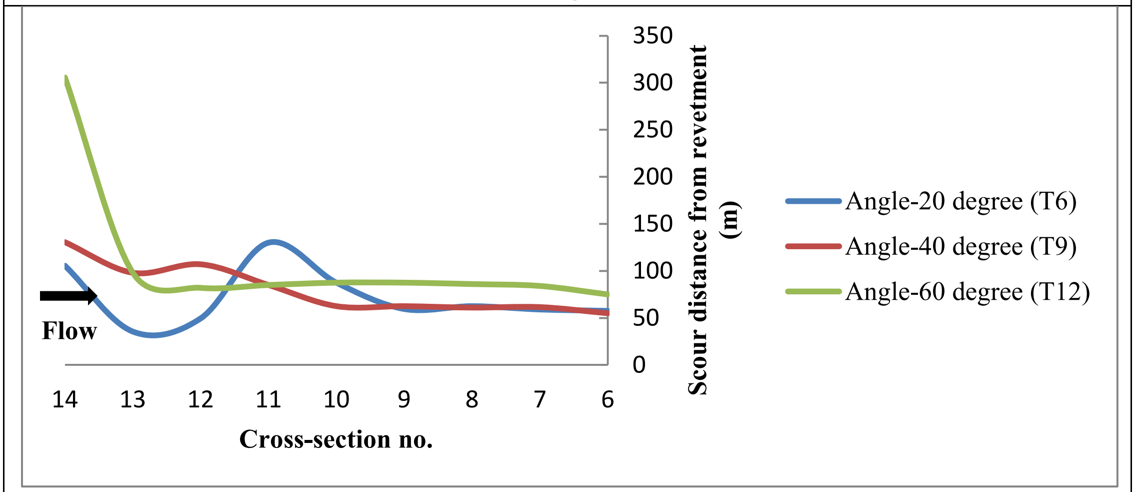
Figure 5.29: Thalweg Channel Pattern for Variable Q_r at Different Θ_o



(a) Discharge ratio (Q_r)-1.2



(b) Discharge ratio (Q_r)-1.4



(c) Discharge ratio (Q_r)-1.6

Figure 5.30: Thalweg Channel Pattern for Variable Θ_o at Different Q_r

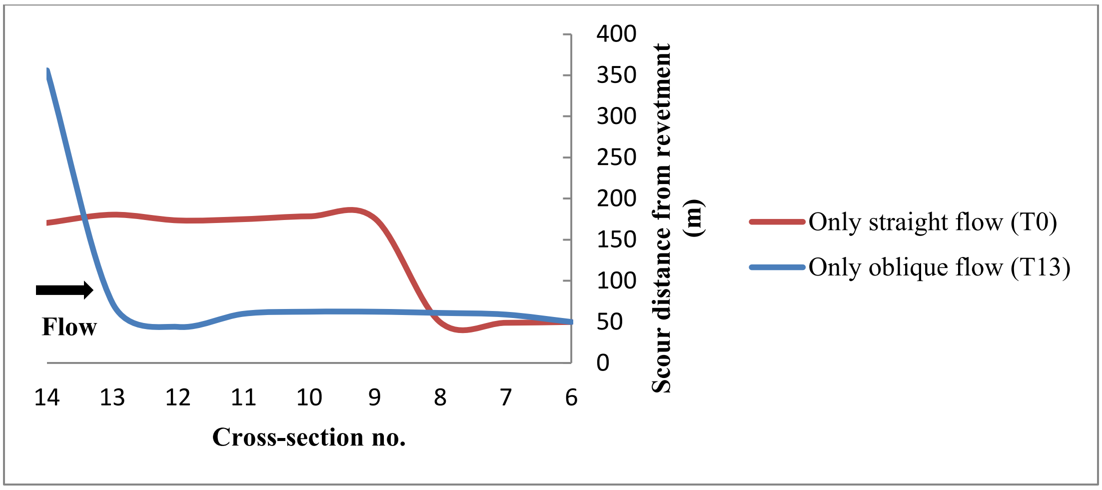


Figure 5.31: Thalweg Channel Pattern for Only Straight and Oblique Flow (Θ_o:- 60^0) at Fixed Q:- Full Conditions

5.8 Thalweg Channel Analysis

From the Figure 5.32 (a), varying with discharge ratio for different oblique flow angle, following behaviors of scour depth for stone boulder served as bank protective materials have been observed.

a) For smooth angle as 20^0, position of maximum scour depth from meeting point has been gradually moved far away with the increase of discharge ratio (Q_r) or oblique flow stream power. At the same time scour depth has been increased along with the increase of oblique flow discharge.

b) For further increase of angle, position of maximum scour depth from meeting point has been determined not to change any more but the distance is more than previous oblique angle like 20^0.Thus here it has been found with a progression of scour depth with the advancement of discharge ratio.

c) And for most sharp angle, maximum scour depth position has gradually reduced from meeting point and its measured depth has consecutively increased more than all of less sharp oblique flow angle.

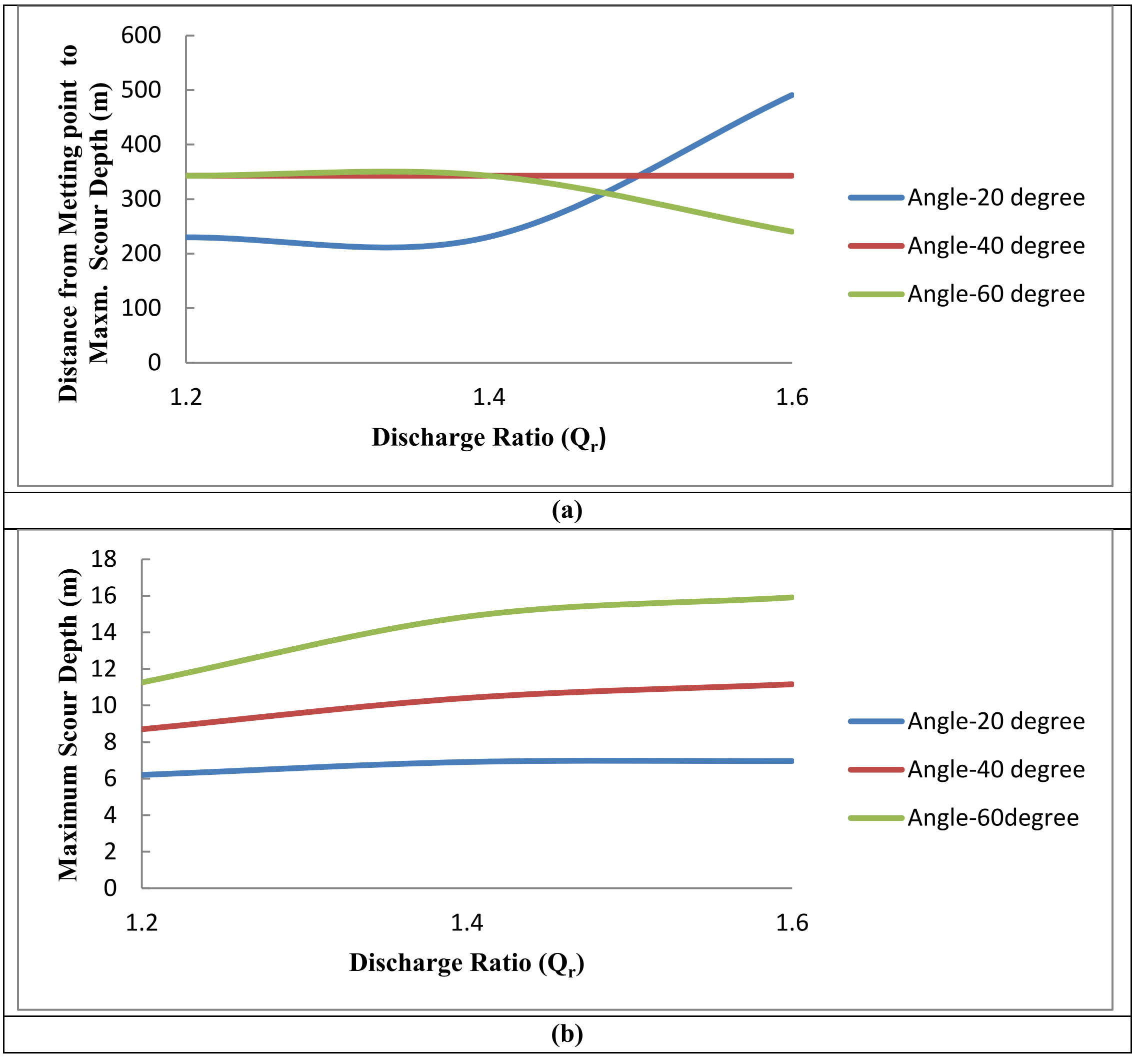


Figure 5.32: Determination of Maximum Scour Depth and its Location from Meeting Point for Different Conditions

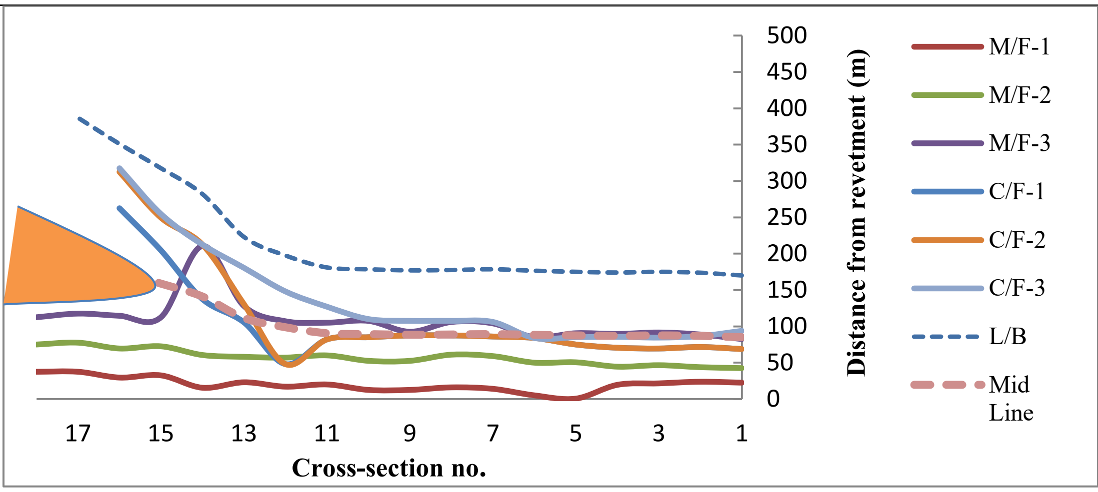
Vice versa from the Figure 5.32 (b), it has been observed that for oblique discharge ratio as Q_r- 1.2,1.4,1.6 with the progression oblique flow angle maximum scour depth position has been advanced to high with significant proportion. But progression of discharge ratio (Q_r) as 1.2, 1.4 and 1.6 with fixed oblique angle, scour depth has been enhanced comparatively less significant proportion as preceding described conditions.

5.9 Observation of Surface Flow Line at Combined Channel

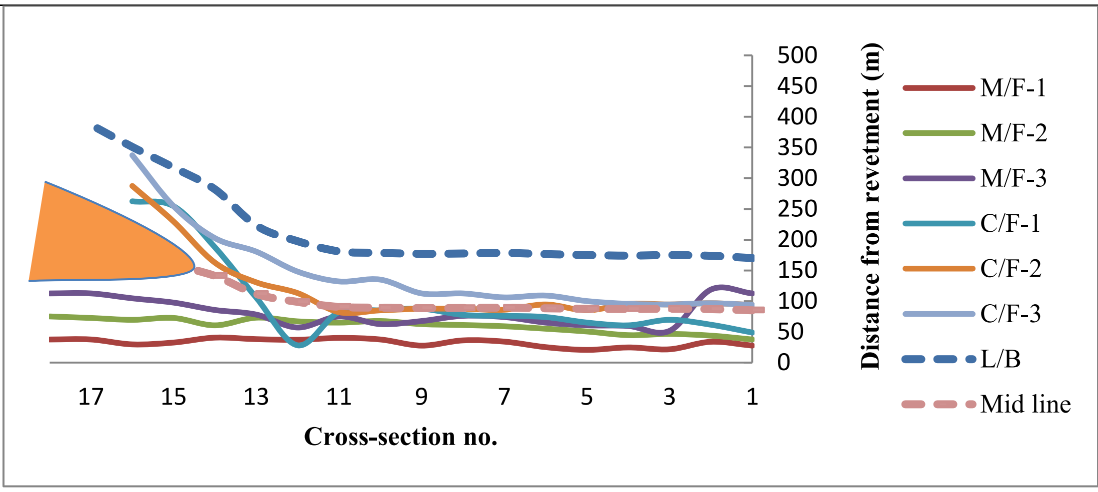
To observe the flow concentration of stream it has been executed with three flow line for each channel as main channel and oblique channel. For such kind of clarification flow line has been identified in the Figure as M/F-1 to M/F-03 and C/F-1 to C/F-3 respectively for main channel and oblique channel. In the Figure 5.33 (a), it has been observed that oblique flow has concentrated with straight flow at mostly mid zone to downstream zone adjacent to revetment, but stream intensity is normal. And in the Figure 5.33 (b), increasing discharge ratio to 1.4 which has strengthened steam power that pushes main straight flow to the right bank and has been merged at the same zone that is comparatively more intensive concentrated stream power. But, In the Figure 5.33 (c), increasing discharge ratio to 1.6 it has been behaved as a separate stream flow near to left bank that somehow has attracted to oblique stream.

According to Figure 5.34, to flow with variable discharge ratio (Q_r) with a fixed oblique flow 40^0 angle as a most flatter angle respective to straight flow. In the Figure 5.34 (a), it has been found that with primary Q_r as 1.2, two stream flow has been tried to merge together by pushing method from down mid zone as CS-10 to CS-06 and thus act as single flow criteria. And, In the Figure 5.34 (b) and (c), increasing oblique flow power to 1.4 then it has started to merge meeting zone to downstream zone except some flow has been diverted from that to left part. But angular attraction as 40^0angle has attracted both stream together from meeting zone to downstream zone and thus flowing with single stream is susceptible to revetment.

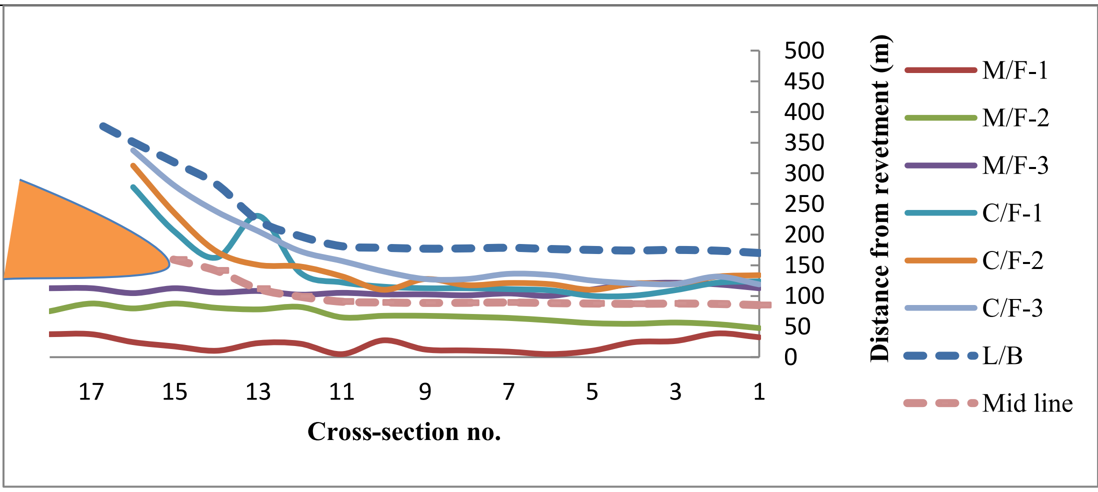
According to Figure 5.35, to flow with variable discharge ratio (Q_r) with a fixed oblique flow 60^0 angle as a sharp angle respective to straight flow. In the Figure 5.35 (a), it has been found that with primary Q_r as 1.2 two stream flow has been tried to merge together by pushing method from meeting zone as CS-13 to downstream zone but acting as some separate diverting channel. But increasing with discharge ratio, it has behaved as a single combined channel from upper mid zone to downstream zone that is adjacent to revetment.



a) T4

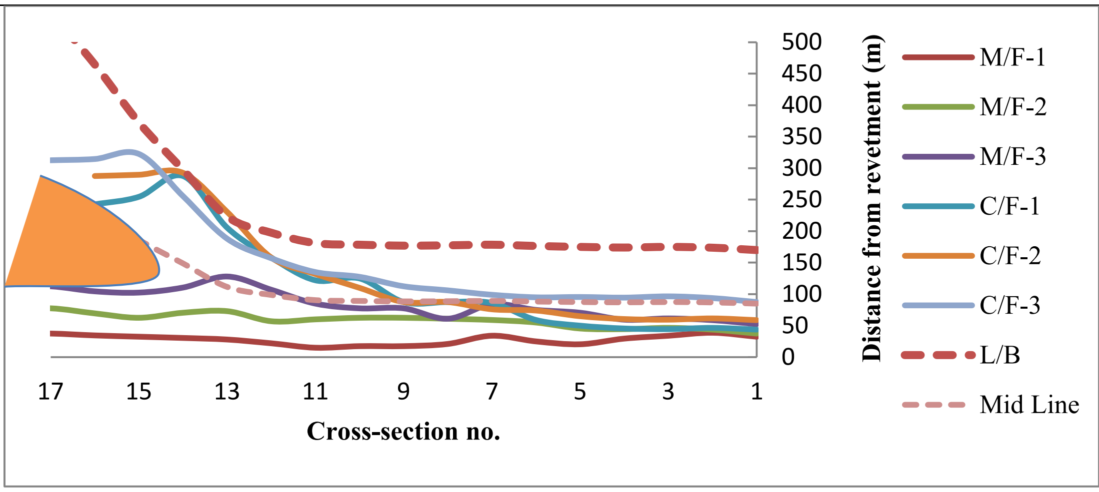


b) T5

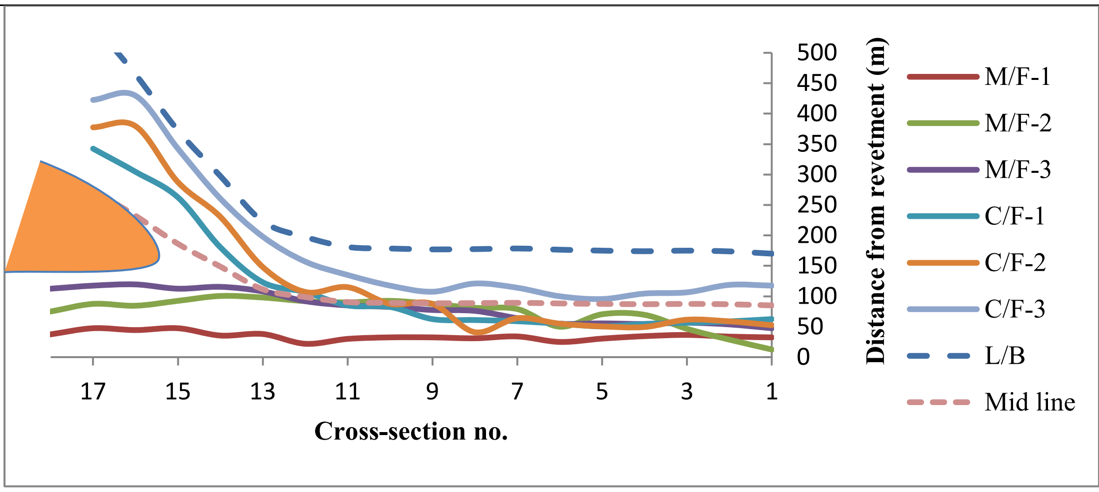


c) T6

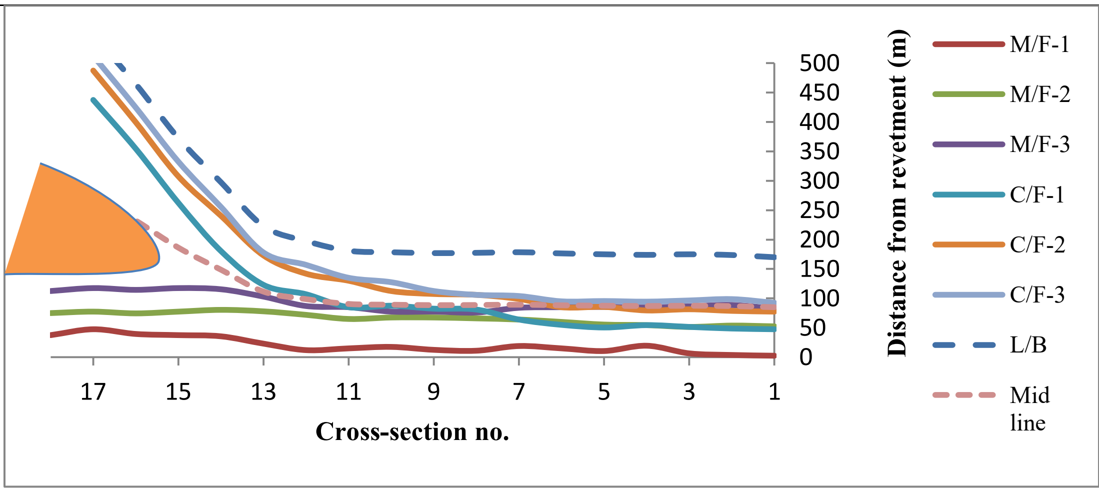
Figure 5.33: Comparison of Surface Flow Line for Variable Q_r at Fixed Θ_o:- 20^0



a) T7

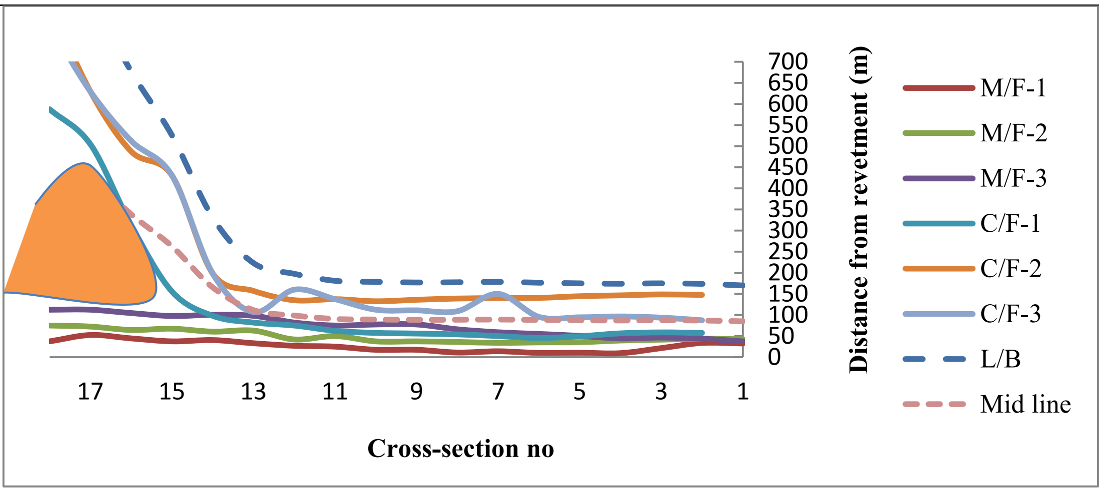


b) T8

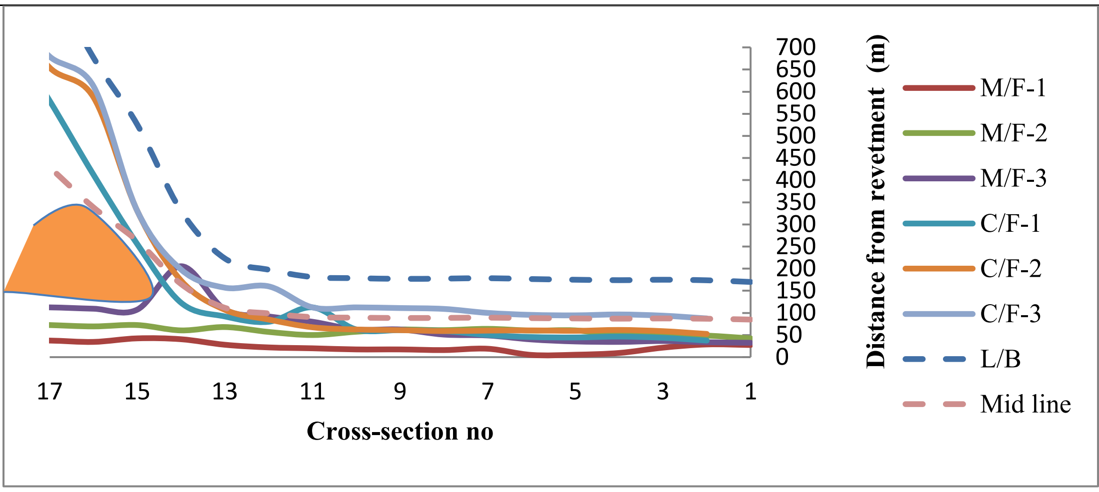


c) T9

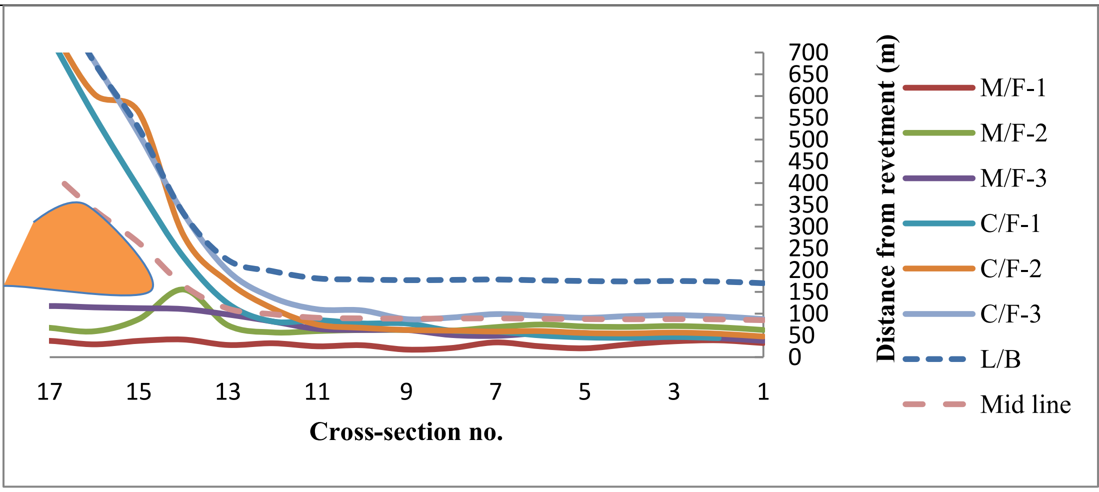
Figure 5.34: Comparison of Surface Flow Line for Variable Q_r at Fixed Θ_o:- 40^0



a) T10



b) T11



c) T12

Figure 5.35: Comparison of Surface Flow Line for Variable Q_r at Fixed Θ_o:- 60^0

5.10 Relationship between Velocity and Scour Depth for Stone Boulder

In conventional design, scour depth is to be assumed by maximum velocity of the channel, not average dominant velocity of the channel. It has been observed some variations with the point of calculation of scour depth although design velocity has been kept maximum in factor of safety, but in economic consideration it should be justified as a whole.

In the physical model, several test run have been maneuvered with some conditions of hydraulic and morphological parameters and so on bank materials (Stone boulder and Geobag). According to run schedule (Table 5.1), a number of test runs have been successfully covered by stone boulder used as bank protection work. Now to analyze the relation between scour depth and velocity, here velocity contour profile has been superimposed to scour profile whether to check the present theory of compilation that maximum scour zone is susceptible to maximum velocity or other else for stone boulder. For the convenience of analysis, there have been given emphasis on some salient features of velocity distribution surfer profile which is responsible for morphological change as scour depth and other hydraulic parameters like sediment concentration, velocity distribution & its extent of area, interchange of velocity range, and over all maximum scour depth and dominant scour profile depth range.

5.10.1 Variable Discharge Ratio (Q_r) with Fixed 20^0 Oblique Angle

In this set of physical model, there have two hydraulic parameters which have to be controlled and according to this limitations it has been selected three stage of discharge ratio (Q_r-1.2,1.4,1.6) with a fixed oblique angle 20^0.

According to above described analysis features, from Figure 5.36 (b), it has been observed that for Q_r-1.2, velocity has been gradually increased towards maximum scour depth contour zone. It has been analyzed that when the two channels has started to meet each other respectively with oblique flow angle, secondary flow has been generated and thus the action of such flow, bed shear stress develops at a level that must be responsible for scour depth. Depending upon the oblique flow discharge, extent of scour depth has increased its vulnerability with the enhancement velocity flow field.

According to Figure 5.36 (c), for Q_r-1.4, two channel has come to merge from mid zone (CS-11) to downstream zone (CS-6) respective to oblique flow angle and the extent of dominant velocity 2.9 to 3.5 m/s has been increased towards scour contour zone and maximum scour depth is approximately 6.9 m that has been developed downstream zone adjacent to launching apron.

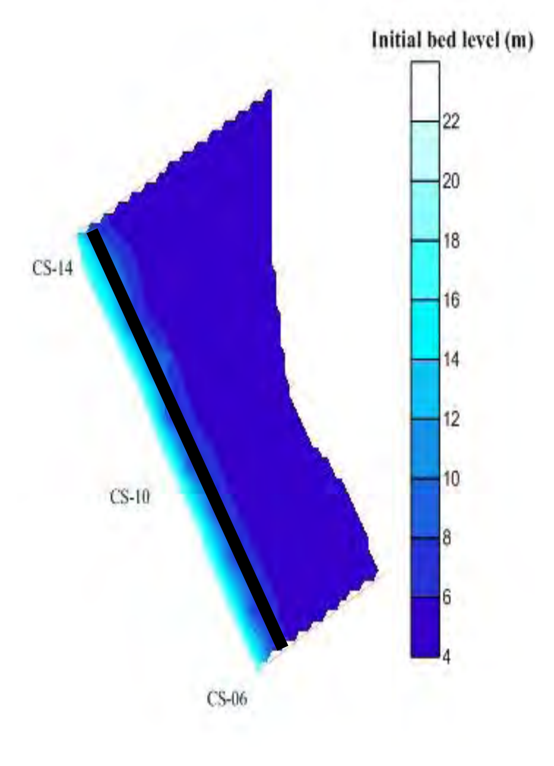
According to Figure 5.36 (d), For Q_r-1.6, velocity range 2.9 to 3.3 m/s has been increased at a level which is almost covered the whole combined channel at all. Here discharge of oblique channel is as high than main channel which has dominated in the combined channel with its stream power and developed maximum scour depth almost same as previous discharge ratio (Q_r) at the mid portion of the combined channel in the mid zone but tends to left bank.

Now it has been observed that maximum scour prone zone depends with the consecutive increase of velocity distribution and its extent of area, oblique flow stream power, bed material as well as sediment concentration of the stream.

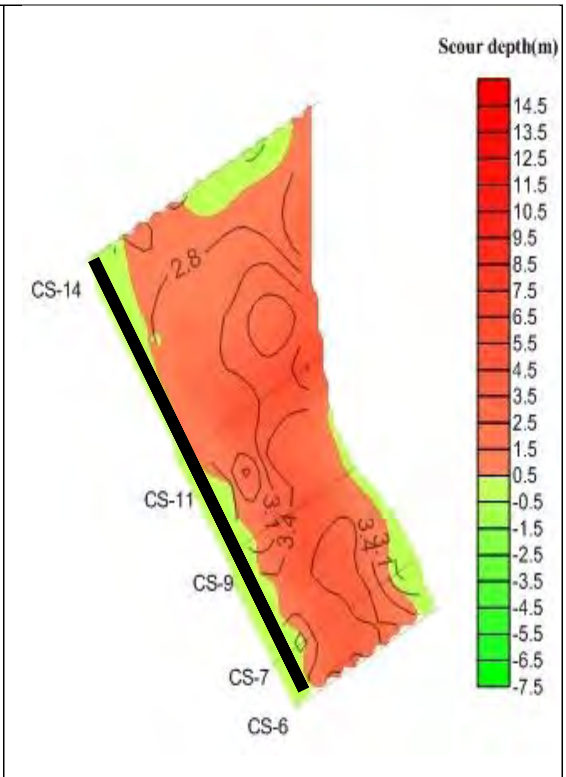
5.10.2 Variable Discharge ratio (Q_r) with Fixed 40^0 Oblique Angle

According to Figure 5.37 (b), for discharge ratio 1.2, it has been observed that velocity distribution has induced to the scour prone zone with increasing its intensity. But it has been found that at between CS-10 and CS-09 maximum scour depth contour about 8.7 m has developed within those velocity range zone, especially alteration of velocity range boundary although it is not high velocity.

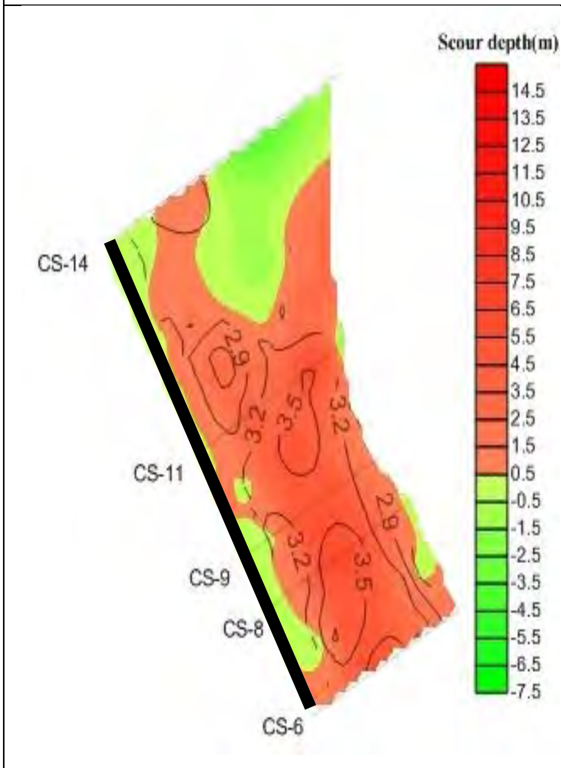
According to figure 5.37 (c), for discharge ratio 1.4, it has been observed that velocity distribution has quickly moved towards scour prone zone from 2.2 m/s to approximate 3.8 m/s up to downstream zone. Basically scour has induced by some factors, at where among them velocity distribution has identified as major factor. It has also found that at the downstream zone velocity has increased gradually adjacent to revetment. Moreover, from figure 5.37 (d) for Q_r- 1.6 scour has also gradually attracted to the right bank at where launching apron has been launched with the enhancement of velocity distribution.



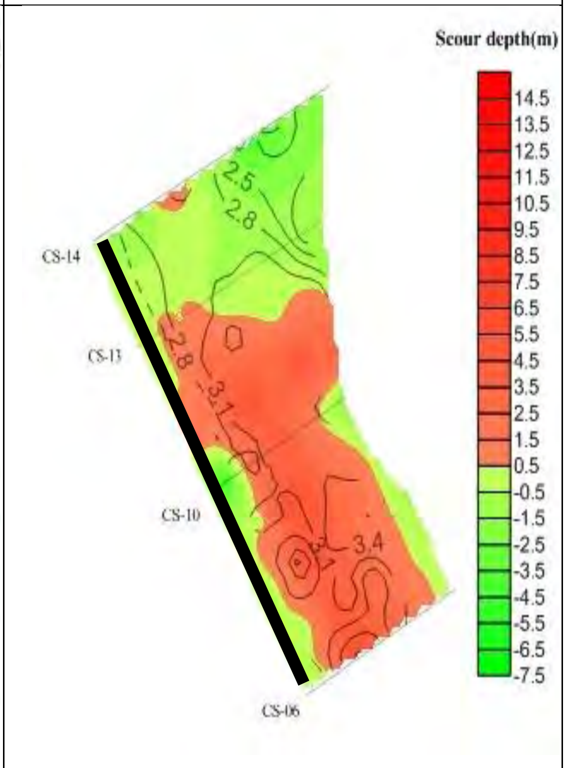
a) Initial Bed level



b) T4

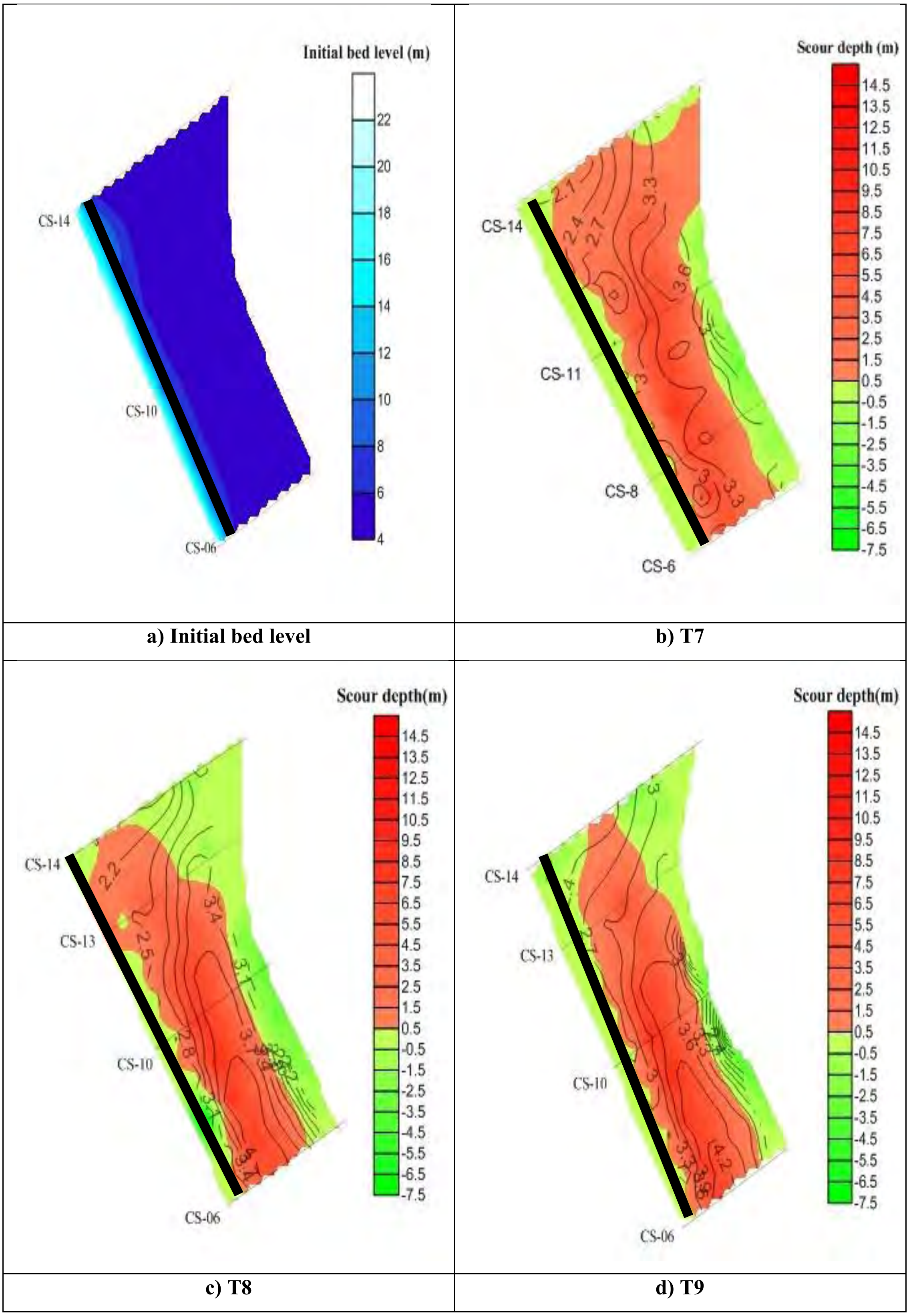


c) T5



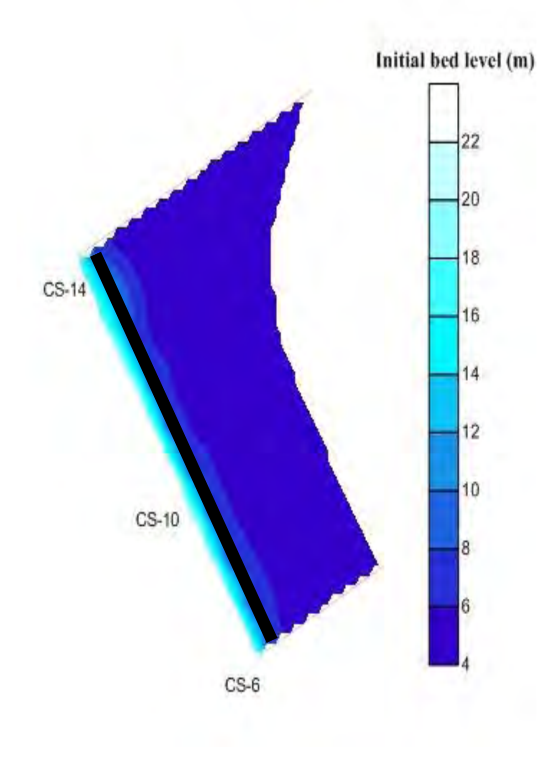
d) T6

Figure 5.36: Relationship between Scour Depth and Velocity for Variable Q_r at Fixed Θ_o:- 20^0

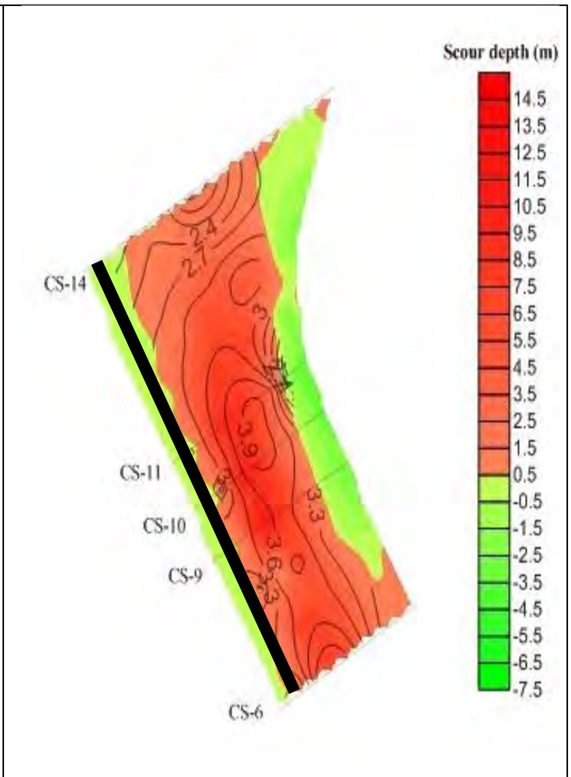


a) Initial bed level | **b) T7** | **c) T8** | **d) T9**

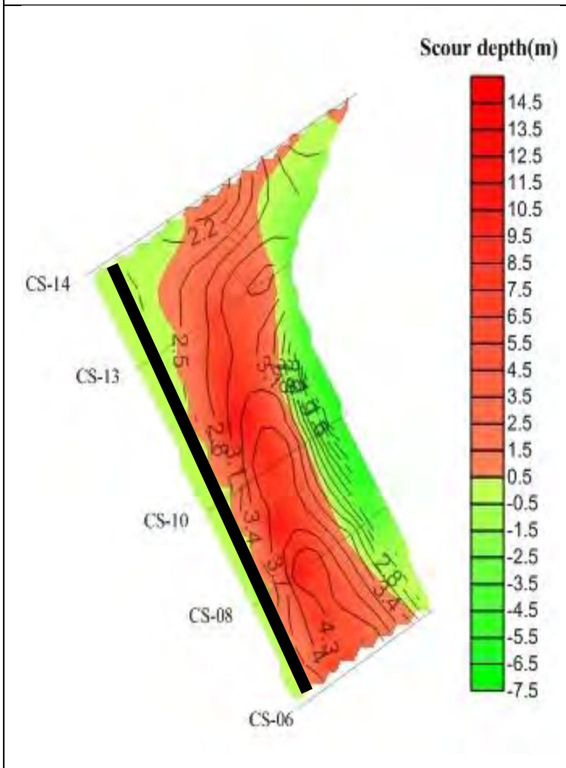
Figure 5.37: Relationship between Scour Depth and Velocity for Variable Q_r at Fixed Θ_o:- 40^0



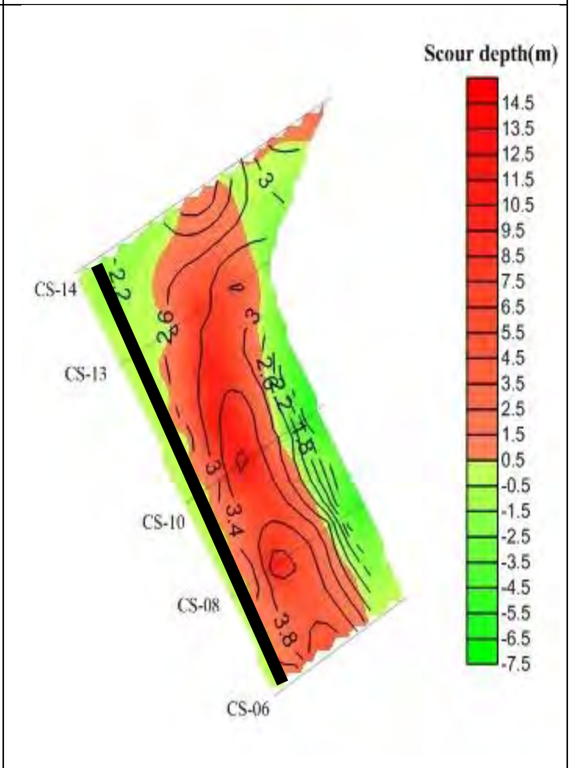
a) Initial bed level



b) T10



c) T11



d) T12

Figure 5.38: Relationship between Scour Depth and Velocity for Variable Q_r at Fixed Θ_o:- 60^0

5.10.3 Variable Discharge ratio (Q_r) with Fixed 60^0 Oblique Angle

According to Figure 5.38 (b), for discharge ratio 1.2, velocity has been consecutively increased from approx. 2.4 m/s to 3.9 m/s. Scour has been moved away from downstream of meeting zone to mid zone along with increasing velocity distribution. Eventually scour has reduced at downstream, but velocity distribution has not reduced at same rate.

From the Figure 5.38 (c), for discharge ratio 1.4 , velocity has been also increased from approx. 2.2 m/s to 4.3 m/s, but it has been shown that scour has also been enhanced along to velocity distribution that is adjacent to revetment due to angular action of oblique flow to the bank protection work.

Now at Figure 5.38 (d) , it has been observed that maximum scour prone area has been developed from meeting zone to upper downstream zone and gradually with reduction. Here, velocity has been increased from approx. 2.2 to 3.8 m/s upto the continuation of scour prone zone. Thus it has been clearly identified that scour is very much incorporated with resultant velocity.

5.11 Comparison of Different Bank Protection Materials

In this research, two types of bank protective materials have been executed to observe the hydraulic parameters and morphological behavior under oblique flow condition. Here, scaled down stone boulder have been used for several tests as T4 to T13 and T0 Then some test runs as T14 to T20 have been done for two types of geo bag as large size geo bag and small geo bag equivalent to the prototype. It has been selected as oblique angle (Θ_o)- 60^0 and maximum discharge ratio (Q_r)-1.6 to compare bank protection materials due to oblique flow.

5.11.1 Comparison of Velocity Distribution

Now from Figure 5.39 (b), velocity has been increased gradually up to 4.6 m/s to the downstream zone. It has been observed that velocity distribution has intensified its vulnerability to the oblique flow direction angle and eventually attacked adjacent to the launching apron area. But from Figure 5.39 (c), it has been investigated that the enhancement of velocity distribution has not distributed gradually rather forming a velocity zone as 2.6 to 4.0 m/s from mid zone to downstream zone. Moreover, a low velocity zone has been developed near to revetment. But from Figure 5.39 (d), it has been observed that velocity distribution has increasingly moved towards downstream zone from 2.3 to 3.7 m/s, although it is lower than large geo bag protection work.

5.11.2 Comparison of Scour Depth

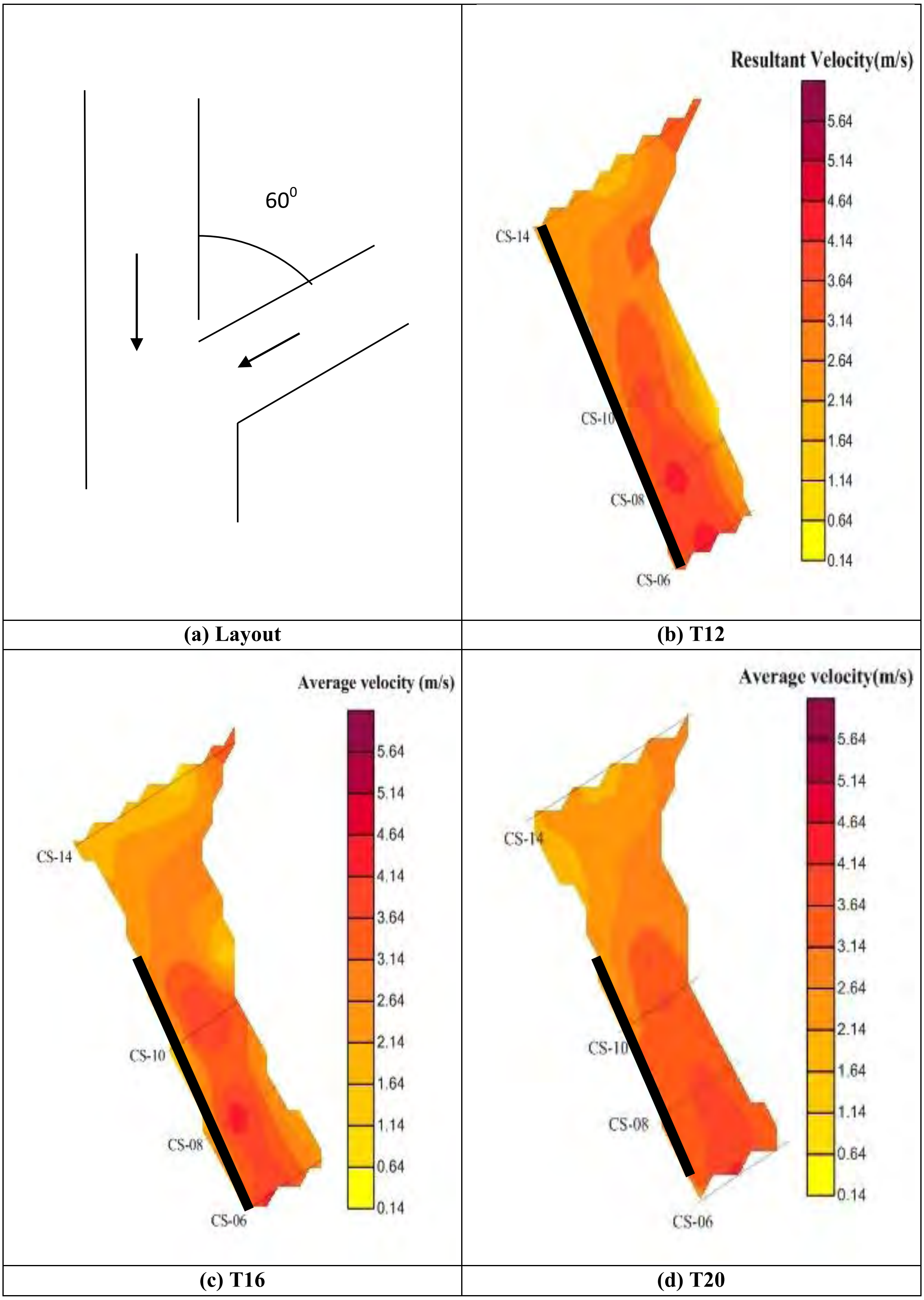
From the Figure 5.40 (b), at the model run T12, it has been found that maximum scour prone zone has developed from CS-13 to CS-08, thus it has reduced eventually. In the other hand a siltation zone has been observed to the left bank line of the combined channel due to the attraction of oblique angle as well as sharpness of angle. Here it has been understood that maximum scour zone has generated far away from launching apron due to proper falling of stone boulder.

But from figure 5.40 (c), and 5.40 (d), scour prone zone has attracted too much to the launching apron and intruded to the revetment due to the irregular mode of falling of geobag. Deposition phenomenon has shown common for sharp angle.

5.11.3 Comparison of Thalweg Pattern

In the figure 5.41 (a), thalweg channel has been gradually intruded to bank protection work flowing through meeting zone to downstream due to inefficient falling behavior of geo bag. But thalweg pattern for Stone boulder has been comparatively far away from the bank protection even as parallel thalweg pattern from revetment line due to the effective falling of stone boulder to the developed scour hole adjacent to launching apron.

But from Figure 5.41 (b), at critical condition whether oblique channel has been conveyed full discharge as oblique flow to the combined channel (Main channel dead) having two types of launching apron (Large geobag & Stone boulder) at revetment, it has been observed that same type thalweg pattern have been developed for both bank protection materials. Although some critical intrusion of scour has been found toward launching apron at meeting zone. Eventually thalweg line has been slightly moved adjacent to revetment conveying to downstream.



(a) Layout (b) T12 (c) T16 (d) T20

Figure 5.39 : Comparison of Velocity Distribution for Different Protective Works at Fixed Q_r:-1.6 and Θ_o:- 60^0

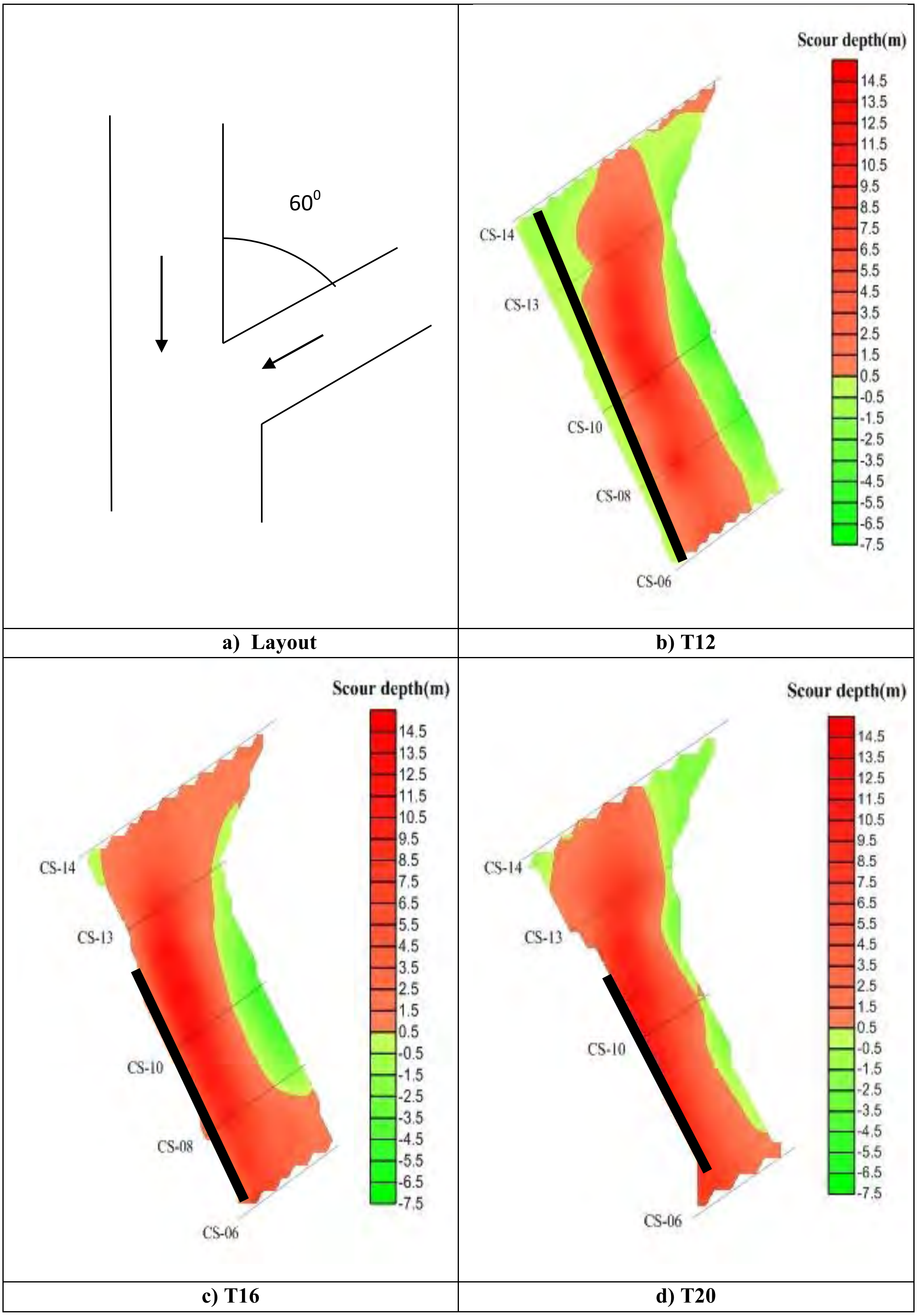
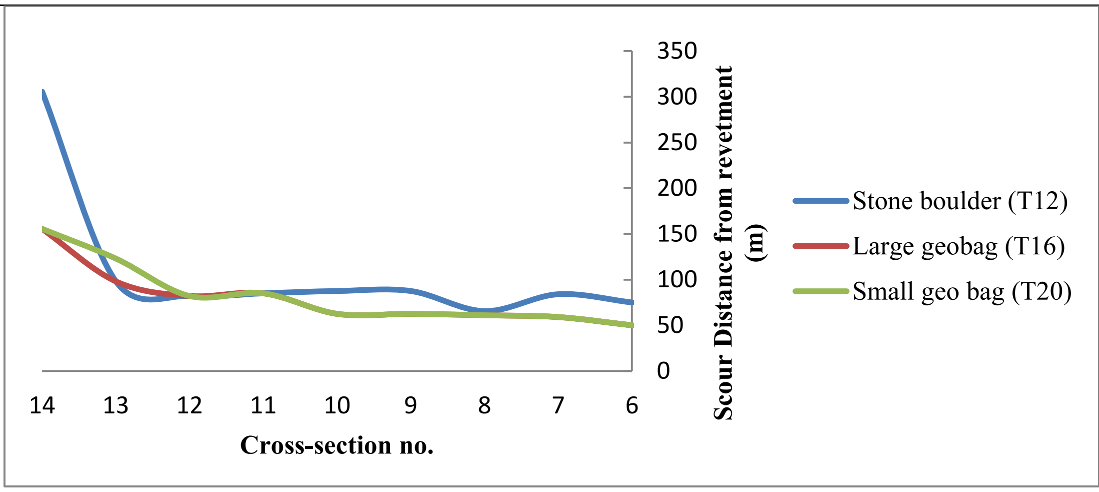
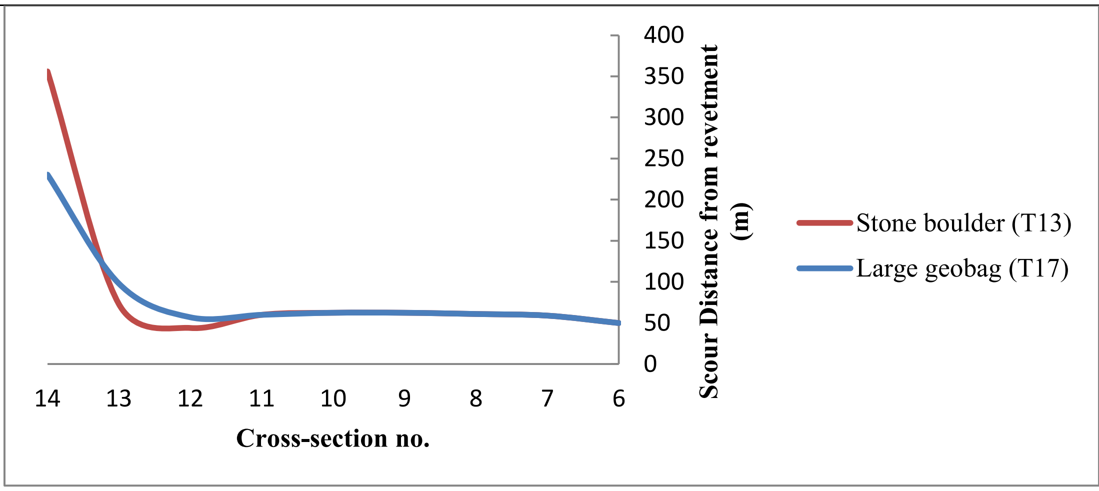


Figure 5.40: Comparison of Scour Depth for Different Protective works at Fixed Q_r:- 1.6 and Θ_o:- 60^0



(a) For, Oblique angle (Θ_o)- 60^0 and Discharge ratio (Q_r)- 1.6



(b) For, Oblique angle (Θ_o)- 60^0 and Only Oblique channel flow

Figure 5.41: Comparison of Thalweg Channel Pattern for Different Bank Protective Works at Different Conditions

Table 5.2: Comparison of Scour Depth for Different Bank Protective Works

Hydraulic parameter	T12	T16	T20	Remarks
	Stone boulder	Large geobag	Small geobag	Sensitivity
Scour depth (prototype), m	15.91 m	15.21 m	12.75 m	Stone boulder
Section	CS-10	CS-11	CS-11	
Zone	Mid zone	Mid zone	Mid zone	
Approximate Scour distance from revetment, m	70m	63m	65m	

5.12 Observation of the Velocity Distribution for Stone Boulder

i) For oblique angle (θ_o)- 20^0

1. Extent of velocity distribution with specific velocity range has increased for the increase of oblique stream power but it may not be higher velocity range. It should be termed as Dominant velocity distribution.
2. Enhancement of velocity distribution has always initiated from upstream to downstream direction.

ii) For oblique angle (θ_o)- 40^0

1. Intensity of velocity distribution has intended to the direction of oblique flow angle.
2. High velocity distribution has found at the most downstream zone. It has increased its vulnerability towards bank protection work due to increase of oblique stream power.
3. Extent of vulnerable velocity distribution has developed with the progression of oblique flow discharge ratio (Q_r).

iii) For oblique angle (θ_o)- 60^0

1. Velocity distribution of Oblique channel has behaved as less extent of distribution for maximum oblique flow angle and discharge ratio.
2. But for minimum oblique flow discharge, average velocity has dominated overall the combined channel.

5.13 Observation of Scour Depth for Stone Boulder

In the research some spectacular observation have been initiated to determine about the hydraulic process as well as morphological behavior of a braided river as where sand bar to attract flow vulnerability on bank protection work .These are as follows –

i) For oblique angle (θ_o)- 20^0

1. Flow concentration is determined by oblique angle.
2. For Q_r-1.2, As discharge difference of both channel is the smallest, so minimum secondary flow generates in the combined channel which reduces the extent of scour

Table 5.3: Comparison of Velocity Distribution at Different zone of the Combined Channel for Stone Boulder (01) Unit: m/s

Position	Element	T4	T5	T6	T0	T13
	Oblique Angle (Θ_o)	20^0	20^0	20^0	Straight	60^0
	Discharge Ratio (Q_r)	1.2	1.4	1.6	Full	Full
Adjacent to Revetment	**Meeting zone**	2.7-3.2	2.8-3.3	2.4-3.4	3.1-3.6	0.4-2.9
	Mid zone	2.7-3.7	2.8-3.8	2.4-3.4	3.1-3.6	2.4-3.9
	Downstream zone	3.2-3.7	2.8-3.8	2.4-3.4	3.1-3.6	2.4-3.9
Mid Portion	**Meeting zone**	2.2-3.2	2.8-3.3	2.4-3.4	3.1-3.6	1.4-4.4
	Mid zone	2.7-3.7	2.8-3.8	2.9-3.4	3.1-3.6	2.4-3.9
	Downstream zone	3.2- 3.7	3.3-3.8	2.4-3.4	3.1-3.6	2.4-3.9

Table 5.4: Comparison of Velocity Distribution at Different Zone of the Combined channel for Stone Boulder (02) Unit: m/s

Position	Element	T7	T8	T9	T0	T13
	Oblique Angle (Θ_o)	40^0	40^0	40^0	Straight	60^0
	Discharge Ratio (Q_r)	1.2	1.4	1.6	Full	Full
Adjacent to Revetment	**Meeting zone**	1.8-2.7	1.6-3.0	2.1-3.0	3.1-3.6	0.4-2.9
	Mid zone	2.8-3.2	2.1-3.5	2.6-3.5	3.1-3.6	2.4-3.9
	Downstream zone	2.8-3.2	2.6-4.0	3.5-4.6	3.1-3.6	2.4-3.9
Mid Portion	**Meeting zone**	2.3-3.7	1.6-3.5	2.1-3.5	3.1-3.6	1.4-4.4
	Mid zone	2.8-3.7	3.1-4.0	3.1-3.6	3.1-3.6	2.4-3.9
	Downstream zone	2.8-3.7	3.6-4.1	3.6-4.5	3.1-3.6	2.4-3.9

Table 5.5: Comparison of Velocity Distribution at Different Zone of the Combined Channel for Stone Boulder (03) Unit: m/s

Position	Element	T10	T11	T12	T0	T13
	Oblique Angle (Θ_o)	60^0	60^0	60^0	Straight	60^0
	Discharge Ratio (Q_r)	1.2	1.4	1.6	Full	Full
Adjacent to Revetment	**Meeting zone**	1.7-3.1	2.1-3.1	2.1-3.0	3.1-3.6	0.4-2.9
	Mid zone	2.7-3.6	2.6-4.1	2.6-4.0	3.1-3.6	2.4-3.9
	Downstream zone	2.7-3.6	3.1-4.6	3.1-4.0	3.1-3.6	2.4-3.9
Mid Portion	**Meeting zone**	1.7-3.6	1.6-3.6	1.6-3.0	3.1-3.6	1.4-4.4
	Mid zone	3.2-4.1	3.1-4.1	3.1-4.0	3.1-3.6	2.4-3.9
	Downstream zone	3.7-4.2	3.6-4.6	3.6-4.5	3.1-3.6	2.4-3.9

and maximum scour prone area develops just far away from meeting zone.

3. Flow concentration has increased due to the enhancement of oblique flow discharge ratio upto 1.6 along the left bank of combined channel with smooth oblique angle as if flow velocity has reduced at the char mouth that increasing deposition. It has observed due to the action of the curvature of left bank line.

4. Increasing oblique stream force has pushed onto gradually lowered main straight flow, as a result there have created a reverse circular current at the downstream of meeting zone which is partially influenced to movement of sand bar to the direction of oblique angle.

5. Vulnerability has come to near revetment along with progression of oblique flow discharge.

ii) For oblique angle (θ_o)- 40^0

1. Flow separation and oblique flow concentration process have been involved together.

2. Flow separation with defined angle has developed a void stagnant zone as deposition at left bank.

Table 5.6: Detail of Scour Depth at Different Flow Conditions for Stone Boulder

Test run	Angle	Discharge ratio (Q_r) [$Q_o : Q_m$]	Maximum Scour depth (m)	Distance from Meeting zone (m)	Distance from Revetment (m)	Approximate Position (C/S)	Extent of Scour prone area (C/S)	Remarks
04	20^0	1.2 : 1	6.20	194	138	CS-11	CS-12 to CS-07	No Left bank deposition
05	20^0	1.4 : 1	6.91	197	135	CS-07	CS-13 to CS-06	Deposition at char mouth
06	20^0	1.6 : 1	6.96	438	62	CS-08	CS-13 to CS-06	Deposition (At meeting zone)
07	40^0	1.2 : 1	8.70	300	67	CS-09	CS-13 to CS-06	Deposition (L.B)
08	40^0	1.4 : 1	10.41	299	63	CS-09	CS-13 to CS-06	Deposition (L.B)
09	40^0	1.6 : 1	11.16	315	70	CS-09	CS-11 to CS-06	Deposition (L.B)
10	60^0	1.2 : 1	11.26	310	71	CS-09	CS-13 to CS-07	Deposition (L.B)
11	60^0	1.4 : 1	14.86	212	72	CS-10	CS-13 to CS-06	Deposition (L.B)
12	60^0	1.6 : 1	15.91	359	70	CS-10	CS-13 to CS-06	Deposition (L.B)

3. Oblique flow concentration has attracted secondary flow near to revetment.

4. Gradually increasing oblique flow stream power has pushed off straight flow generating reverse flow toward meeting zone thus creates siltation at char mouth.

5. Scour depth has reduced consecutively flowing through downstream zone.

iii) For oblique angle (θ_o)- 60^0

1. Flow separation process has pre-dominantly increased with the increase of oblique angle and thus initiated deposition along left bank of oblique channel.

2. Scour depth has declined gradually at downstream.

3. Combined effect of comparatively sharper oblique angle and enhancing oblique stream power has significantly effected on deposition process at right bank of meeting zone basically due to upstream back water effect.

4. Flow has concentrated to the outer bend of combined channel increasing with oblique flow discharge (right bank).

5.14 Summary

The test results and observations from the physical model setup have been described in this chapter. To analyze different hydraulic and morphological parameters, it has been expressed in contour maps and graphical presentation. Hydraulic parameters such as velocity distribution and scour depth have been shown by contour profile with different color identification. In addition to comparison of both scour depth and velocity with different oblique angle and discharge ratio have been analyzed by graphical analysis. Finally, the relation between scour depth and velocity has been determined. In this chapter, a comparative analysis has been carried out to determine the efficiency of bank protective materials as with Stone boulder and geobag.

CHAPTER SIX
CONCLUSIONS AND RECOMMENDATIONS

6.1 General

To understand the fluvial process of a channel and hydro-morphological parameters of bank protection work at straight bank, induced by oblique flow phenomenon, it has been observed physically at where it occurred or attacked and what process has involved and how the process has proceeded to. In this study, some key parameters has been demonstrated to identify and compare the process depending upon various parameters such as, smoothness of oblique flow angle, distribution of average velocity, dominant average velocity, local scour or deposition, extent of scour, intensity of scour adjacent launching apron, siltation at meeting zone of two channel and left bank.

6.2 Conclusions of the Study

There have been carried out 21 (Twenty one) model run to observe aimed objectives in this research work. Among these model run, at first 3 (three) runs have been performed with no protection work (earthen natural bank). Basically, it has been performed for the requirements of calibration parameters and just carry on as individual study, no comparison with other model run has not been done in the research study. Stone boulder and geobag has been used as the bank protection works at revetment for the remaining model run. Some observations have been concluded among these model run under different conditions. These are as follows:

1. The effect of oblique flow at straight natural earthen bank is not only visible but also measureable. Here, scour depth has increased steadily from 5.50 m to 10.60 m for varying oblique flow angle from 20^0 to 60^0 at fixed median discharge ratio (Q_r)-1.4.

2. Increasing discharge ratio (Q_r) from 1.2 to 1.6 with fixed oblique flow angle (Θ_o)-20^0 average velocity has been increasingly varied approximately from 2.64 m/s to 3.80 m/s in combined channel for stone boulder used as bank protective materials.

3. Increasing discharge ratio (Q_r) from 1.2 to 1.6 with fixed oblique flow angle (θ_o)-40^0 average velocity has been increasingly varied approximately from 2.0 m/s to 4.50 m/s in combined channel for stone boulder used as bank protective materials.

4. Increasing discharge ratio (Q_r) from 1.2 to 1.6 with fixed oblique flow angle (θ_o)-60^0 average velocity has been increasingly varied approximately from 1.7 m/s to 4.60 m/s in combined channel for stone boulder used as bank protective materials.

5. Average velocity has been increased adjacent to revetment with gradual distribution in the downstream of the channel and its intensity has been found vulnerable to the direction of oblique flow angle as 60^0 but for discharge ratio-1.4 measured up to 4.6 m/s.

6. Maximum scour depth has been increased eventually from 6.2 m to 6.96 m, 8.7 m to 11.16 m, 11.26 m to 15.91 m with the progression of discharge ratio from 1.2 to 1.6 respectively at 20^0, 40^0, 60^0 whereas stone boulder used as bank protective works.

7. Maximum scour depth has been raised vulnerably from 6.2 m to 11.26 m, 6.91 m to 14.86 m, 6.96 m to 15.91 m with the progression of oblique angle from 20^0 to 60^0 respectively at 1.2, 1.4, 1.6 whereas stone boulder used as bank protective works.

8. In this study, it has been observed that oblique angle is more susceptible than discharge ratio belonging to its flow velocity distribution and scour depth.

9. Thalweg channel has been attracted to closely approx. 50-75 m distance far away from revetment (Stone boulder) along meeting zone to downstream zone with varying discharge ratio with fixed oblique angle and vice-versa that enhancing vulnerability of bank gradually.

10. Scour channel has been attracted to revetment (Stone boulder) with the advancement of oblique angle from meeting zone.

11. Maximum scour depth has been generated approximately 15.21 m for large geobag and its intensity of scour has been near to revetment as approx. 63m away from revetment. But for stone boulder maximum scour depth 15.91 m has been

generated approx. 70m far away from revetment but for small geobag maximum scour depth 12.75 m generating 65 m far away from revetment.

12. It has been observed that velocity has gradually increased into the scour prone area but it is limited up to lower part of mid zone. On the other hand it has been found that maximum velocity zone has been observed at downstream recovery zone, but scour prone area has been mostly developed within meeting zone to upper downstream zone.

6.3 Recommendations for the Further Study

1. Oblique angle may be increased up to 90^0 to find out the most vulnerable condition for the development of oblique flow.

2. In this research, oblique angle has been produced at 20^0,40^0 and 60^0, but it can be further done with small interval of oblique angle as 2.5^0 or 5^0 to determine critical oblique angle.

3. It has been observed with some hydraulic and morphological parameters of the combined channel as if char moves toward oblique channel but it could be further investigated as if char could be moved toward main channel or direction of oblique flow.

4. Bed material can be used as scaled light materials to observe the actual scour phenomenon.

5. In this research, stone boulder and geobag have been used as bank protective materials but it can be done by mixed bank protective materials to observe their efficiency under different oblique flow conditions.

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APPENDIX- A

PICTORIAL PRESENTATION
OF
PHYSICAL MODEL

Physical Model Setup Construction Phase: (Left to Right)

Research Name Board

Layout of Oblique Channel

Excavation Work

Main Channel Brick work

Main Channel (Fixed Bed)

Leveling Machine Set-up

Oblique Channel Brick Work

Stilling Basin of Oblique channel

Figure A.1: Pictorial View of Physical Model Setup Construction at Field

Continued: (Left to Right)

	
Sand Sieving	**Model Bed Preparation**
	
Sand Compaction	**Perforated Drainage Pipe**
	
Meeting zone (Partial view)	**Meeting zone (Full view)**
	
Preparation of Small geobag	**Preparation of Large geobag**

Figure A.2: Pictorial View of Physical Model Setup Construction at Field

Model Running Phase: (Left to Right)

	
Velocity Accelerator	**Sand Feeding**
	
Rehbokh's Weir	**Tail Gate**
	
Initial Bed (Calibration-T1)	**Final Bed (Calibration-T1)**
	
Initial Bed (Calibration-T3)	**During Run (Calibration-T3)**

Figure A.3: Pictorial View of Model Run Setup at Different Conditions

Continued: (Left to Right)

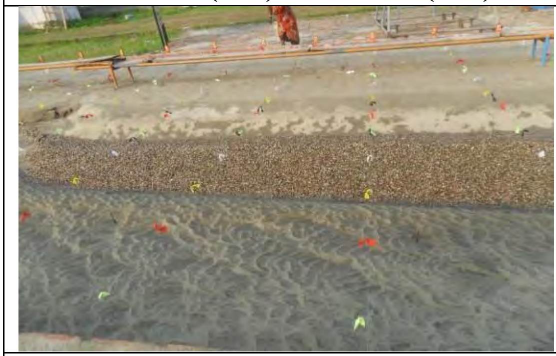
	
Initial Bed (T4)	**Final Bed (T4) / Initial Bed (T5)**
	
Final Bed (T5) / Initial Bed (T6)	**Final Bed (T6)**
	
During Run (T7)	**Final Bed (T8) / Initial Bed (T9)**
	
Final Bed (T9)	**Initial Bed (T10)**

Figure A.4: Pictorial View of Model Run Setup at Different Conditions

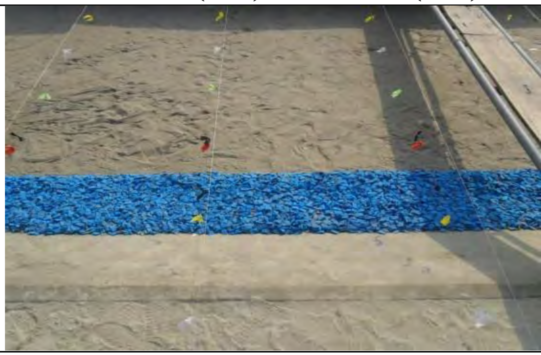
Continued: (Left to Right)

Final Bed (T10)/Initial Bed (T11)

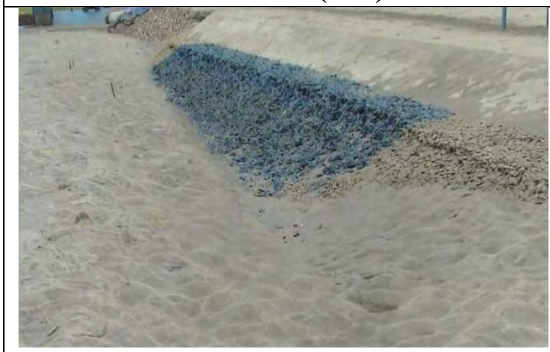
Final Bed (T11)/Initial Bed (T12)



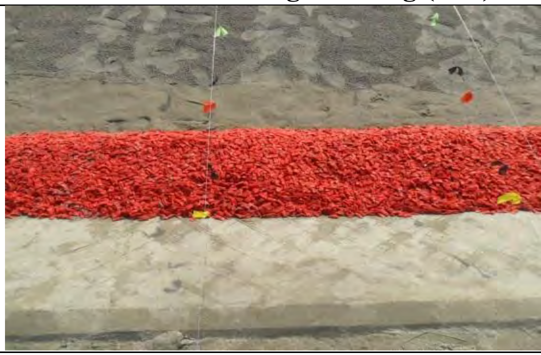
Final Bed (T12)



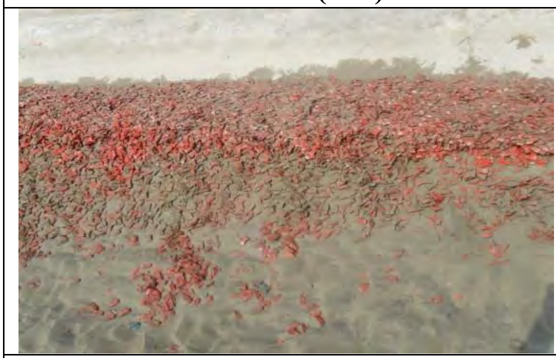
Initial Bed for Large Geobag (T14)



Final Bed (T16)



Initial Bed for Small Geobag (T18)



Final Bed (T20)

Figure A.5: Pictorial View of Model Run Setup at Different Conditions

APPENDIX- B

SAND FEEDING DATA

Table B.1: Sand Feeding at Different Conditions of Model Run for Stone Boulder

Test No.	Oblique Angle (Θ_o)	Discharge Ratio (Q_r)	Design Value		Field value		Unit
			Main Channel	Oblique Channel	Main Channel	Oblique Channel	
1	20	1.4	1.76	12.86	1.87	10.09	ft^3/hr
2	40	1.4	1.76	12.86	1.87	10.09	ft^3/hr
3	60	1.4	1.76	12.86	1.87	10.09	ft^3/hr
4	20	1.2	1.91	9.56	2.40	7.69	ft^3/hr
5	20	1.4	1.76	12.86	2.40	11.53	ft^3/hr
6	20	1.6	0.74	17.02	2.21	13.84	ft^3/hr
7	40	1.2	1.91	9.56	1.87	11.33	ft^3/hr
8	40	1.4	1.76	12.86	1.87	11.66	ft^3/hr
9	40	1.6	0.74	17.02	1.14	13.02	ft^3/hr
10	60	1.2	1.91	9.56	2.50	9.50	ft^3/hr
11	60	1.4	1.76	12.86	1.71	13.03	ft^3/hr
12	60	1.6	0.74	17.02	1.56	14.45	ft^3/hr
13	60	Full	Nil	65.45	Nil	65.0	ft^3/hr

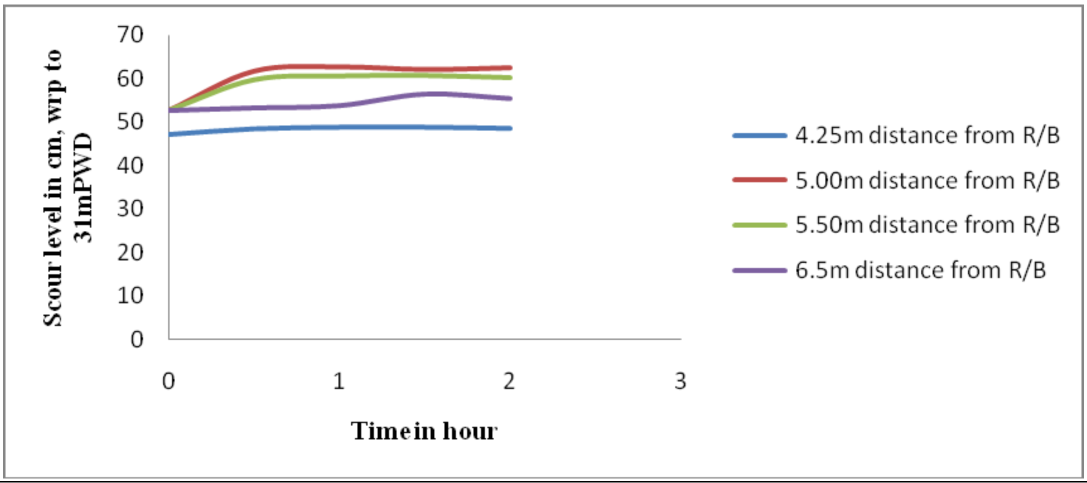
*N.B: Sand feeding has also been applied to remaining model run setup for different sizes of geobag.

APPENDIX- C

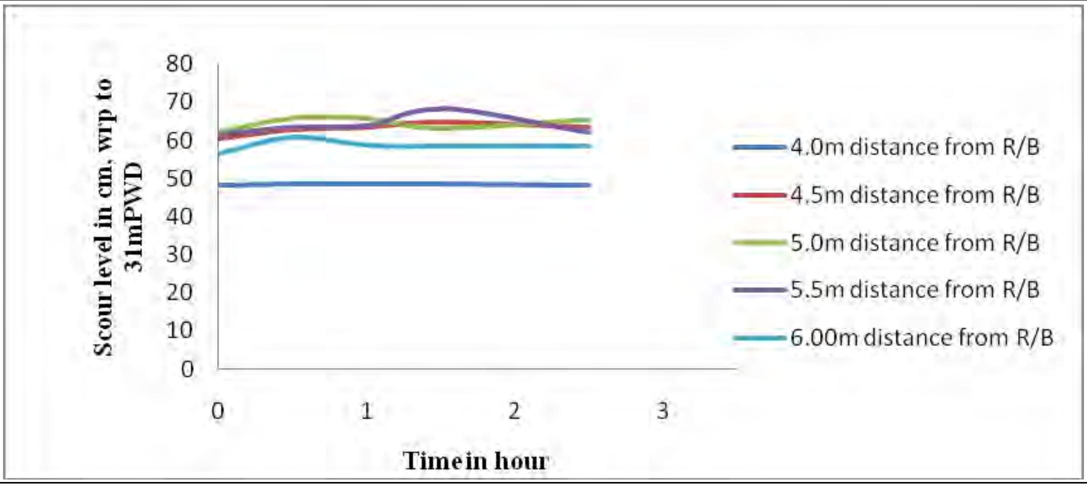
DYNAMIC EQUILLIBRIUM

FOR

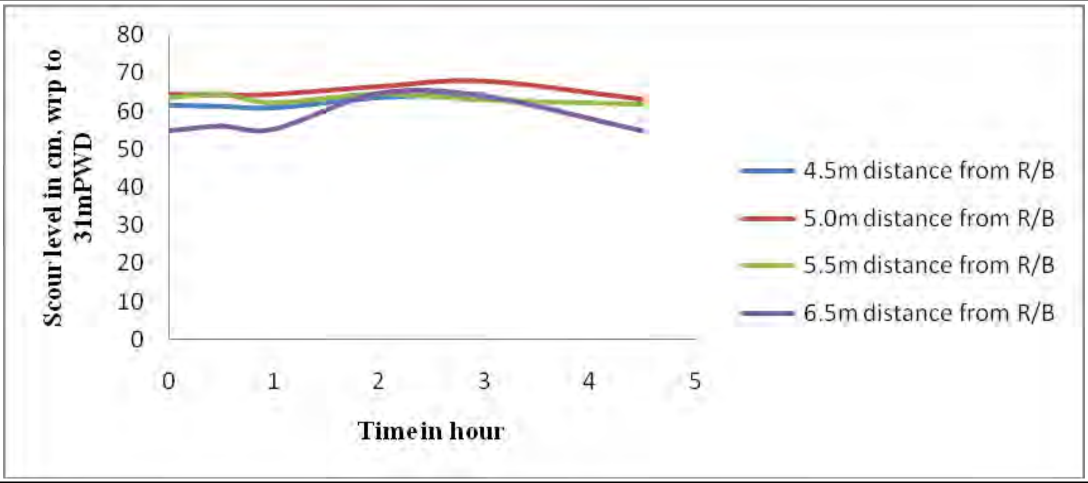
STONE BOULDER



a) T4



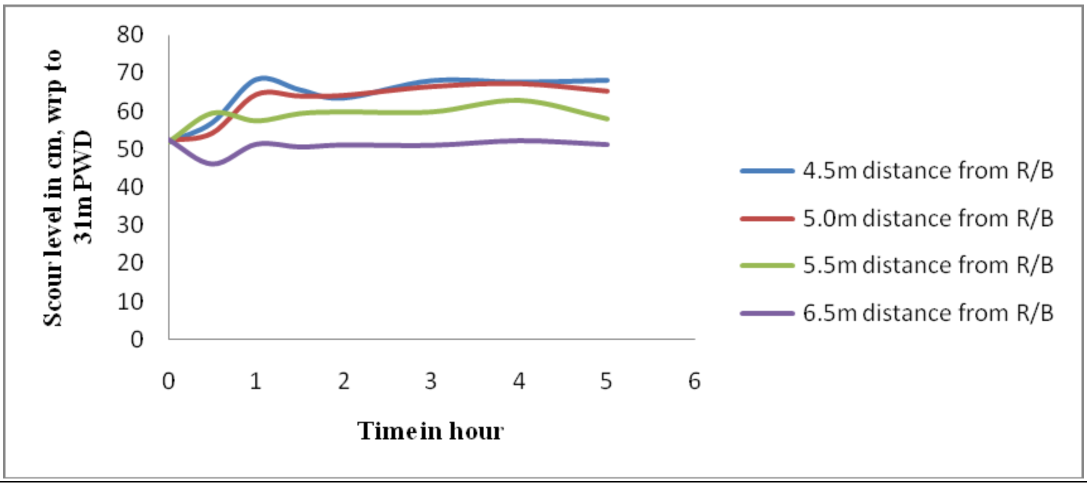
b) T5



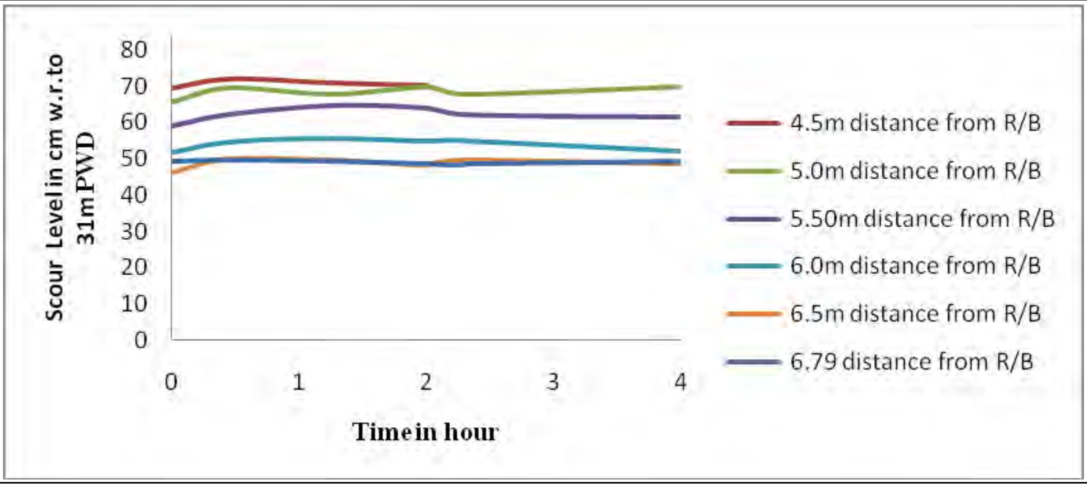
c) T6

Figure C.1 : Scour Equilibrium for Variable Ratio at Fixed 20^0 Oblique Angle;

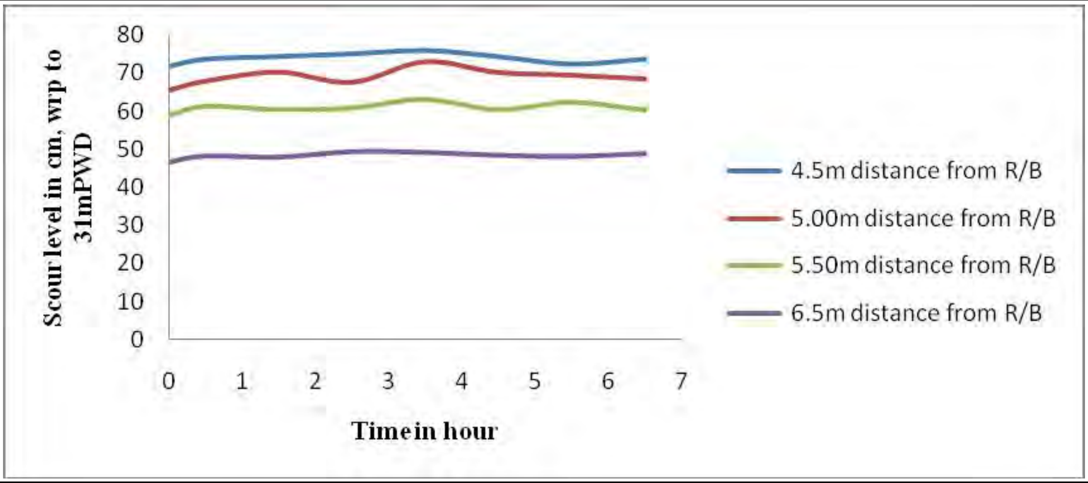
a) For, Q_r-1.2 b) For, Q_r-1.4 c) For, Q_r-1.6



a) T7



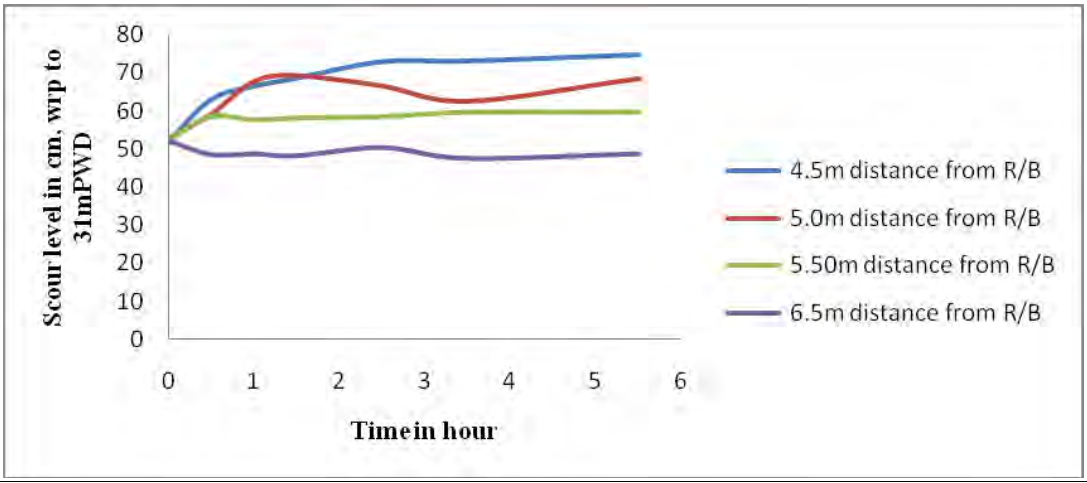
b) T8



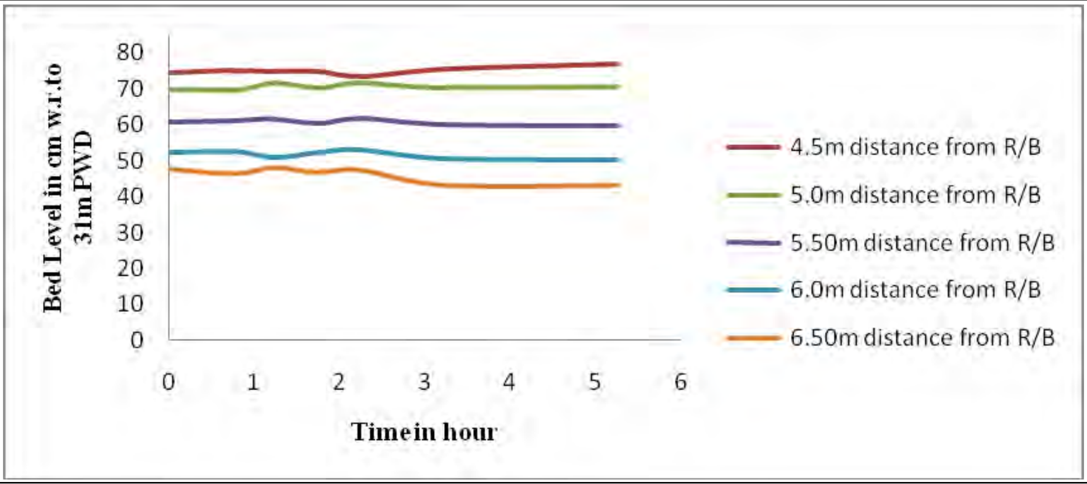
c) T9

Figure C.2 : Scour Equilibrium for Variable Ratio at Fixed 40^0 Oblique Angle;

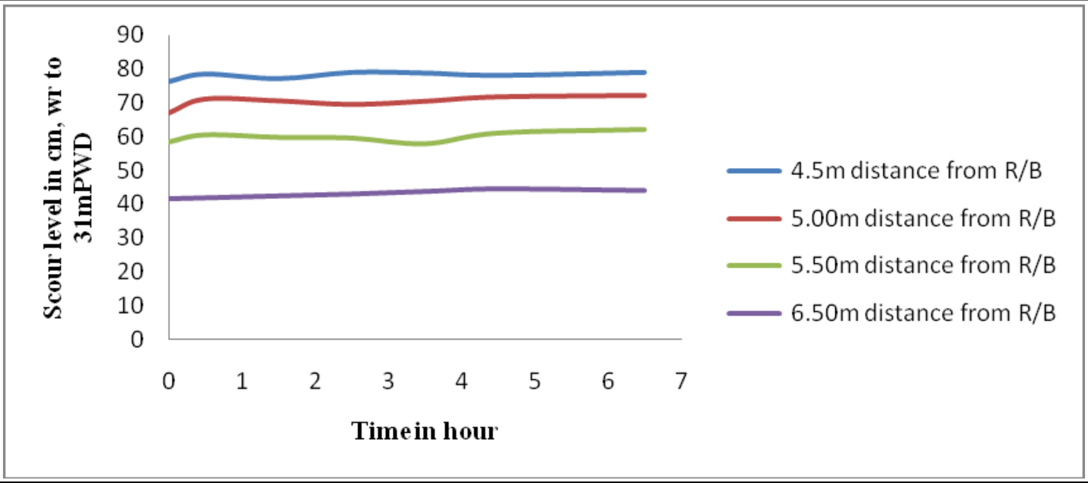
a) For, Q_r-1.2 b) For, Q_r-1.4 c) For, Q_r-1.6



a) T10



b) T11



c) T12

Figure C.3 : Scour Equilibrium for Variable Ratio at Fixed 60^0 oblique angle;

a) For, Q_r-1.2 b) For, Q_r-1.4 c) For, Q_r-1.6

APPENDIX- D

CALIBRATION OF WEIR FOR DISCHARGE

Discharges of the Main Channel and Oblique Channel have been controlled by gate valves those have been fixed at Weir-1 (For main channel) and Weir-2 (For oblique channel). These specified discharges have been calculated by Rebohk's formula with maintaining the effective head of water at Weir-1 and Weir-2. Some particulates of these two weirs have been specified below:

a) Features for Weir-1 (For Main Channel):-

Weir height : 0.416 m
Weir length : 1.80 m
Initial head : 0.01 m
Initial discharge : 0.01 m^3/s

Table D.1: Calibration of Weir-1 (For Main Channel)

Effective head, H_e (m)	Coefficient of Discharge, K	Velocity of Approach (m/s)	Discharge with Velocity Approach (m^3/s)	Discharge without Velocity Approach (m^3/s)
0.118	1.852	0.140	0.137	0.135
0.119	1.852	0.142	0.139	0.137
0.120	1.853	0.143	0.140	0.139
Intermediate values are not shown here (Rate of head variation usually 0.001)				
0.125	1.855	0.151	0.150	0.148
0.126	1.856	0.153	0.151	0.149
0.127	1.857	0.155	0.153	0.151
Intermediate values are not shown here (Rate of head variation usually 0.001)				
0.132	1.859	0.163	0.163	0.161
0.133	1.860	0.165	0.165	0.162
0.134	1.861	0.166	0.167	0.164
Intermediate values are not shown here (Rate of head variation usually 0.001)				
0.218	1.908	0.313	0.360	0.350
0.219	1.908	0.315	0.363	0.352
0.220	1.909	0.317	0.366	0.355
0.221	1.910	0.319	0.368	0.357
0.222	1.910	0.320	0.371	0.360

b) Features for Weir-2 (For Oblique Channel):-

Weir height : 0.511 m

Weir length : 1.52 m

Initial head : 0.01 m

Initial discharge : 0.01 m^3/s

Table D.2: Calibration of Weir-2 (For Oblique Channel)

Effective head, H_e (m)	Coefficient of Discharge, K	Velocity of Approach (m/s)	Discharge with Velocity Approach (m^3/s)	Discharge without Velocity Approach (m^3/s)
0.167	1.862	0.188	0.196	0.193
0.168	1.862	0.190	0.198	0.195
0.169	1.863	0.191	0.200	0.197
Intermediate values are not shown here (Rate of head variation usually 0.001)				
0.174	1.865	0.199	0.209	0.206
0.175	1.865	0.200	0.211	0.208
0.176	1.866	0.202	0.213	0.209
0.177	1.866	0.203	0.215	0.211
Intermediate values are not shown here (Rate of head variation usually 0.001)				
0.181	1.868	0.209	0.222	0.219
0.182	1.869	0.211	0.224	0.221
0.183	1.869	0.212	0.226	0.222
Intermediate values are not shown here (Rate of head variation usually 0.001)				
0.245	1.897	0.310	0.359	0.350
0.246	1.898	0.312	0.362	0.352
0.247	1.898	0.314	0.364	0.354
0.248	1.899	0.315	0.366	0.356
0.249	1.899	0.317	0.369	0.359
0.250	1.900	0.319	0.371	0.361